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Spatial-temporal neighborhood-scale urban water demand estimation

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By

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B.S., Computer Engineering, University of Missouri, 1986
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THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

Geography

The University of New Mexico
Albuquerque, New Mexico

May 2011

Dedication

This is dedicated to my friends and family, but mostly to Victoria for allowing me the space to pursue this interest.

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I have many people to thank for helping me along the way: Dr. Paul Zandbergen of the University of New Mexico (UNM) Geography Department for detailed, experienced, and thoughtful guidance with my thesis research; Dr. Paul Matthews of the UNM Geography Department for counsel on coursework and thesis topics; Dr. Timothy McPherson of Los Alamos National Laboratory (LANL) for guidance, support, and creativity in addressing technical challenges; the City of Santa Fe (City) Water Division, including Rick Carpenter for introducing me to City staff, Eric Armstrong for helping me obtain measurements from the supervisory control and data acquisition (SCADA) system, and especially Robert Jorgensen, P.E., for taking time from his schedule on several occasions to meet and discuss the City pipeline network; Jacob Young of Brown and Caldwell for clarifying technical details about the City of Santa Fe 2009 Master Plan; Dr. Darrin Visarraga of LANL for discussion on water systems and mathematics, and, especially, for his detailed review of and comments on parts of the thesis; Dr. Sheila Van Cuyk, Dr. Brett Okhuysen, and Dr. Dave Judi of LANL for guidance related to water systems and statistics; Dr. Tom Caudell of UNM for providing me a comfortable on-campus workspace in the Visualization Laboratory; Steve Smith of Los Alamos Visual Analytics (LAVA) for general support; Dr. Kevin Saeger and Dr. Kristin Omberg of LANL for allowing me to integrate my school and work schedules; Dr. Brad Cullen of the UNM Geography Department for getting me up to speed on Geographic thought, concepts, and history; Jaz Knight for keeping us students on-track and informed; Paul Neville for initially hooking me into the geography department by offering two evening courses in remote sensing and image analysis; and my fellow geography graduate

students who, as an interdisciplinary group of engaged and thoughtful people with diverse perspectives and interests, have enriched my experience at UNM.

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ABSTRACT OF THESIS

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Abstract

Water distribution systems are one of the vital infrastructures within the urban environment. The urban population is highly dependent on a reliable, clean, safe, and affordable supply of drinking water. Understanding and characterizing the demand for water on municipal water distribution systems is critical for managing this resource. A reasonable estimate of water demand for a municipal system would provide meaningful characterization and potentially enable defensible hydraulic analyses of that system. Much of the previous research and methods on estimating demand required detailed system data to estimate demand at coarser spatial and temporal resolutions for a specific system. The objective of this research, in contrast, is to develop a method to estimate water demand at high spatial (e.g., neighborhood-scale) and temporal (e.g., one-hour) resolutions for any municipal water distribution system in the U.S. using publically available data. The demand estimation method was implemented as an ArcGIS ArcMap extension.

The proposed demand estimation methodology was applied to a real municipal system in the U.S. A distribution pipeline network and demand model for the City of Santa Fe, New Mexico master plan was used to assess the performance of the research method. The method was first calibrated using the extent of the pipeline network within one pressure zone of the water system. The calibrated method was then validated using

different, independent pressure zones within the water system. The results indicate that the estimate of water demand using the initial, default parameter values produced a relative error which was within the typical variance between an average day and a peak day for a municipal system. The best-fit validation case produced a demand estimate with a relative error for the entire Santa Fe system which was shown to be within the smaller tolerance of error required for hydraulic analyses for engineering studies. This suggests that the demand estimates produced, based on the best-fit validation case, are more likely to be defensible for hydraulic studies.

Lastly, the validated model was applied to estimate the change in water demand from 2008 to 2020 under different water-conservation policies for the Santa Fe municipal system. Applying the validated method to a real-world issue showed that the estimated demands on the Santa Fe system for year 2020 could be nearly offset by enacting water-conservation policy.

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Chapter 1: **Introduction**

Water distribution systems are one of the vital infrastructures within the urban environment. The urban population is highly dependent on a reliable, clean, safe, and affordable supply of drinking water that simultaneously meets the requisite demands of fire protection. To ensure that a metropolitan water distribution system satisfies the needs and requirements of its constituents, municipal utilities develop and exercise models of their physical water distribution systems and customer demand behavior. The models are essential for operating and maintaining existing systems, and for planning future system changes, as urban demand for water evolves. For these models, a neighborhood-scale spatial resolution is employed to partition the area served by a utility into many subregions. The subregions, known as demand service areas, are necessary in order to accurately model the spatial-temporal dynamics of demand throughout a system.

This research explores the feasibility of using publically available, national-scale data to model customer demand on a water distribution system. Knowledge obtained from this research could lead to similar exploratory research on inferring demand for other utility networks such as electric power, natural gas, and wastewater treatment. The research could also provide benefits to utility personnel. Engineers and operations staff could use the approach to enhance the understanding of system demand characteristics. Planning engineers could employ the demand model to anticipate how future growth could affect municipal water use and what system modifications could be made to accommodate evolving demand characteristics. Water resource managers and decision-makers could use the demand model to explore the potential impacts of policy changes on the operation of water distribution systems. For example, cases of conservation by residential customers or limiting water use for specific classes of customers during an emergency or period of drought could be studied.

The goal of this thesis is to develop a method for estimating the water demand of a municipal system that could be applied anywhere in the U.S. The research objectives are:

1. develop a methodology to estimate the water demand of a municipal water distribution system at a neighborhood-scale spatial resolution and an hourly temporal resolution;
2. calibrate and validate the water demand model using empiric demand data and the pipeline network for a municipal water distribution system; and
3. apply the method to a real-world problem related to water conservation policy.

The proposed methodology for estimating the water demand of a system uses publically available data with national coverage. Therefore, the approach could potentially be applied to any municipal water distribution system in the U.S. A neighborhood-scale spatial resolution is employed to characterize water demand service areas. The service areas, which represent subregions of the utility service territory, generally contain several-to-many homes or businesses. The method will be calibrated and validated using the municipal water distribution system and empiric water demand data for the City of Santa Fe, New Mexico.

Currently, customer demand for water is typically ascertained by water utilities using some combination of measured end-use consumption and system production, which requires access to internal customer billing and engineering records. Statistical techniques are then employed using these proprietary data in order to portray the water-demand behavior of the system. The challenge of the research is to develop a method to estimate the spatial and temporal distribution of water demand for a municipal water distribution system using publically available data. Some of the data sources are available at aggregated spatial and temporal units so that methods were devised to disaggregate these data to finer spatial and temporal resolutions. The desired resolutions for the model are one-hour temporal resolution and neighborhood-scale spatial resolution. These temporal and spatial resolutions are commonly used by engineers to perform hydraulic and water quality analyses in order to accurately characterize the behavior of municipal water systems. Hydraulic solvers, such as EPANET (Rossman 2000) or the commercial products H20Water and WaterGems, which support the EPANET model format, are frequently used to perform analyses. Other data sources to be used for the methodology are proxies for the actual empiric data that the methodology infers. Strategies must be

developed to effectively integrate these data into the model. The measure of success for the methodology will be how accurately the approach estimates the fluctuation of demand through space and time for a municipal water system.

While much of the previous research on forecasting urban water demand focuses on monthly or yearly temporal scales, few papers address daily or hourly water-use estimates (Gato *et al.* 2007). This research will focus on the higher temporal resolution of an hour. Additionally, this research will target the higher spatial resolution of a neighborhood-scale region, while much of the previous research has used coarser spatial resolutions, such as a metropolitan region. There is an absence of research on estimating water demand for a water distribution system without the use of historical water demand for the system being studied. The novel approach presented by this thesis would begin to address this void in the research literature. In addition, an effective method of estimating the spatial-temporal fluctuation of water demand for a municipal pipeline network with reasonable accuracy would provide utility in several of the previously mentioned areas.

Chapter 2: **Literature Review**

2.1 Trends and Characteristics of Water Demand

2.1.1 Global

The world increasingly demands more from a limited supply of global water resources. Rapid population growth, which increasingly occurs in urban areas (UN 2006), and urbanization have had the greatest affect on levels of worldwide freshwater use (UNEP 2006). The predicted impacts of a warming global climate further compound these issues (IPCC 2007a; IPCC 2007b). As global demand increases, the competition for water resources intensifies. Future wars and regional conflicts over natural resources, including water, are predicted because of increased demands exacerbated by climate change (CNA 2007). The threat of terrorism has emerged as another potential risk to water resources. With well-publicized terrorist attacks occurring in the U.S., Spain, Japan, England, and Scotland, there is growing awareness of the vulnerability of urban water distribution systems. Central to many of these issues is the need for a safe and affordable public supply of drinking water. Enhanced knowledge of community water use is fundamental to making better-informed decisions regarding the management, operations, planning, and protection of this critical resource.

2.1.2 National

Although demands are increasing globally, the U.S. has stabilized water demand. Figure 2.1 shows the trends in total water withdrawals by water-use category for the period 1950–2000. After decades of increases, aggregated national water use remained relatively stable from 1980 to 1995 (Solley *et al.* 1998). For the U.S. Geological Survey (USGS) report of estimated water use in the U.S. for 2000, Hutson *et al.* (2004) attributed the relatively stable water use since 1980 to improved technology, State and Federal laws, economic issues, and water conservation programs. The report provides several insights into national water-use trends. Since 1980, all of the main sectors of water use, including irrigation, power production, and industrial use, have stabilized or declined.

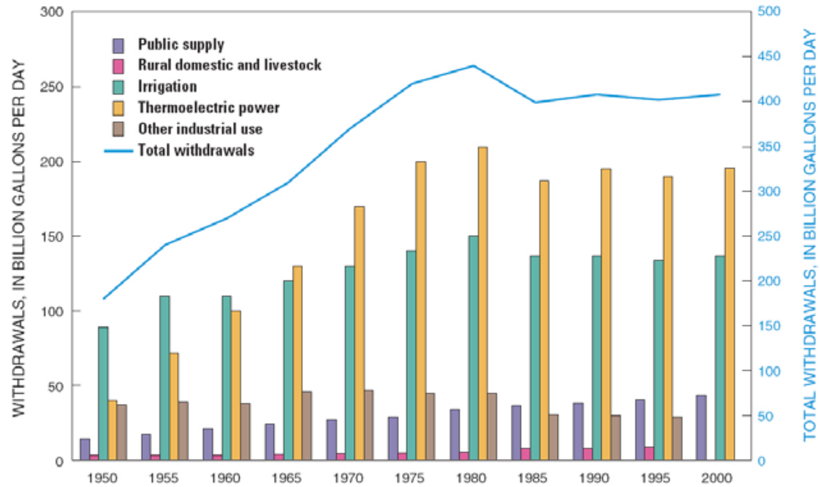


Figure 2.1. Trends in total water withdrawals by water-use category in the U.S. for 1950-2000 (Hutson et al. 2004)

In contrast to the main sectors of national water use, demand within the public supply sector, which delivers water to municipal water systems, has increased. The growth in demand for water by the public supply sector reflects a rise in the number of residential customers. These customers primarily receive their water from local and regional water supply systems (Hutson *et al.* 2004). The increase in water demand in the public supply water-use category parallels the growth of the overall U.S. population. Even with the trend from 1995 to 2000 of population migration from metropolitan areas to non metropolitan areas (Schachter *et al.* 2003), the population in metropolitan areas increased from 1995 to 2003 because of natural (i.e., more births than deaths) occurrences (Mackun 2005). Figure 2.2 shows the breakout of freshwater usage by Solley *et al.* (1998) within the public supply category for the estimated 1995 U.S. water usage. At 56%, the domestic subcategory, which primarily serves residential households, represents the largest user within the public supply category. In 2000, 242 million people or 85% of the U.S. population depended on water from public suppliers. From 1995 to 2000, both the public-supply withdrawals and the population served by them increased by 8% (Hutson *et al.* 2004).

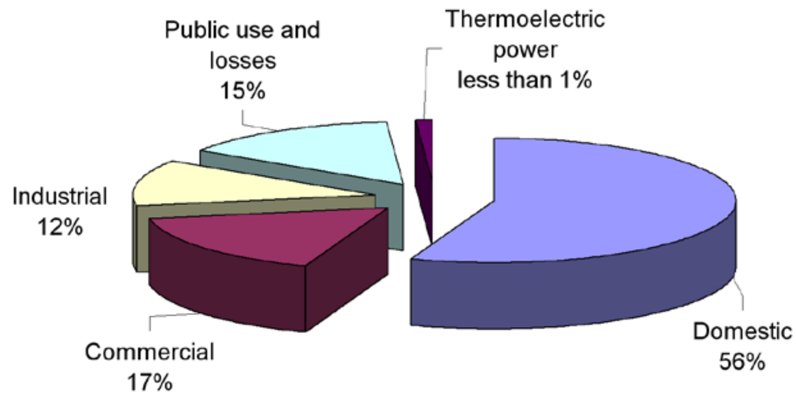


Figure 2.2. Estimated freshwater use of the public supply category in the U.S. in 1995 (Solley *et al.* 1998).

2.1.3 Local-Residential

Residential customers typically account for a significant percentage of the water demand on public and private water distribution systems serving urban populations (EPA 2002). Figure 2.3 shows the aggregated system-wide hourly water-use patterns during a one-week period for the predominantly-residential city of Arlington, Texas (Homwongs *et al.* 1994). With peaks in the morning and early evening, the daily use patterns in the figure demonstrate the diurnal behavior of residential water demand. This is especially notable on weekdays. As illustrated in Figure 2.3, weekend water use typically differs from weekday water use with the morning peak occurring later and at a reduced level, and a generally higher use throughout the day. While the residential urban U.S. population grows, more strain is placed on municipal water systems. The need to better characterize the growing current and future demand for water on these systems is critical for managing this vital resource.

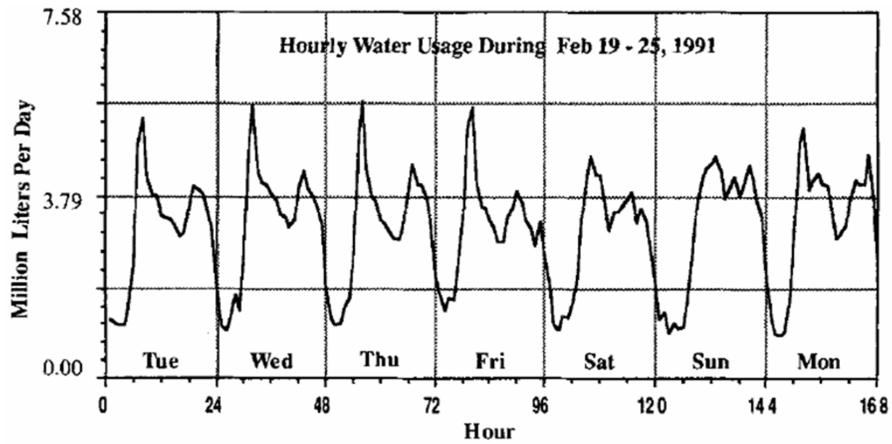


Figure 2.3. Aggregated system-wide hourly water-use patterns for Arlington, Texas, for the week of Feb. 19–25, 1991 (Homwongs et al. 1994).

2.2 Influences on Water Demand

There are many influences on residential water use. The primary influences include climate and season, building variables, population demographics, and conservation. Linweaver *et al.* (1966) and Buchberger and Wells (1996) found that water consumption at single-family residences depends on the number of household members, household income, lot size, water price, metering, and climate. Buchberger and Wells (1996) also found that residential water use varies on hourly, daily, and seasonal time scales; and average per capita demand is inversely related to the number of household occupants and with the age of the home.

Residential water demand at metropolitan, regional, and national scales is commonly assessed using empirically-derived values for per capita residential water use. This indicator can be used to monitor and compare residential water use among various water supply systems. Several studies (CSF 2006, Dietrich and Henderson 1963; Dziegielewski 2000; EWA 2003; Solley *et al.* 1998; White *et al.* 1972; WRA 2003) have examined water use and derived per capita residential water usage. Table 2.1 presents recent per capita water use for several U.S. cities and comparably-developed European countries.

Table 2.1. Per capita residential water-use estimates for U.S. cities and European countries in gallons per capita per day (gpcd). (Compiled from multiple sources: CSF 2006; EWA 2003; WRA 2003.)

Region	Per capita water use (GPCD)	Year of estimate	Source of data
U.S. cities			
Albuquerque, NM	135	2001	WRA
Denver, CO	159	2001	WRA
El Paso, TX	122	2001	WRA
Las Vegas, NV	230	2001	WRA
Phoenix, AZ	144	2001	WRA
Santa Fe, NM	140	2001	CSF
Santa Fe, NM	108	2005	CSF
Tucson, AZ	107	2001	WRA
European countries			
Denmark	35	1999	EWA
France	43	1995	EWA
Germany	34	1998	EWA
Netherlands	58	1999	EWA
Norway	59	1999	EWA
Spain	70	1998	EWA
United Kingdom	91	2000	EWA

Residential water use varies by season and weather. Water use generally increases during hot and dry periods, and decreases during cool and wet periods (Balling and Gober 2007; Bougadis *et al.* 2005; Gato *et al.* 2007; Maidment and Miaou 1986). Figure 2.4 illustrates both the summertime peak and wintertime minimum for demand on the system serving Toronto and York Region (CT 2002). The difference in total water demand between an average day and peak day for a municipal system typically ranges within a factor of 1.2 to 3.0 (Haestad 2003). Maidment and Miaou (1986) studied the variability of water use to rainfall and air temperature in nine U.S. cities in three states. Their study and the research by Jain *et al.* (2001) found that rainfall occurrence is more important than rainfall quantity as a predictor of water demand. This suggests that behavior and not need may be driving the demand. Balling and Gober (2007) concluded that water use in Phoenix, Arizona, is sensitive to changes in temperature, precipitation, and drought conditions. However, the magnitude of the response was relatively low for an urban area with a significant percentage of outdoor water use. The researchers suggested that social and behavioral issues may be responsible for this unexpected finding.

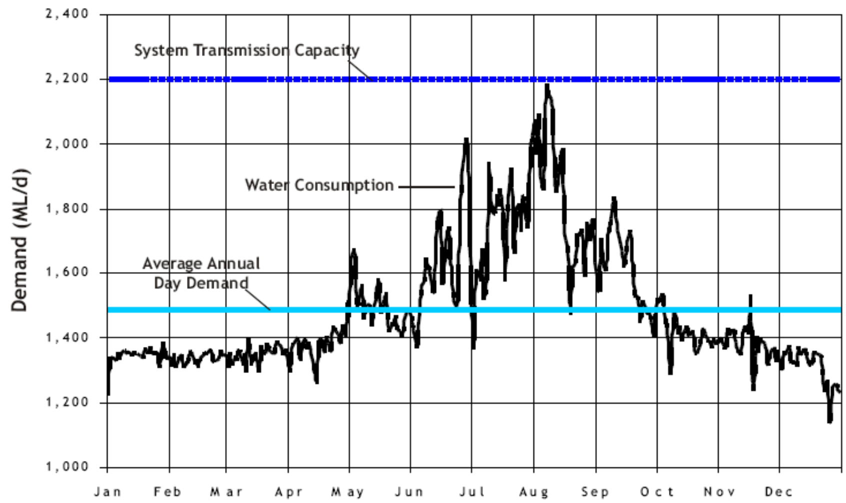


Figure 2.4. The 2001 combined water consumption for Toronto and York Region, Ontario, Canada, illustrates the peak summertime demand (CT 2002).

Because water demand is sensitive to climate and therefore varies by geographic region, some researchers studying national water use have partitioned the U.S. into climatic zones. Baumann *et al.* (1998) used the Köppen climate classification system when studying national water consumption. The system defines eight major climatic zones in the continental U.S. characterized by long-term weather patterns, vegetation, elevation, and other physical features. Foster and Beattie (1979) also found that water demand varies by geographic region. Their research partitioned the U.S. into six climatic regions and used the associated predominant factors of drought potential, agricultural production patterns, manufacturing, and monthly precipitation as model parameters.

Socioeconomic variables affect water use. Research by Loh and Coghlan (2003) found peak water-use periods during the Australian summer for November, 1999–February, 2000. The study identified a positive correlation between water demand and income. Figure 2.5 shows seasonal water-use patterns for three income levels and for single- and multi-residential households in Perth, Australia. The lower water use of multi-residential dwellings was attributed to two main factors: the reduced lot size of multi-residential dwellings significantly lowered the external water usage; and the multi-residential households averaged fewer inhabitants per unit than single-residential households.

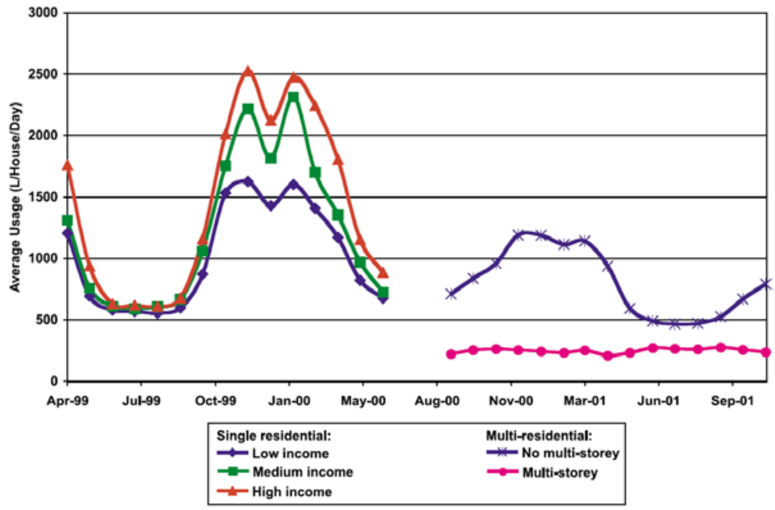


Figure 2.5. Average monthly water usage for single- and multi-residential households in Perth, Australia (Loh and Coghlan 2003). Note that the peak water demand occurs during the Australian summer.

2.3 Empiric Hourly Water Demand

To better understand how residential water demand changes throughout a single day, higher temporal resolution data of water use are needed. Loh and Coghlan (2003) collected empiric data on hourly residential water use. Figure 2.6 displays the average water usage over a 24-hour period of single-residential households for three different income levels. The hourly water-use curve has a pronounced bimodal distribution. Other research (Buchberger and Wells 1996; Homwongs *et al.* 1994; Rhoades 1995; Shvartser *et al.* 1993) has observed a bimodal hourly curve for weekday water use. Figure 2.7 shows the weekend and weekday hourly residential water-use curves for two residences over a 24-hour period. The hourly water use for Residence 1 is shown in the graph on the left. The water-use curve for Residence 2 is shown on the right.

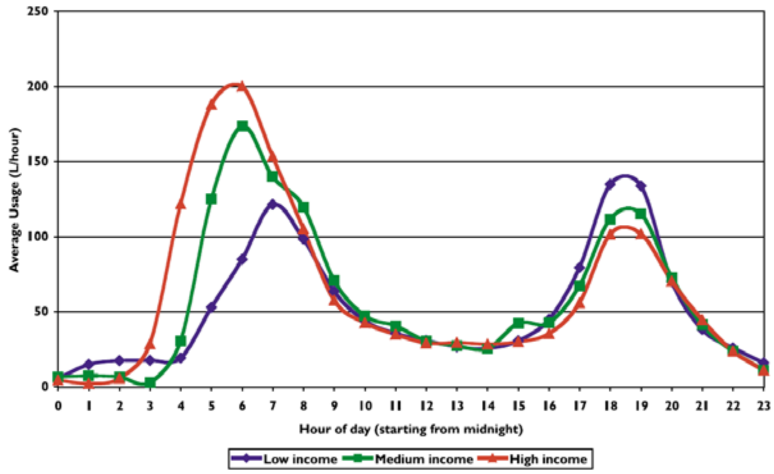


Figure 2.6. Hourly profile of average water usage of single-residential households during summer in Perth, Australia, for a 24-hour period (Loh and Coghlan 2003). Water usage for three income levels is represented.

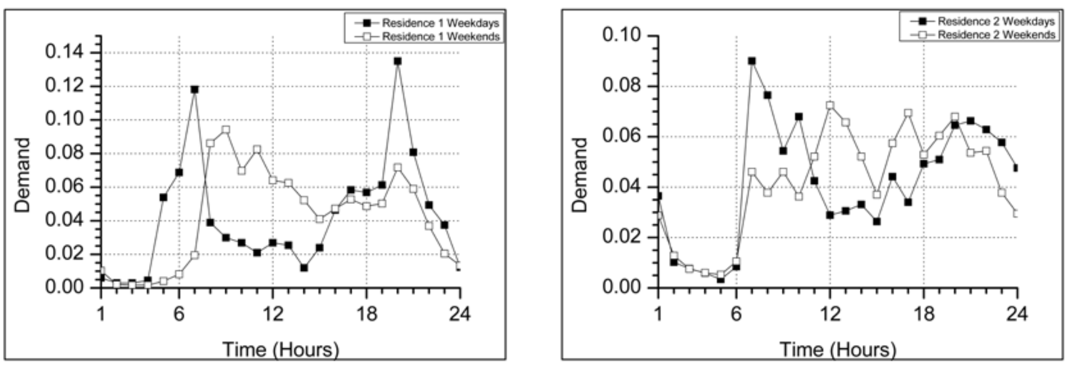


Figure 2.7. Weekday (solid squares) and weekend (hollow squares) residential water-use curves over a 24-hour period for (a) Residence 1 and (b) Residence 2 (Buchberger and Wells 1996).

Hourly water demand data were collected at the city of Austin, Texas, to provide the municipal utility with a statistical basis for refining customer class categories and updating the rate structure. Rhoades (1995) used transit-time ultrasonic flow meters to collect summertime (i.e., peak) water demand data from a sample of single-family residential customers by use category during 1992–1994. In addition to providing statistics for rate and class adjustments, the data are also useful for other purposes, such as day-to-day operations, calibrating and validating water distribution models, and for estimating the effects of water conservation programs. In the area of water conservation and demand-side controls, several researchers (Dziegielewski 2000; Gleick *et al.* 2003; Jacobs and Haarhoff 2004; Loh and Coghlan 2003; Whitcomb 2002) have examined the

effects on water demand of the increased use of water-conserving measures, such as retrofitting households with low-flow appliances.

2.4 Model Development

2.4.1 Water Pipeline Networks

Computer models of water pipeline networks are created to study the operation, maintenance, and planning aspects of water distribution systems. The models are digital representations of physical pipeline networks and their components, such as pipes, pumps, valves, tanks and reservoirs. Water demand is also an integral component of a pipeline network model (Rossman 2000). Sensitivity studies show that water demand has the greatest influence on the overall response of a water distribution network (Garcia *et al.* 2004). Researchers have developed water demand models for a multitude of activities related to urban water systems, including optimal selection of pumps for energy-saving (Homwongs *et al.* 1994); planning least-rcost strategies to expand water supply and distribution facilities (Bougadis *et al.* 2005); and reducing physical water losses (Guercio *et al.* 2001).

2.4.2 Calibration and Validation

Before computer models of water pipeline networks can be used to perform reliable engineering studies, the models must be calibrated. *Calibration* is the process of defining and adjusting model parameters to achieve an acceptable match between simulated values and observed measurements. For water distribution models that are calibrated for time-varying or extended period simulations (EPSs), the observed measurements are tank levels, pressures, and pipeline flows (ECAC 1999). Mainly, EPS calibration involves the examination of plots of observed versus modeled tank water levels (Haestad 2003). An important consideration for model calibration is the intended use of a model, which helps define the necessary degree of accuracy of the model (Janssen and Heuberger 1995). Water distribution networks require that the degree of accuracy of the calibrated model be higher when the model is used for daily operations than for long-range planning (ECAC 1999).

The methods for calibrating water network models range from more traditional trial and error approaches (Walski 1983; Bhave 1988) to sophisticated approaches using non-linear optimization algorithms (Kapelan et al. 2007; Wu et al. 2002; Greco and Giudice 1999). Regardless of the technique employed for model calibration, criteria are needed to determine the acceptable closeness of modeled and measured values. The Engineering Computer Applications Committee of the American Water Works Association (AWWA) elucidated standard criteria used to calibrate models in the United Kingdom and suggested possible calibration criteria for use in the U.S.

After a model has been calibrated, the last step in model development is validation. Validation is the process of assessing the strengths and weaknesses of the calibrated model by using a different dataset (Janssen and Heuberger 1995) or under different conditions (Haestad 2003) than were used for calibration. Increasing the number of independent datasets during validation, results in a higher degree of confidence in the model (NRC 2006). The knowledge obtained from model validation enables the user of the model to better gauge its applicability for engineering studies.

2.5 Estimating Water Demand

Estimating urban water demand involves assimilating the myriad influences on how, when, and where water is used. An assortment of water demand models have been developed that can be applied at different temporal and spatial resolutions. Forecasts of water demand can range from long-term (e.g., predicting water demand in 20 years) and metropolitan-scale for long-range planning purposes to short-term (e.g., predicting water demand for the next day, hour or minute) and neighborhood-scale for day-to-day operational planning activities. The predictive techniques include traditional approaches, such as regression analysis and time series analysis, to more sophisticated methods, such as the use of artificial neural networks. A review of recent water-demand forecasting methods is next, generally, in the order of long- to short-term temporal resolution. This is followed by discussion of these studies with a perspective on spatial resolution.

2.5.1 Temporal Water Demand

2.5.1.1 Multi-Year

Whitcomb (2002) forecasted the water demand of Redwood City, California, for a 20-year period from 2000 to 2020 using five-year intervals. The method examined seven sectors of water use, three of which were residential. The residential sectors included single family, multiple family, and residential irrigation. Whitcomb used future drivers or predictors of water use, such as the number of housing units, to estimate residential water use. Coefficients for single-variable equations were developed based on historical water-use correlations for each sector. The technique also considered the influence of conservation programs (e.g., installing low-flow toilets and shower heads, and other water-conserving appliances) over time to reduce the per capita water-use of indoor appliances.

2.5.1.2 Monthly, Weekly, and Daily

A method was developed by Aly and Wanakule (2004) to provide short-term forecasts of municipal water use at daily and monthly temporal resolutions. The forecasts are based on a smoothing algorithm that considers climatic and seasonal factors (e.g., winter versus summer, tourist population, etc.), daily weather factors (precipitation, temperature, and relative humidity), and day-to-day activities (e.g., weekday versus weekend). Their approach used an adaptive exponential smoothing algorithm that employed a linear regression component. The algorithm provided highly accurate monthly average forecasts and reasonably accurate daily forecasts for six days into the future. The model assumes that recent historic patterns of water use will be applicable in the near future. This assumption will require further validation.

Other techniques for estimating water demand rely on artificial neural networks (ANNs). Jain *et al.* (2001) modeled weekly water demands using three techniques: conventional methods of regression analysis, time series analysis, and with the use of ANNs. The researchers found that the ANN models consistently outperformed the conventional techniques in forecasting weekly water demands. Maier and Dandy (2000) reviewed 43 papers on using ANNs to predict and forecast water resources variables. The use of ANNs was found to be potentially useful for predicting and forecasting water

resources. The authors recommended that ANNs be employed as an alternative to more traditional approaches and not as a replacement methodology; artificial neural networks are an addition to the toolkit of techniques for estimating water demand.

Zhou *et al.* (2000) estimated daily water use for Melbourne, Australia, using a time series model. Water consumption was characterized by weather-insensitive and weather-sensitive components. The model comprised a set of equations representing the primary factors of water use: trend, seasonality, climatic correlation, and autocorrelation. Using past demand data and weather forecasts, the model estimated consumer demands, 24-hours in-advance.

2.5.1.3 Hourly

To forecast hourly water demand 24 hours to several days ahead, Shvartser *et al.* (1993) developed a model that uses pattern recognition and time-series analyses. The approach utilizes a general daytime water demand pattern that is made up of a *rising* segment, an *oscillating* segment, and a *falling* segment. Figure 2.8 shows actual and modeled water demand, and illustrates the rising, oscillating, and falling segments of daytime water use. The method assumes the daily demand pattern is a stochastic process with segments, where the transition between segments is a Markov chain. Within each segment the demand is described by low-order auto-regressive integrated moving average models. The authors report acceptably adequate accuracy using the approach. The statistical approach of the model assumes stable meteorological and other environmental parameters, so these variables are ignored in the model.

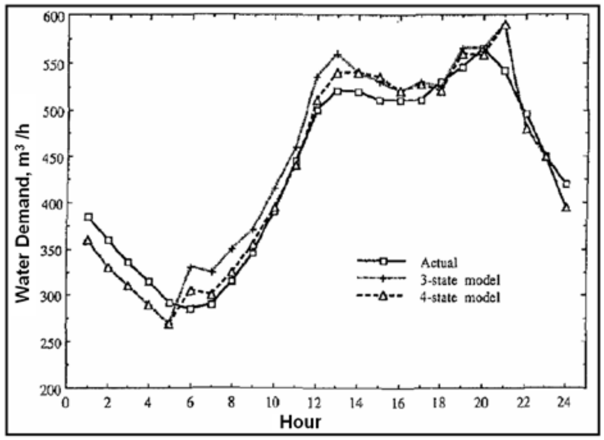


Figure 2.8. Actual and modeled water demand of the Sorek Water Supply District, Israel, for Saturday, July 6, 1991. The graph also illustrates the rising, oscillating, and falling segments corresponding to daytime water demand. The model is based on pattern recognition and time-series analyses (Shvartser *et al.* 1993).

Homwongs *et al.* (1994) developed an automated on-line water demand forecasting methodology for estimating hourly water consumption time series for a municipal water utility in Arlington, Texas. The approach is based on a seasonal time-series model and adaptive smoothing-filtering algorithm that is influenced by weather conditions and considers measurement outliers. The authors report accurate forecasts of water demand from one hour to 24 hours ahead. The adaptive approach can capture time-dependent water use patterns "quite well" for weekdays and weekends, and over different seasons of the year. The authors suggest further model development to incorporate real-time meteorological data into the forecasting model.

2.5.1.4 Sub-Hour

A model of indoor residential water demand was developed by Guercio *et al.* (2001) to forecast the instantaneous temporal and spatial variability of water flow. The temporal resolution of water-demand estimates was one-minute intervals. This study extended the work of Buchberger and Wu (1995) and used a Poisson rectangular pulse stochastic process to characterize the intensity, duration, and frequency of water use by single- and multi-residential households. Experimental data were collected from 85 single-family residences in Latina, Italy, with the same socio-economic status to define the parameters of the model.

Alvisi *et al.* (2003) used a cluster Neyman-Scott stochastic process to model residential water demand. Water demand was simulated at one-minute temporal resolution on a small dataset to derive a water demand time series. An aggregation approach was then used to examine the water demand of a larger number of users. The study found issues of scalability related to the temporal and spatial aggregation.

2.5.2 Spatial Water Demand

While the research on estimating demand reviewed previously has varied in temporal resolution from decades to minutes, the spatial resolution varies from a metropolitan area to a single residence. The studies exhibit an approximate correlation in scales such that longer temporal resolutions correspond with coarser spatial resolutions and shorter temporal resolutions correspond with finer spatial resolutions. For example, while the Whitcomb (2002) study did consider some projected growth rates by region (e.g., forecasting a 63.3% increase in multi-family units in the downtown area), the spatial resolution for the forecasted demand was the whole of Redwood City, California. Similarly, Zhou et al. (2000) used the metropolitan area of Melbourne, Australia and Shvartser et al. (1993) used the region served by a specific water system as the spatial resolutions for their respective studies. Other studies subdivided metropolitan areas or water system service territories to create subregions to use as the spatial resolution. Homwongs et al. (1994) subdivided a city water system into two pressure zones, and Aly and Wanakule (2004) studied the region served by a specific treatment plant for Tampa Bay Water. The next finer spatial resolutions represented in the reviewed studies were sub-neighborhood and residence-scale. Research by Guercio et al. (2001) and Buchberger and Wu (1995) employed spatial resolutions of sub-neighborhood clusters of residences and individual residences. The high spatial resolution of these studies corresponded with the measured and estimated demand at high temporal resolutions, such as one-minute intervals

Chapter 3: **Methodology**

3.1 Overview

The research method was developed to explore the feasibility of using publically-available, national-scale data to estimate water demand for a municipal water distribution system. The spatial resolution of a neighborhood and the temporal resolution of one hour were selected because these are commonly used by engineers for hydraulic modeling of a pipeline network. A technique to estimate demand that is based on nationally-available data, calibrated with higher-resolution local empiric data, and that provides the spatio-temporal resolution required for hydraulic modeling could, in principle, be applied to estimate demand for pipeline network models of municipal systems anywhere in the U.S. In addition, while water scarcity will continue to be a critical issue, especially in the west, sound methods for estimating current and future water demand will be vital to develop plans to mitigate the consequences of water shortages. A validated method could be used to explore the use of conservation strategies to affect near- and long-term water demand.

To address the research problem, the thesis is divided into three phases (see Figure 3.1). In the first phase, the methodology to estimate the water demand of a municipal water distribution system is developed. In the second phase, the method is calibrated and validated for selected regions of the empiric pipeline network for the City of Santa Fe. In the last phase, the method is applied to a real-world problem to support decision makers with understanding how water conservation policy could affect future water use. The next section describes the study area and the empiric water distribution system. This is followed by a more detailed explanation of the research methodology.

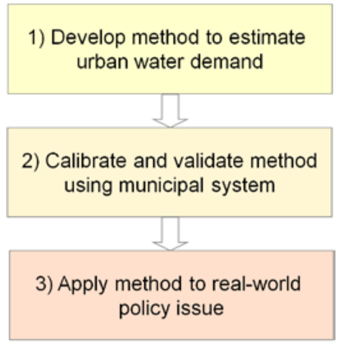


Figure 3.1. The three phases of the research are: 1) development of the method, 2) calibration and validation of the method, and 3) application of the method to a real-world policy issue.

3.2 Study Area and Empiric Water Distribution System

The municipal water distribution system studied for this research serves the City of Santa Fe, NM. Located in northern New Mexico, Santa Fe sits in the foothills of the Sangre de Cristo Mountains at an elevation of 7,000 feet (see Figure 3.2). The city is on the edge of the Rio Grande Valley and is 60 miles northeast of Albuquerque along Interstate 25. The climate is arid, with low humidity. Santa Fe receives an average annual precipitation of around 14 inches.

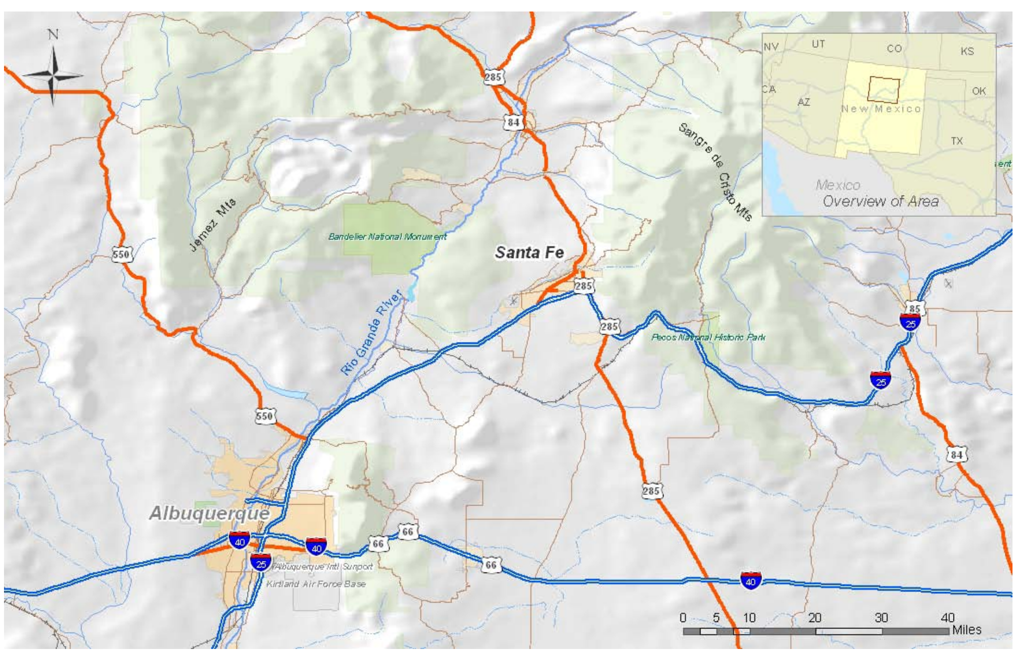


Figure 3.2. The City of Santa Fe, located in Northern New Mexico, sits in the foothills of the Sangre de Cristo Mountains at an elevation of 7000 feet. The city is on the edge of the Rio Grande Valley and is 60 miles northeast of Albuquerque on Interstate 25.

The City of Santa Fe resides in a region where water is scarce. Because of the lack of water, City officials have acted to lower water consumption. As a result of conservation programs, such as the distribution of low-flow toilets, rebates on water-conserving appliances, and enacting water-use restrictions, the per capita water demand has decreased from 137 GPD in 2000 to 104 GPD in 2007 (Brown and Caldwell 2009). The existing water sources include reservoirs of snowmelt runoff from the Sangre de Cristo Mountains and several groundwater well fields. In addition, the City has sought new sources of water to supplement the existing sources. One of the new water sources, currently under construction, is the Buckman Direct Diversion (BDD) Project, which will treat and pump water from the Rio Grande to the City.

Santa Fe's water distribution system serves customers through the pipeline network shown in Figure 3.3. Also shown in the figure is the utility service territory, which covers an area of approximately 58 square miles. The water utility service territory is used as the bounding geographic area for calibration and validation of the method studied for this research.

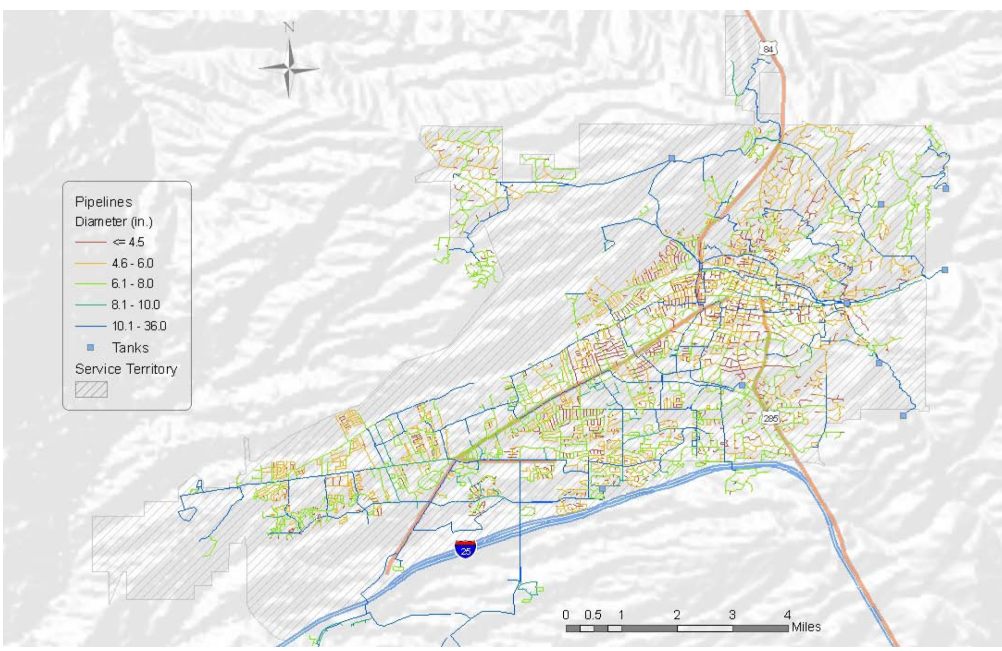


Figure 3.3. The City of Santa Fe water distribution system serves customers within the utility service territory through pipelines that range in size from several inches to 36 inches in diameter.

There are eleven pressure zones within the water utility service territory. The pressure zone boundaries, shown in Figure 3.4, are primarily defined by elevation and were created to maintain system pressures within acceptable ranges. The zones, which are contiguous, non-overlapping regions, can be hydraulically isolated or separated by water system components, such as pressure reducing valves (PRVs) (Brown and Caldwell 2009). Because the pressure zones are functionally independent areas of the system, one pressure zone can be selected for calibration and different pressure zones can be used for validation.

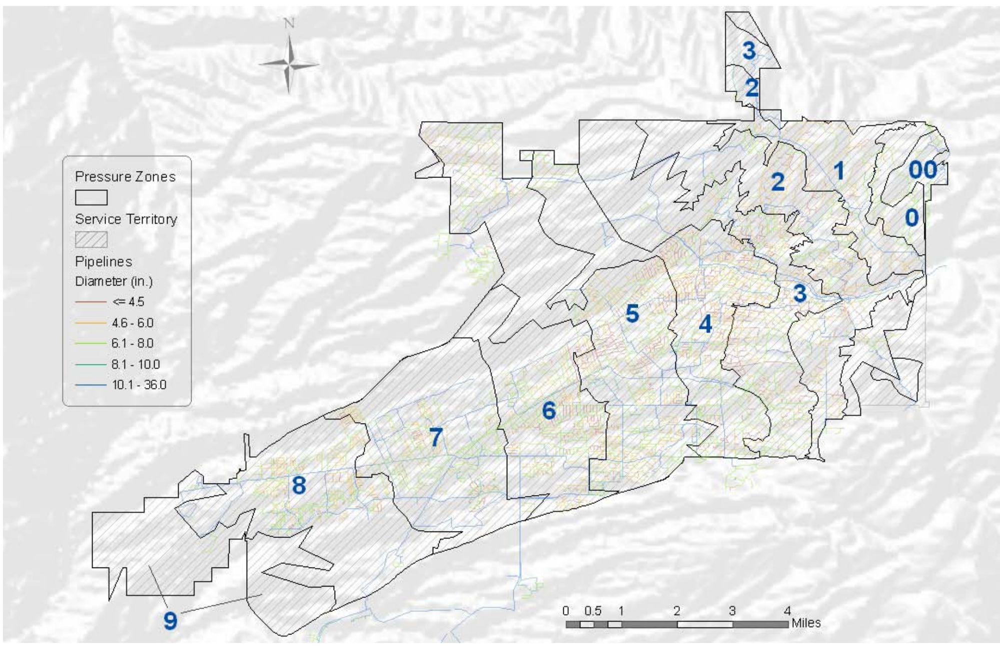


Figure 3.4. There are eleven pressure zones within the water utility service territory. The pressure zones, labeled on the map, divide the pipeline network into regions for operational and planning purposes.

Land use regions within the city are used to define areas based on their predominant classification. Figure 3.5 shows the spatial distribution of 10 land use categories within the water utility service territory. As seen in the figure and in Table 3.1, the four residential land use types are the primary features, comprising 68% of the area within the service territory. The land use data are employed within the research to characterize the types of water demand customers within each pressure zone. Figure 3.6 and Table 3.2 illustrate the land use makeup for each of the pressure zones, and show that all of the pressure zones except for pressure zone 9 are predominantly residential.

Pressure zone 9 is largely comprised of the airport, which has an industrial land use classification.

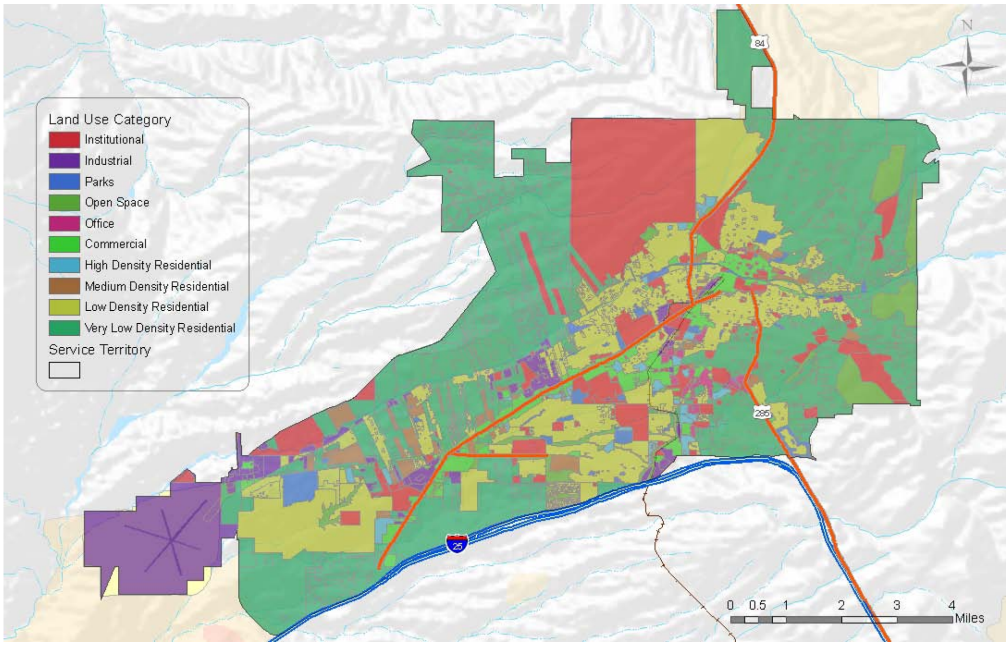


Figure 3.5. The predominant land use classification within the water utility service territory is residential. The residential areas are distributed throughout the water utility service territory. The large red area to the north is city-owned land (i.e., institutional) and the large purple area to the southwest is the airport (i.e., industrial).

Table 3.1. The table shows the percent (%) of land use by area for the service territory.

Land Use Category	Percent of Service Territory (%)
Institutional	15
Industrial	8
Parks	2
Open Space	3
Office	1
Commercial	4
High Density Residential	1
Medium Density Residential	2
Low Density Residential	20
Very Low Density Residential	45

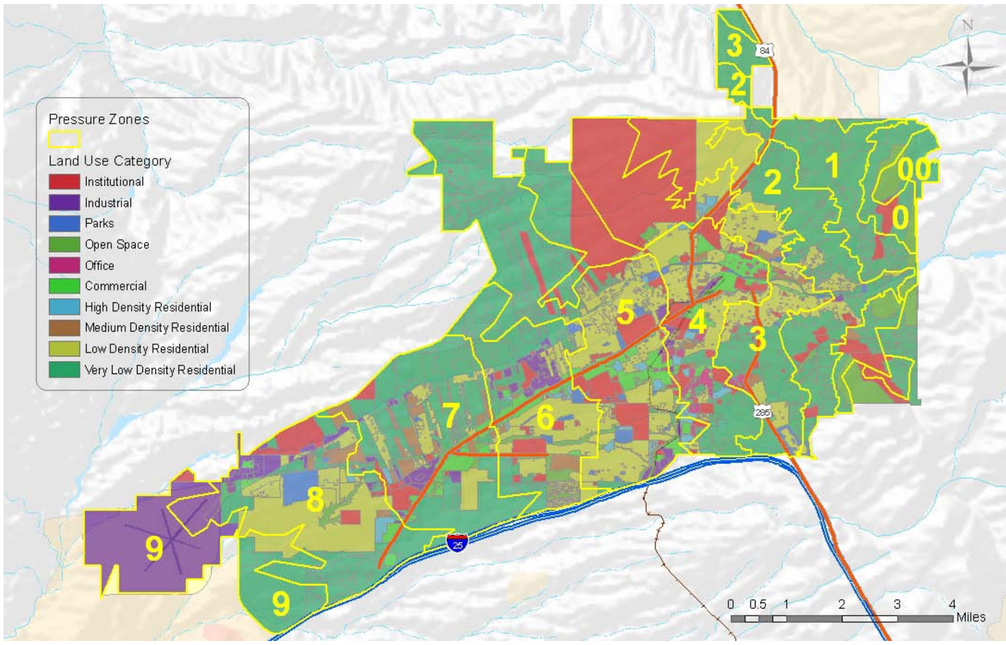


Figure 3.6. The land use regions and pressure zones are shown, with the pressure zone IDs labeled in yellow.

Table 3.2. The table shows the percent (%) of land use by area and the total area for each pressure zone within the utility service territory.

Land Use Category	Pressure Zone										
	0	1	2	3	4	5	6	7	8	9	00
Institutional	11	7	19	38	24	14	7	5	8	1	2
Industrial	0	0	0	0	2	2	7	5	14	62	0
Parks	0	0	1	2	1	2	2	0	4	0	0
Open Space	20	9	1	1	0	2	6	1	2	0	35
Office	0	0	0	1	4	0	0	0	0	0	0
Commercial	0	0	0	1	10	7	6	7	2	0	0
High Density Residential	0	0	0	1	2	2	1	1	2	0	0
Medium Density Res.	0	1	0	2	2	0	3	9	3	0	0
Low Density Residential	0	4	21	25	22	27	30	13	34	6	0
Very Low Density Res.	69	79	58	29	34	44	38	60	31	30	63
Area (sq. mi.)	1.1	3.7	6.3	7.0	6.4	9.4	5.1	6.3	6.2	4.4	0.7

The calibration and validation phase of the research rely on the empiric hydraulic and demand models developed for the 2009 City Master Plan by the engineering consulting firm Brown and Caldwell. Displayed with pressure zones in Figure 3.7, the empiric demand has a neighborhood-scale spatial resolution, where each polygon represents a demand junction service area. The details on how the service areas are created are illustrated later in the paper. In the next section, the data used by the method are described.

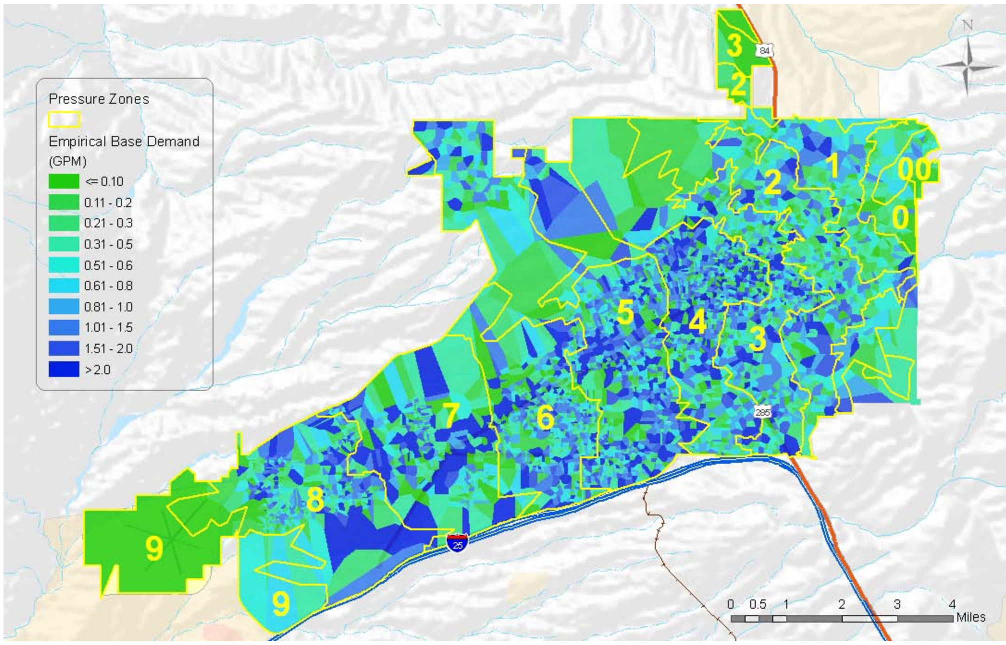


Figure 3.7. The total empiric base demand for each neighborhood-scale service area is shown, with the pressure zones and pressure zone IDs.

3.3 Data

The research methodology for estimating water demand uses several different sources of geospatial and tabular data, and includes public, commercial, and published data products (see Table 3.3). The data products include: aggregated water-use estimates produced by the U.S. Geological Survey (USGS); U.S. Census residential data; LANL diurnal population data; a commercial database of businesses representing commercial, industrial, and institutional (CII) facilities; published research describing daily water-use quantity per employee by facility type; and published water-use patterns for residential and non-residential or CII facility types. Additional data, required to perform the calibration and validation phase of the thesis, are provided by the City of Santa Fe. These data include the empiric municipal water pipeline network and water demand, supporting datasets that were used or derived for the 2009 Master Plan, newly acquired SCADA data, and base map layers.

Table 3.3. Summary table of data used to estimate residential and CII (i.e., non-residential) water demand. The demand category column indicates if a data source is used to estimate the residential demand, CII demand or both.

Data title and metadata		Demand category	
		Res.	CII
Residential water use by county		x	
Description:	Average daily water use for public supply by county		
Source (format):	USGS (tabular)		
Data time stamp:	1995/2000		
References:	Solley *et al*. 1998; Hutson *et al.* 2004		
Residential population		x	
Description:	Residential population by Census Tract		
Source (format):	US Census Bureau (geographic polygon features with attributes)		
Data time stamp:	2005		
References:	http://www.census.gov		
Diurnal population		x	
Description:	Daytime/nighttime residential and worker populations		
Source (format):	LANL (raster, 250m cell size)		
Data time stamp:	2005		
References:	Ching *et al*. 2009;		
CII facilities			x
Description:	Database of commercial, industrial and institutional facilities		
Source (format):	Dun and Bradstreet (geographic point features with attributes)		
Data time stamp:	July 2007		
References:	http://www.dnb.com		
Daily water use by facility			x
Description:	Daily water use per employee per facility type		
Source (format):	Published literature (tabular)		
Data time stamp:	Various		
References:	Dziegielewski *et al.* 2000		
Water use patterns		x	x
Description:	24-hour water use patterns for residential and CII customers		
Source (format):	Published literature (tabular)		
Data time stamp:	Various		
References:	Loureiro *et al.* 2006; Haested 2003; Buchberger and Wells 1996		
Empiric water pipeline network and water demand		x	x
Description:	Empiric water pipeline network, water demand and SCADA data		
Source (format):	City, Brown and Caldwell 2009 Master Plan (geog. features, tab)		
Data time stamp:	2007-2009		
References:	Brown and Caldwell 2009		
Supplemental empiric water demand		x	x
Description:	SCADA data of water production and tank levels		
Source (format):	City (tabular)		
Data time stamp:	April 2009		
References:	Brown and Caldwell 2009		
City base map layers		x	x
Description:	Base map geographic layers, including land use, service territory		
Source (format):	City of Santa Fe (geographic features with attributes)		
Data time stamp:	April 2009		

3.4 Research Method

The first phase of the research is to develop a method for estimating water demand for a municipal water distribution system for an average day at a temporal resolution of one hour. Sample demand units are gallons per day (GPD) or gallons per minute (GPM). The method is partitioned into approaches for estimating residential (e.g., single-family and multi-family) and non-residential demands. Here, non-residential demand refers to commercial, industrial and institutional (CII) water demand. Mathematically, the average daily demand can be represented by:

$$D_{Tot} = D_R + D_{CII} \tag{1}$$

where D_{Tot} is the average daily demand, D_R is the average daily residential demand, and D_{CII} is the average daily CII demand.

3.4.1 Estimating Residential Water Demand

Assuming each demand junction j in the water distribution system corresponds to a particular service area, the daily residential demand D_R is defined by:

$$D_R = \sum_{j=1}^{J} P_j R_R \tag{2}$$

where J is the total number of junctions in the water distribution system, P_j is the residential population served by junction j , and R_R is the daily use rate for each residential person.

The approach for estimating the residential water demand (see Figure 3.8) entails deriving the per-capita water use rate per county, combining this with residential population data to calculate daily use rates per service area, and temporally disaggregating the daily rates to one-hour averages over a 24-hour period. Using USGS estimates of water use, the per-capita water use rate is determined by dividing the per-county estimate of public supply water by the county population. Population data are converted from Census tracts in vector format to raster format (i.e., disaggregating the tract units to smaller regular cellular units) to provide a uniform and more-usable data structure. The neighborhood-scale service areas are then used as the aggregation regions

to group and sum the population count. For each service area, the population is multiplied by the per-capita water use rate to obtain the daily residential water demand. Typical residential water-use patterns, available in published research, are applied to temporally disaggregate water use from a daily resolution to an hourly resolution. Figures 2.6 and 2.7 show examples of empiric hourly residential water-use patterns obtained from prior research.

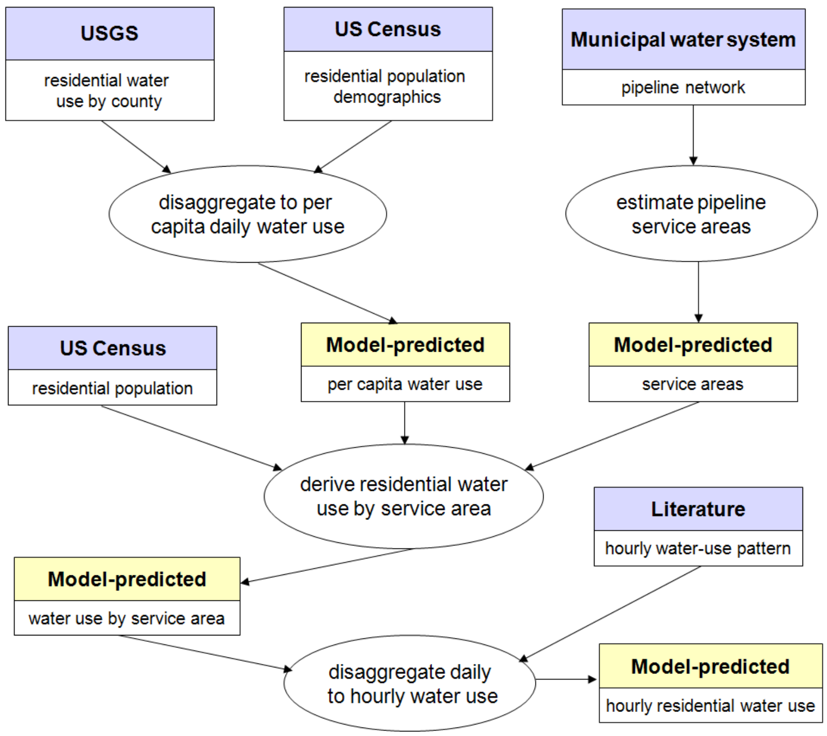


Figure 3.8. Process and data flow for the estimation of residential water demand. In the diagram, an ellipse represents a process, the yellow data field is a model-derived result, and the blue data field is a primary external data source.

Given the daily use rate for each residential person and using the multiplicative factor p_t supplied by the 24-hour residential use pattern, the average hourly residential demand rate per person can be represented by:

$$R_{Rt} = \frac{R_R}{24} p_t \qquad (3)$$

where R_R is the daily use rate for each residential person and p_t is the multiplicative factor supplied by the 24-hour use pattern that is used to scale the daily demand rate to

the average hourly demand at hour t. Substituting equation (3) into equation (2) results in the daily residential demand D_R represented by:

$$D_R = \sum_{j=1}^{J} \sum_{t=1}^{24} P_j R_{Rt} \tag{4}$$

where J is the total number of junctions in the system. t is the hour, which varies from 1 to 24. P_j is the residential population served by junction j. R_{Rt} is the use rate at hour t for each residential person.

3.4.2 Estimating CII Water Demand

The daily commercial, industrial, and institutional (CII) demand D_{CII} is defined by:

$$D_{CII} = \sum_{j=1}^{J} \sum_{k=1}^{K} E_{jk} R_{CII\,k} \tag{5}$$

where J is the total number of junctions in the system. K is the total number of CII facility types. E_{jk} is the number of employees working for facilities of type k within the service area served by junction j. $R_{CII\,k}$ is the daily use rate per employee for facilities of type k.

The process and data flow for the approach to estimate water demand for commercial, industrial, and institutional (CII) customers is shown in Figure 3.9. To characterize CII customers, a commercial database of businesses is utilized. The properties of the business records include geolocation, number of employees, and business type. The business type property in the original dataset is the National American Industrial Classification System (NAICS) code. For the research, the NAICS code is correlated with the Standard Industrial Classification (SIC) code and then generalized to a two-digit SIC code. (The correlation of NAICS codes to SIC codes is shown in Appendix A, while the two-digit SIC code facility categories are shown in Appendix B.) Water use for each business facility is estimated based on the facility type, the number of employees, and the per employee water use rate specific to each facility type. The values of per employee water use are available from published studies (see Appendix C). Using

service areas as the spatial unit, water use by the facilities is aggregated per service area and then associated with the pipeline network. The estimated water demand uses published typical daily water-use patterns by CII facility to disaggregate the total daily water use to an hourly temporal resolution.

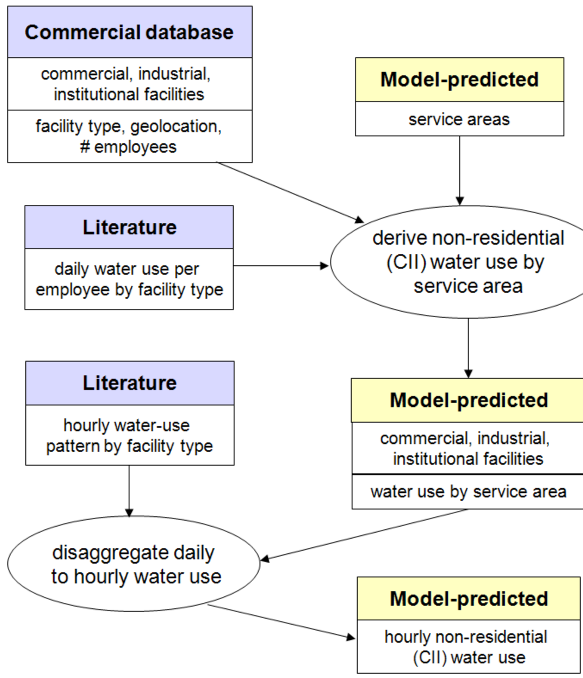


Figure 3.9. Process and data flow for the estimation of non-residential water demand, where an ellipse represents a process, the yellow data field is a model-derived result, and the blue data field is a primary external data source.

Analogous to the residential demand approach, the average hourly facility demand rate per employee $R_{CII\,kt}$ can be represented by:

$$R_{CII\,k\,t} = \frac{R_{CII\,k}}{24}\, p_{k\,t} \qquad (6)$$

where $R_{CII\,k}$ is the daily use rate for each employee of facility type k and $p_{k\,t}$ is the multiplicative factor supplied by the 24-hour use pattern for facility type k at hour t. The multiplicative factor is used to scale the daily demand rate to the average hourly demand at hour t. Substituting equation (6) into equation (5), the daily CII demand D_{CII} can be written as:

$$D_{CII} = \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{t=1}^{24} E_{jk} R_{CII\,kt} \quad (7)$$

where J is the total number of junctions in the system. K is the total number of CII facility types. t is the hour and varies from 1 to 24. E_{jk} is the number of employees working for facilities of type k within the service area served by junction j. $R_{CII\,kt}$ is the use rate per employee for facilities of type k at hour t.

An additional issue that affected the use of the CII facilities database was discovered during the research. The utility-provided data, used for the model calibration and validation, represented a Saturday instead of a weekday. Assumptions were made on which business types would be open or closed on a Saturday. These assumptions are shown in Appendix B.

3.4.3 Assigning Demand to the Pipeline Network Using Service Areas

Another aspect of the research method is the creation and use of service areas. Service areas are created at a neighborhood-scale spatial unit for modeling purposes to approximate localized regions within which water is withdrawn from the water pipeline network. The component on the water pipeline network where water is withdrawn and around which a service area is constructed is known as a demand junction. Each service area corresponds with one and only one demand junction. [Note that water pipeline networks contain many junctions, but only those that serve demand are called demand junctions. The junctions not serving demand are simply referred to as junctions.] Stated a different way, demand junctions are points on the network where all of the water demand of nearby customers (i.e., residential and CII customers) is aggregated and assigned to one location within the model. A customer is assumed to be supplied water by the demand junction whose corresponding service area contains that customer's demand point location. By combining nearby customer demand points into one location (i.e., a demand junction) on the pipeline network rather than representing every individual residential and CII customer, the amount of data is reduced, the model performance is improved, and the reduction in model accuracy is insignificant (Haestad 2003).

To further clarify what a service area represents, Figures 3.10, 3.11 and 3.12 are provided. Figure 3.10 shows the roads, parcels, and water distribution system for an area that contains both residential and CII water customers. The junctions are divided into those that serve demand (i.e., a demand junction) and those that do not serve demand (i.e., a junction). Figure 3.11 shows service areas for each of the demand junctions overlaid onto the previous figure. Lastly, Figure 3.12 shows how each service area can contain residential and CII demand customers. The service areas are then used to spatially associate the residential and CII customers within each service area with its associated demand junction.

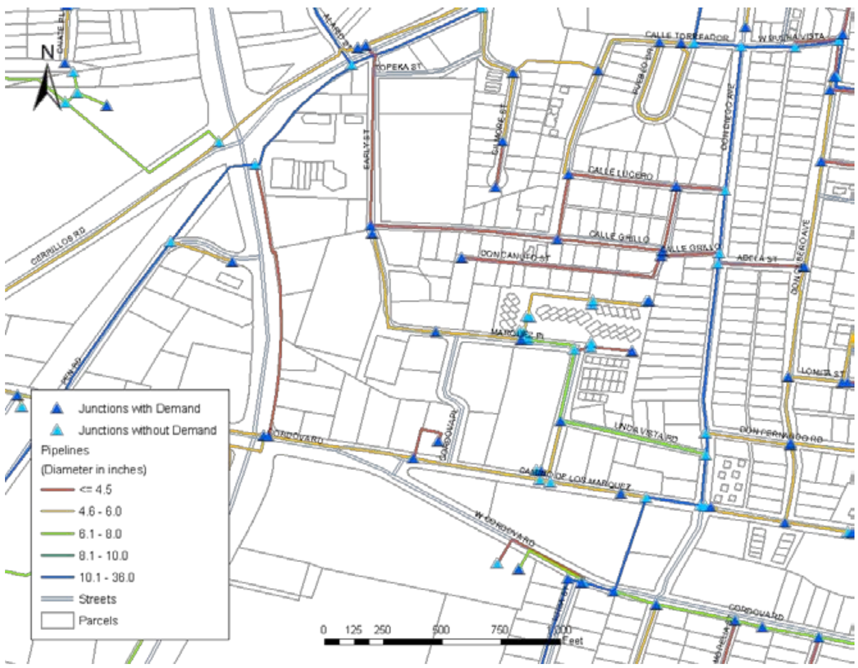


Figure 3.10. Parcels, streets, and the water system, represented by junctions with demand, junctions without demand, and pipelines, are shown.

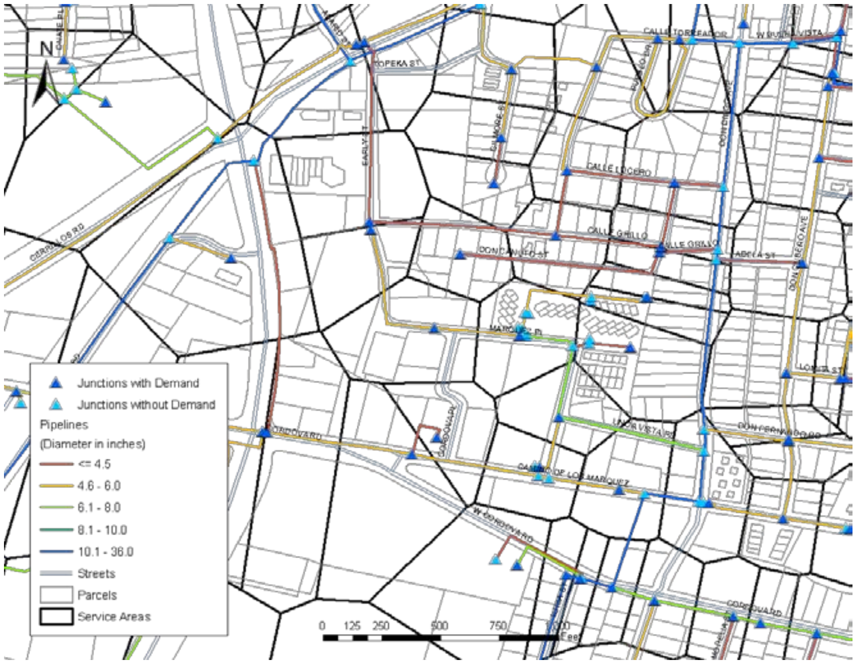


Figure 3.11. The neighborhood-scale service areas (black polygons), constructed around each demand junction, are shown. Each service area corresponds with one and only one demand junction. Service areas are used to associate water demand customers with specific demand junctions.

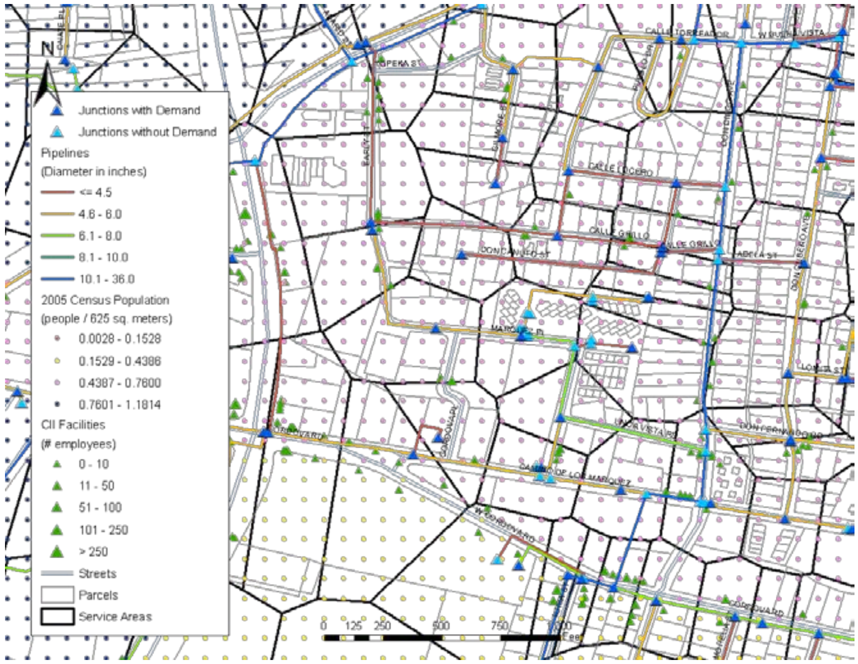


Figure 3.12. The figure shows the residential (i.e., 2005 Census Population density layer) and CII facilities (i.e., employee counts per CII facility) demand point features within the service areas (black polygons). The population density point locations are the centroids of each grid cell in a grid representation of the data. Each service area can encompass residential demand and demand from CII facilities.

To be consistent with the service areas used to create the empiric water demand for the 2009 Master Plan, the Voronoi technique is used to calculate the service areas for this research. The approach is based on calculating and using lines of bisection between all demand junctions (i.e., points) to form areas. The Voronoi technique guarantees that any selected point that falls within a Voronoi area will be closer to the demand junction associated with that area, than to any other demand junction.

3.4.4 Implementing the Method as a Software Tool

For the research, the thesis method was implemented as a custom software tool built as an extension to the Esri ArcMap GIS product. The custom application, called the GIS Water Use Model or GWUM, provides a menu-driven user interface to enable a user of the tool to select input options and execute the method with a handful of button clicks. The inputs include geospatial data, such as CII facilities, residential population grids, demand junctions, and service areas, and tabular data, such as 24-hour use patterns, and daily water use per residential person or CII facility employee. By developing the

software application as an extension to ArcMap, all of the geospatial programming libraries within ArcMap (i.e., ArcObjects) could be harnessed. The geospatial libraries provide core functionality for the GWUM application which is central to the method, such as analyzing the spatial relationships of the model features. The output of the application includes the base demand and the 24 hourly demands at all of the demand junctions. In addition, the application can export the estimated demand in a format that will plug into a format used by the EPANET hydraulic solver.

Additional ArcGIS geoprocessing models and Microsoft Excel spreadsheets were developed to streamline the process of summarizing the detailed estimated demand for graphing and error calculation. The ArcGIS geoprocessing models are shown in Appendix D.

3.5 Calibration and Validation

The second phase of the research focuses on calibrating and validating the method for estimating water demand using the municipal water system for the City of Santa Fe. A series of cases will be examined for the calibration and validation phase. Each case will be referred to by a unique identifier (e.g., Case 1J) and employ a specific set of input parameters to examine the response of the method under different assumptions. The demand model estimates will be compared to empiric demand data for the municipal water system. The steps involved in each of the two parts of this phase are described separately below.

3.5.1 Calibration

The purpose of the calibration section is to assess the response of the model when varying the model input parameters. Multiple calibration cases are created, with each case referenced by a case identifier, such as Case 1, Case 1A, Case 1B, etc. The case that results in the best fit of the empiric and modeled data is selected as the preferred calibration case. The selected calibration case is then used to validate the method. The model input parameters will be discussed in the results chapter.

There are three main steps to calibrating the method, as shown in Figure 3.13. First, the parameters of the model are defined. Second, the thesis method is applied to estimate water demand using the chosen calibration case parameter values. The third step

is to compare the water demand estimates to empiric demand data for the municipal water system for the City.

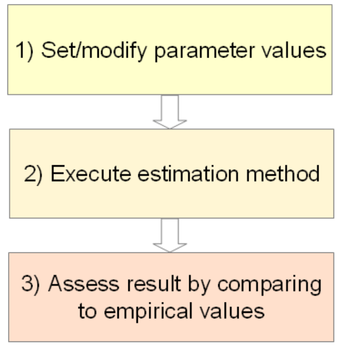


Figure 3.13. The three steps for calibrating the method.

The bounding area for the analysis is the service territory for the water utility. Eleven pressure zones subdivide the service territory into non-overlapping regions. For calibration purposes, one pressure zone with characteristics representative of the entire water system is used as the analysis region for all of the calibration cases. In the next section of the study, other pressure zones, geographically independent of the calibration pressure zone, are used for validation of the method.

3.5.1.1 Error Metrics

Two metrics are used to compare the estimated and empiric demands. The first metric is the Percentage Difference. The Percentage Difference between the total estimated and empiric demands is calculated to provide an initial, overall metric. The Percent Difference (PD) between observed and simulated values is defined by:

$$\text{PD} = \frac{|S - O|}{O} \text{ or } \frac{S - O}{O} \quad (8)$$

where *O* is the observed (or empiric) value and *S* is the simulated (or estimated) value. A positive percent difference indicates the simulated value overestimated the observed value; a negative percent difference indicates the simulated value underestimated the observed value. The unit for PD values is percentage.

Because one of the goals of the research is to estimate demands at an hourly resolution, the estimated and empiric demands over the specific calibration demand zone

are compared for each of the 24 one-hour time slices. The second metric used to gauge the effectiveness of the method is the Relative Error. The Relative Error metric is a useful means for analyzing time-series data and is therefore useful for this analysis. The Relative Error is defined by:

$$RE = \frac{\sum_{i=1}^{N} |O_i - S_i|}{\sum_{i=1}^{N} O_i} \text{ x } 100 \qquad (9)$$

where O_i is the observed value, S_i is the simulated value, and N is the number of observations. The unit for RE values is percentage. The next section provides an overview of validation of the research method.

3.5.2 Validation

The second part of phase two of the research is testing or validating the method. To validate the method, parameter values from the most favorable calibration case are applied to estimate water demand for pressure zones not used for calibration. To evaluate the effectiveness of the model for validation, the metrics of Percent Difference and Relative Error, which were employed for the calibration section, are used. Each of the validation cases is referred to by an identifier, such as 1J-PZ6, where the first part (i.e., 1J) identifies the specific calibration case, and the second part (i.e., PZ6) identifies the specific pressure zone used for validation.

3.6 Application

The third phase of the research applies the method to real-world policy issues related to water conservation for a municipal water system. Because water scarcity is an issue throughout the southwest, and the City of Santa Fe has worked diligently over the years to conserve water, the application phase examines the potential effects of using demand-side management policies to reduce future water demand on the Santa Fe system. The application phase will address the following questions:

1) What is the estimated water demand at 2020 on the City of Santa Fe water distribution system?

2) How could the estimated water demand at 2020 be affected by water conservation policies put into place today?
    a. One policy examines the effect on water demand by providing a credit for purchasing a front-loading washing machine.
    b. Another policy examines the effect on water demand by providing a credit for purchasing low-flow toilets, such as dual-flush toilets.

This chapter describes the methodology and the results of the application phase.

3.6.1 Application Method

Initially, water demand for the baseline cases for the current 2008 system and the projected 2020 system was estimated. To examine the effects of implementing demand-side management policies, the projected water demand for three additional cases were estimated. The cases represent the use of policies, such as rebates or account credits, to encourage water customers to replace less-efficient clothes washers and toilets with water-conserving appliances.

The forecast for water demand at the year 2020 was based on future projections for residential population and business growth. The projected residential population dataset for Santa Fe County for the year 2020 was obtained from the Bureau of Business and Economic Research (BBER) at the University of New Mexico (BBER 2008). To estimate business activity at 2020, employment projections for 2008-2018 for the Santa Fe Metropolitan Statistical Area (MSA) were obtained from the New Mexico Department of Workforce Solutions, Economic Research and Analysis Bureau (NMDWS 2009).

Forecasting Residential and CII Change at 2020

The 2020 population forecast was obtained from the projected populations of New Mexico counties by the Bureau of Business and Economic Research (BBER) at the University of New Mexico. The 2020 projected population of 165,719 for Santa Fe County was used. This represents a 23.4% increase from the 2005 Census population of 134,275, which was used as the current 2008 population.

The forecasted change in CII employment was obtained from a report by the New Mexico Department of Workforce Solutions (NMDWS) Economic Research and

Analysis Bureau on the 2018 Santa Fe Metropolitan Statistical Area (MSA) employment projections (NMDWS 2009). The report (see Table 3.4) includes projected rates of change for major industry sectors and for the fastest growing industry subsectors over the period 2008-2018 for Santa Fe MSA. Correlating the sectors to CII facility types used by the method, the projected changes were applied to estimate the number of employees at 2020 for the current CII facilities (see Table 3.5). For example, the NMDWS report projects a change in employment within the Santa Fe MSA from 2008 to 2018 of 23.6% for the *Health care and social assistance* industry category. One of the CII facilities is St. Vincent Hospital. The 25.5% growth rate for facilities within the *Health care and social assistance* was applied to St. Vincent Hospital to increase the current employee count of 1,555 to a projected count of 1,922 employees. To estimate the water demand at 2020 for St. Vincent Hospital, the facility is assumed to have 1,922 employees. Other CII facility types, with negative projected average annual rates of change, result in fewer employees at 2020. *Manufacturing* is one sector projected by the NMDWS report to have a negative growth rate for the Santa Fe MSA.

Table 3.4. The table shows the 2018 employment projections by industry and subsector for the Santa Fe Metropolitan Statistical Area (MSA) compiled by the New Mexico Department of Workforce Services (NMDWS). The percent change in employment represents the projected change from 2008 to 2018 (NMDWS 2009).

Santa Fe MSA Employment Projections for 2008-2018				
Industry Change	Change in employment (%)		Subsector Change	Change in employment (%)
Administrative & Support Services	41.0		Museums & Historical Sites	47.4
Educational Services	32.7		Administrative & Support Services	41.9
Health Care & Social Assistance	23.6		Building Material & Garden Suppliers	34.4
Professional, Scientific, & Technical Service	23.3		Couriers & Messengers	32.8
Transportation & Warehousing	17.8		Educational Services	32.7
Wholesale Trade	16.4		Electronics & Appliance Stores	30.0
Accommodation & Food Services	14.7		Ambulatory Health Care Services	29.6
Government	14.1		Social Assistance	28.9
Mining	13.8		Professional, Scientific & Technical Services	23.3
Other Services	10.9		Merchant Wholesalers, Durable Goods	22.8
Arts, Entertainment, & Recreation	9.8		Food Services & Drinking Places	22.4
Construction	8.9		Local Government	21.5
Retail Trade	7.5		Repair & Maintenance	18.9
Finance & Insurance	6.1		Personal & Laundry Services	17.6
Real Estate, Rental & Leasing	4.3		Merchant Wholesalers, Nondurable Goods	15.3
Information	2.5		Heavy & Civil Engineering Construction	14.3
Utilities	1.9		State Government	12.9
Management of Companies	0.2		Credit Intermediation & Related Activities	11.1
Manufacturing	-1.7		Motion Picture & Sound Recording Industries	9.4
Agriculture	-2.1		Construction of Buildings	8.0
Total Employment, All Jobs	14.9		Specialty Trade Contractors	7.8
			Amusement, Gambling & Recreation	5.7
			Clothing & Clothing Accessories Stores	5.0

Table 3.5. The table shows the correlation of CII facility types by two-digit SIC code with the projected employment changes for the Santa Fe MSA over the period 2008-2018, compiled by the New Mexico Department of Workforce Solutions (NMDWS). The right-most percentage is bold when the percentage of change was obtained from the projected subsector for the Santa Fe MSA; non bold values indicate the value was obtained from the projected industry sector for the Santa Fe MSA.

CII Facility Description (2-Digit SIC Category)	Facility Type (SIC Code)	NMDWS Industry Sector and Subsector (in parenthesis)	NMDWS Industry Sector Change (%)	NMDWS Subsector Change (%)	Change Applied for SIC Category (%)
		Agriculture			
Agricultural production- crops	01		-2.1		-2.1
Agricultural production- livestock	02		-2.1		-2.1
Agricultural services	07		-2.1		-2.1
Forestry	08		-2.1		-2.1
Fishing, hunting, and trapping	09		-2.1		-2.1
		Goods-producing, excluding agriculture			
Coal mining	12	Mining	13.8		13.8
Oil and gas extraction	13	Mining	13.8		13.8
Nonmetallic minerals, except fuels	14	Mining	13.8		13.8
General building contractors	15	Construction (Construction of Buildings)	8.9	8.0	**8.0**
Heavy construction contractors	16	Construction (Heavy and Civil Engineering Construction)	8.9	14.3	**14.3**
Special trade contractors	17	Construction	8.9		8.9
Food and kindred products	20	Manufacturing	-1.7		-1.7
Tobacco manufactures	21	Manufacturing	-1.7		-1.7
Textile mill products	22	Manufacturing	-1.7		-1.7
Apparel and other textile products	23	Manufacturing	-1.7		-1.7
Lumber and wood products	24	Manufacturing	-1.7		-1.7
Furniture and fixtures	25	Manufacturing	-1.7		-1.7
Paper and allied products	26	Manufacturing	-1.7		-1.7
Printing and	27	Manufacturing	-1.7		-1.7

CII Facility Description (2-Digit SIC Category)	Facility Type (SIC Code)	NMDWS Industry Sector and Subsector (in parenthesis)	NMDWS Industry Sector Change (%)	NMDWS Subsector Change (%)	Change Applied for SIC Category (%)
publishing					
Chemicals and allied products	28	Manufacturing	-1.7		-1.7
Petroleum and coal products	29	Manufacturing	-1.7		-1.7
Rubber and miscellaneous plastics products	30	Manufacturing	-1.7		-1.7
Leather and leather products	31	Manufacturing	-1.7		-1.7
Stone, clay, glass, and concrete products	32	Manufacturing	-1.7		-1.7
Primary metal industries	33	Manufacturing	-1.7		-1.7
Fabricated metal products	34	Manufacturing	-1.7		-1.7
Industrial machinery and equipment	35	Manufacturing	-1.7		-1.7
Electrical and electronic equipment	36	Manufacturing	-1.7		-1.7
Transportation equipment	37	Manufacturing	-1.7		-1.7
Instruments and related products	38	Manufacturing	-1.7		-1.7
Miscellaneous manufacturing industries	39	Manufacturing	-1.7		-1.7
		Service-providing			
Transportation-Rail	40	Transportation and warehousing	17.8		17.8
Local and interurban passenger transit	41	Transportation and warehousing	17.8		17.8
Motor freight transportation and warehousing	42	Transportation and warehousing	17.8		17.8
U.S. Postal Service	43	Transportation and warehousing	17.8		17.8
Water transportation	44	Transportation and warehousing	17.8		17.8
Transportation by air	45	Transportation and warehousing	17.8		17.8
Pipelines, except natural gas	46	Utilities	1.9		1.9
Transportation services	47	Transportation and warehousing	17.8		17.8
Communications	48	Utilities	1.9		1.9

CII Facility Description (2-Digit SIC Category)	Facility Type (SIC Code)	NMDWS Industry Sector and Subsector (in parenthesis)	NMDWS Industry Sector Change (%)	NMDWS Subsector Change (%)	Change Applied for SIC Category (%)
Electric, gas, and sanitary services	49	Utilities	1.9		1.9
Wholesale trade--durable goods	50	Wholesale Trade (Merchange Wholesalers, Durable Goods)	16.4	22.8	**22.8**
Wholesale trade--nondurable goods	51	Wholesale trade	16.4		16.4
Building materials, hardware, garden supply, & mobile	52	Retail Trade (Building Materials and Garden Suppliers)	7.5	34.4	**34.4**
General merchandise stores	53	Retail Trade	7.5		7.5
Food stores	54	Retail Trade	7.5		7.5
Automotive dealers and gasoline service stations	55	Retail Trade	7.5		7.5
Apparel and accessory stores	56	Retail Trade (Clothing and Clothing Accessories Stores)	7.5	5.0	**5.0**
Furniture, home furnishings and equipment stores	57	Retail Trade	7.5		7.5
Eating and drinking places	58	Wholesale trade (Food Services and Drinking Places)	14.7	22.4	**22.4**
Miscellaneous retail	59	Retail Trade	7.5		7.5
Depository institutions	60	Financial and Insurance	6.1		6.1
Nondepository credit institutions	61	Financial and Insurance	6.1		6.1
Security, commodity brokers, and services	62	Financial and Insurance	6.1		6.1
Insurance carriers	63	Financial and Insurance	6.1		6.1
Insurance agents, brokers, and service	64	Financial and Insurance	6.1		6.1
Real estate	65	Real Estate, Rental and Leasing	4.3		4.3
Holding and other investment offices	67	Financial and Insurance	6.1		6.1
Hotels, rooming houses, camps, and other lodging places	70	Leisure and hospitality	14.7		14.7
Personal services	72	Other Services	10.9		10.9
Business services	73	Other Services	10.9		10.9
Automotive repair,	75	Other Services	10.9		10.9

CII Facility Description (2-Digit SIC Category)	Facility Type (SIC Code)	NMDWS Industry Sector and Subsector (in parenthesis)	NMDWS Industry Sector Change (%)	NMDWS Subsector Change (%)	Change Applied for SIC Category (%)
services, and parking					
Miscellaneous repair services	76	Other Services (Repair and Maintenance)	10.9	18.9	**18.9**
Motion pictures	78	Arts Entertainment and Recreation (Motion Picture and Sound Recording Industries)	9.8	9.4	**9.4**
Amusement and recreational services	79	Arts Entertainment and Recreation	9.8		9.8
Health services	80	Healthcare and social services	23.6		23.6
Legal services	81	Professional, Scientific, and Technical Service	23.3		23.3
Educational services	82	Educational services (Educational Services)	32.7	32.7	**32.7**
Social services	83	Healthcare and Social Assistance (Social Assistance)	23.6	28.9	**28.9**
Museums, art galleries, botanical & zoological garden	84	Arts Entertainment and Recreation (Museums and Historical Sites)	9.8	47.4	**47.4**
Membership organizations	86	Other Services	10.9		10.9
Engineering and management services	87	Professional, Scientific and Technical Services (Preofessional, Scientific and Technical Services)	23.3	23.3	**23.3**
Private households	89	Other services	10.9		10.9
Executive, legislative, and general government	91	Government (State Government)	14.1	12.9	**12.9**
Justice, public order, and safety	92	Government (State Government)	14.1	12.9	**12.9**
Finance, taxation, and monetary policy	93	Government (State Government)	14.1	12.9	**12.9**
Administration of human resources	94	Administrative and Support Services (State Government)	41.0	12.9	**12.9**
Environmental quality and housing	95	Administrative and Support Services (State Government)	41.0	12.9	**12.9**

CII Facility Description (2-Digit SIC Category)	Facility Type (SIC Code)	NMDWS Industry Sector and Subsector (in parenthesis)	NMDWS Industry Sector Change (%)	NMDWS Subsector Change (%)	Change Applied for SIC Category (%)
Administration of economic programs	96	Administrative and Support Services (State Government)	41.0	12.9	**12.9**
National security and international affairs	97	Government (State Government)	14.1	12.9	**12.9**
Unknown	99	NA			

Chapter 4: **Results**

This chapter presents the results of applying the method to estimate water demand for the City of Santa Fe water distribution system. There are four sections to this chapter. The first section describes the input parameters of the method, the mathematical underpinnings, and demonstrates the use of the GIS Water Use Model (GWUM) application to estimate water demand. In the second section, a series of calibration cases are created to explore the results of modifying the values of various input parameters. The purpose of this section is to find cases where adjustments of input parameter values lead to better water demand estimates, with an overarching goal of matching the estimated water demand to the empiric water demand. The statistical metric of Relative Error is used to measure the relative success of the calibration cases. One calibration case is selected as the best-fit calibration model.

The third section examines validating the model by applying the input parameters of the best-fit calibrated model to estimate water demand for geographic regions within the water distribution system that were not used for the calibration section. As for the calibration section, the Relative Error metric is used to gauge the relative success of the validation cases. Section four applies the method to a real-world problem related to estimating future water demand and the potential effects of water conservation strategies. The last section of the chapter addresses issues and considerations of the empiric and method data.

4.1 Input Parameters and Automating the Method

The research method for estimating demand uses input parameters or variables to influence the response of the model. Baseline values for the parameters were established using several data sources. The data sources for the baseline parameters are described in the Methodology chapter. The method, implemented as an ArcMap GIS application, allows a user to enter and modify the input parameters through a series of menus. Use of the GIS Water Use Model (GWUM) application is described by stepping through a sample calibration case and displaying screenshots of the menus. The specific inputs for

the calibration case are presented and the underlying mathematical equations of the method are illustrated. The next section describes the input parameters of the method.

4.1.1 Input Parameters

This section describes the main input parameters of the method. Information about the source and use of the data within the method for some of the parameters is presented in the Methodology chapter. In the section on method calibration, the summary table for the calibration cases lists the values of the main input parameters used for each calibration case.

Scale Factor. The scale factor is a multiplication factor used to uniformly scale the total estimated demand to equal the total empiric demand. It is uniformly applied to the estimated demand at every demand junction. The scale factor is derived using the total demand from a previous estimate as a ratio equal to the total empiric demand divided by the total estimated demand.

Residential Use Rate. The residential use rate is the gallons per day (GPD) per residential person. For the research, the baseline residential use rate data were provided on a per-county basis by the USGS.

Residential Population Data. The residential population data provide the geographic distribution of residential customers. The data are typically provided as a count within a Census areal unit, such as tract or block group, or as a population density within a grid, such as number of persons per square meter.

Residential Use Pattern. The residential use pattern represents the average hourly fluctuation of demand over a 24-hour period for a residential customer. A multiplicative factor for each hour scales the base residential demand at each demand junction to the appropriate level. Residential use patterns are typically diurnal, with peaks in the morning and early evening. The use pattern values are unit less.

CII Use Rate. The CII use rate is the gallons per day per employee per facility type. The facility type is assigned by relating the original National American Industrial Classification System (NAICS) code (found in the Dun and Bradstreet CII facilities database) to the Standard Industrial Classification (SIC) code, then aggregating the SIC codes to the two-digit SIC code categories.

CII Use Pattern. The CII use patterns can be specific to each CII facility type. The pattern represents the average hourly fluctuation of demand over a 24-hour period for a specific type of facility. The facility type is assigned by using the two-digit SIC code. The values of the use pattern are unit less.

4.1.2 Using the GWUM Application to Estimate Water Demand

The method is implemented through the use of the Esri ArcGIS based GIS Water Use Model (GWUM) desktop application (see Figure 4.1). The GWUM application is an ArcGIS ArcMap extension that was developed for this research with the Microsoft Visual Studio 2008 development environment using the VB.Net programming language and the ArcGIS ArcObjects development libraries. The application automates the method and therefore produces the results significantly faster and more reliably than without automation. All of the calibration and validation cases were calculated using the GWUM application.

The following section illustrates how the GWUM application was used to estimate water demand for one of the calibration cases, specifically, Case 1J. Case 1J was selected because it is the best-fit calibration case and was applied during the validation section. The mathematical equations described in the methods chapter are explained again below to clarify where the method is implemented in the application. Screenshots of the GWUM menus for each step in the process are shown along with some maps of the results. If a specific dataset is not identified in the steps below, the baseline dataset was used for a particular parameter. The mathematical equations, outlined in the Methodology chapter, are referred to below in order to explain how the underlying processing takes place within the tool.

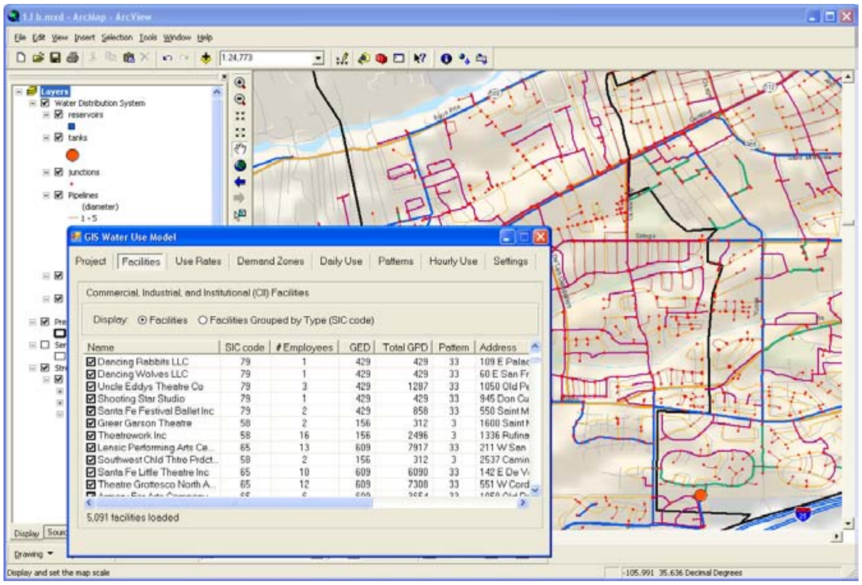


Figure 4.1. The Esri ArcGIS based GIS Water Use Model (GWUM) desktop application.

Initializing and launching the application (Steps 1 – 3)

The first steps were to enable the GWUM extension and toolbar, and launch the application. Because the GWUM application is an ArcMap extension, any new ArcMap session can access and use the GWUM extension.

Step 1: After starting ArcMap, the GWUM extension is enabled by selecting Tools-Extensions from the ArcMap menu and selecting the Water Demand GIS Model item from the list of available extensions (see Figure 4.2).

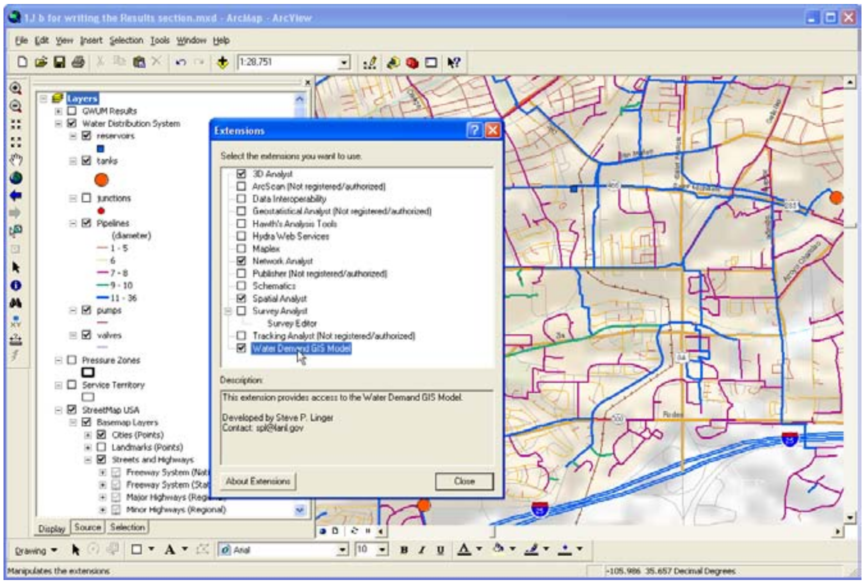


Figure 4.2. The GWUM application is an ArcMap extension.

Step 2. The GWUM Toolbar is activated by selecting Tools-Customize from the ArcMap menu, and selecting the Water Demand GIS Model item (see Figure 4.3). The GWUM Toolbar appears at the top of the ArcMap session (see Figure 4.4).

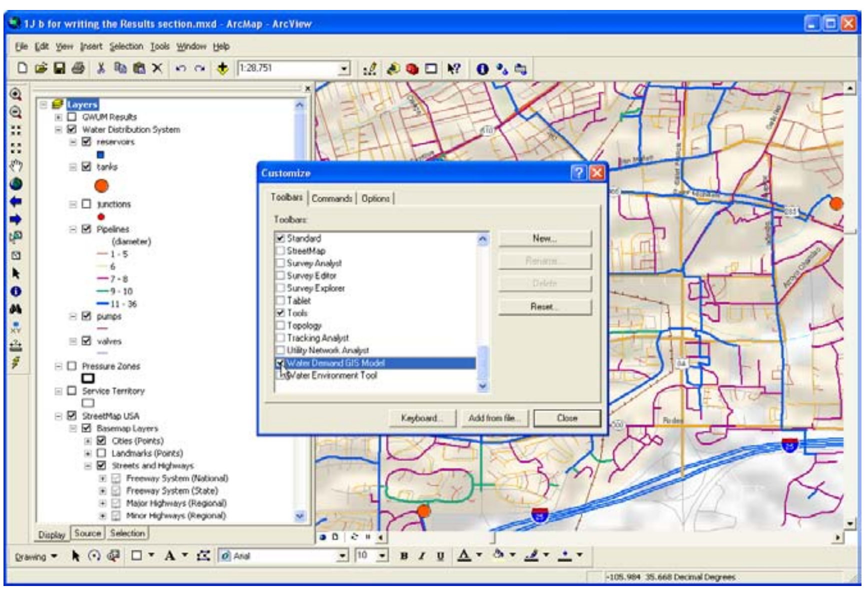


Figure 4.3. The GWUM application Toolbar is activated through the Tools-Customize menu.

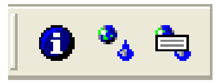


Figure 4.4. From right to left, the GWUM application Toolbar menu includes buttons for help, the GWUM application, and a log/status window.

Step 3. The GWUM application button is selected to launch the GWUM application (see Figure 4.5). The GWUM application uses a multi-tabbed menu to step the user (mostly from left to right) through the process of estimating water demand.

Selecting the input parameters (Steps 4 – 9)

The following steps show how the input parameters are selected for use with the GWUM application. The parameters are not only the tables and geospatial data, but the field names used within those data. As a convenience to the user of the tool, the values of the menu input fields are stored and retrieved, so that the last-used input values will be displayed in the menu when a new instance of the GWUM application is invoked. All references to the *CII facility type* are made through the use of a two-digit Standard Industrial Classification (SIC) code.

Step 4. Select the working folder (which is where results are stored), the Facility Type-Pattern Map table and corresponding fields (this table relates CII facilities to specific use patterns), and the 2005 Census data as the residential population dataset (see Figure 4.5) from the Project-Setup menu. The residential population data are used when estimating the residential component of water demand.

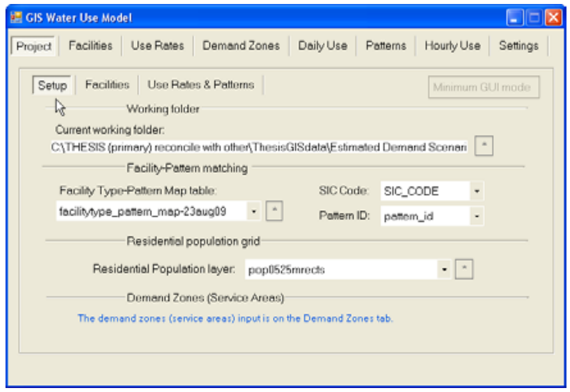


Figure 4.5. The Project-Setup menu allows a user to choose the working folder, Facility Type-Pattern Map table, and residential population dataset.

Step 5. From the Project-Facilities menu (see Figure 4.6), select the Facilities layer (i.e., Dun and Bradstreet CII facilities database) and fields (to represent the CII water customers), and the Facility-Classification table and fields (this table relates the facility type ID to a description field).

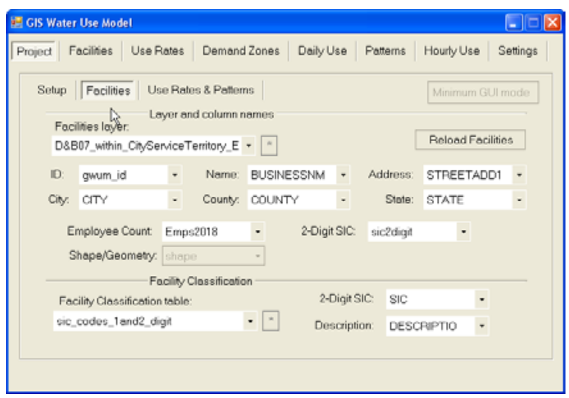


Figure 4.6. The Project-Facilities menu allows a user to select facilities tables.

Step 6. From the Project-Use Rates & Patterns menu (see Figure 4.7), select the Facility-Use Rates table and fields (this table relates facility types to use rates), the Use Patterns Multipliers table and fields (this table represents the use patterns and relates use pattern IDs to the use pattern multipliers), and the Use Pattern IDs table and fields (this table stores the use pattern IDs). Examples of facility type or CII use rates are daily water use per hospital or restaurant employee. The employee use rates by facility type used within the application were obtained from previous studies (Dziegielewski *et al.* 2000).

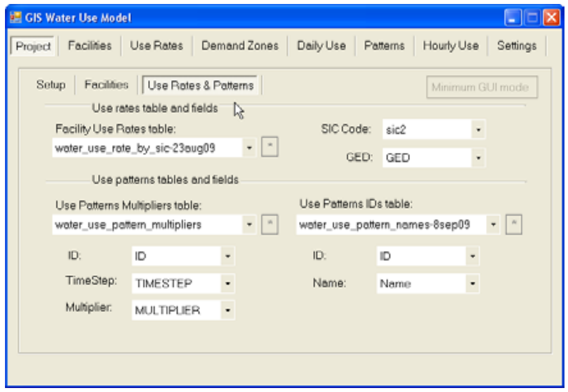


Figure 4.7. The Project-Use Rates & Patterns menu.

Step 7. Select the Facilities menu and the Facilities display option to display each CII facility in the facilities database (see Figure 4.8). Attributes of the facilities are shown, such as facility type (2-digit SIC code), number of employees, street address, city and state. The Facilities Grouped by Type display option shows the facilities aggregated by facility type (see Figure 4.9).

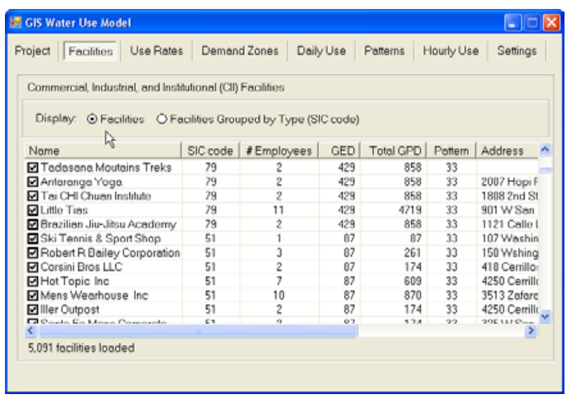


Figure 4.8. The CII facilities list menu.

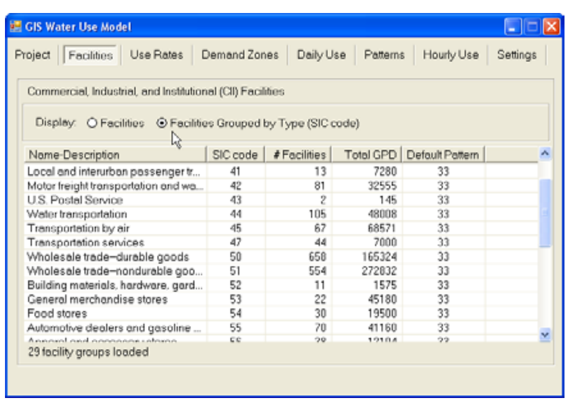


Figure 4.9. The CII facilities grouped by facility type (SIC code).

Step 8. Select the Use Rates menu to display the use rates for CII (select the Commercial, Industrial and Institutional display option) (see Figure 4.10) and enter the Residential use rate (select the Residential display option) (see Figure 4.11).

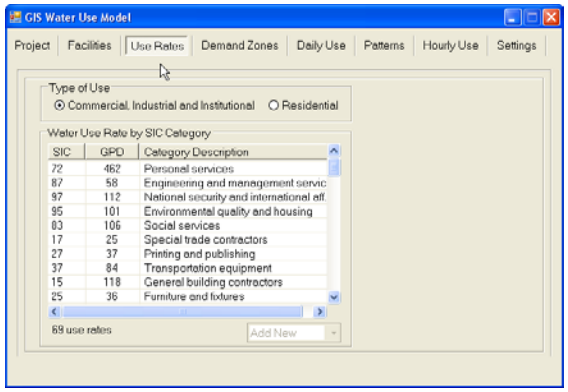


Figure 4.10. The baseline use rates for CII facilities are displayed on the Use Rates menu.

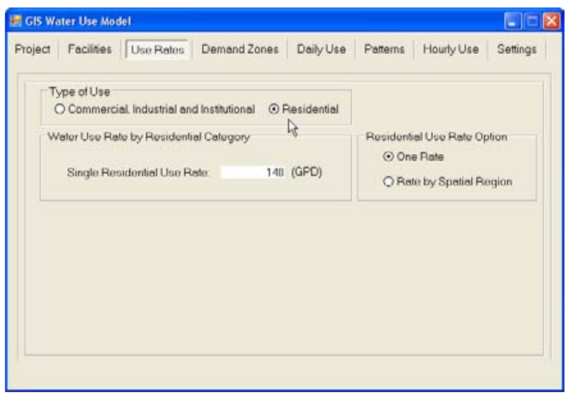


Figure 4.11. The baseline residential use rate of 140 GPD is entered on the Use Rates menu.

Step 9. Select the Demand Zones menu to choose the demand zone or service area layer and fields (see Figure 4.12). The demand zones are the estimated service areas for each demand junction. The Voronoi method of estimating service areas was used to be consistent with the approach used for the 2009 Master Plan. A spatial join operation is used to associate the residential and CII customers within each service area to its related to demand junction.

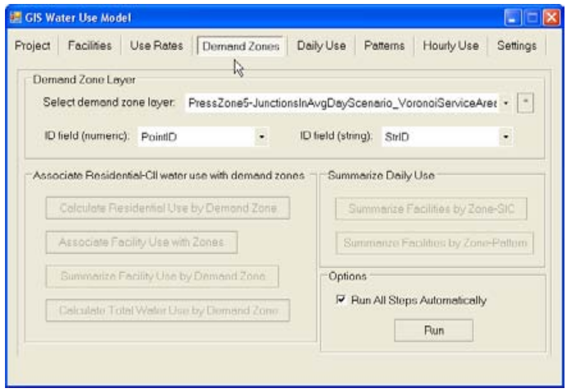


Figure 4.12. The Demand Zones menu allows users to select the service area layer and execute the method to estimate residential and CII demands per service area on a per-day basis.

Executing the method to estimate daily water use (Step 10)

During this step, a significant part of the overall method is performed, which results in the calculation of daily water use rates at each demand junction. The daily water use rate is also referred to as the *base demand* for a demand junction. The input parameters, specified in the previous steps are the inputs for the method. This part of the method is implemented in six main procedures. Each of the main procedures is correlated with a button on the Demand Zones menu, shown in Figures 4.12 and 4.13. The procedures are described next.

Calculate Residential Use by Demand Zone

This procedure implements Equation (2) from the methods chapter (shown below) to calculate the daily residential water demand for each demand junction (i.e., the daily residential demand within each service area or demand zone). The population data, in raster format, are used to estimate the residential population per service area using a zonal statistics operation. The product of the residential count for each service area and the daily residential water use rate input parameter is the total daily residential water demand at each demand junction.

Equation (2) from the Methodology chapter: $D_R = \sum_{j=1}^{J} P_j R_R$

where D_R is the daily residential demand, J is the total number of junctions in the water distribution system, P_j is the residential population served by junction j, and R_R is the daily use rate for each residential person.

Associate Facility Use with Zones

To estimate facility or CII water demand per demand junction, it is first necessary to spatially associate the CII facilities with the demand junction service areas. This is accomplished by spatially joining the CII facilities to the demand junction service areas. After employing the spatial join technique, each CII facility has an attribute of the demand junction and service area from which it is supplied water. This is used in the next procedure.

Summarize Facility Use by Demand Zone

This procedure implements Equation (5) from the methods chapter (shown below) to estimate the CII water demand per demand junction and service area. After spatially associating the CII facilities with their respective service areas in the previous procedure, the total CII demand for each demand junction is ascertained. For each service area, all of the CII facilities of a particular facility type (e.g., restaurants) are processed individually. These subtotals are necessary to then derive the total CII demand for each service area but are also stored and used to display the total demand by CII facility type.

Equation (5) from the Methodology chapter: $D_{CII} = \sum_{j=1}^{J}\sum_{k=1}^{K} E_{jk} R_{CII\,k}$

where D_{CII} is the daily commercial, industrial, and institutional (CII) demand. J is the total number of junctions in the system. K is the total number of CII facility types. E_{jk} is the number of employees working for facilities of type k within the service area served by junction j. $R_{CII\,k}$ is the daily use rate per employee for facilities of type k.

Calculate Total Water Use by Demand Zone

This procedure sums the residential demand and CII demand to derive the total daily water demand for each demand junction service area (i.e., demand zone). These results are only used to provide summary reports of the estimated demands.

Step 10. Estimate the daily water demand per demand zone using the Demand Zones menu (see Figure 4.13). There are two modes for the estimation process: each step can be executed individually (as described in the procedures above) or all steps can be executed automatically, when the Run All Steps Automatically box is checked. With this box checked, select the Run button. When the results have been calculated, the daily base demands per service area can be displayed on the map (See Figure 4.14). The daily demand estimates per service area by CII facilities (see Figure 4.15), residential customers (see Figure 4.16), total (see Figure 4.17), and total CII demands per facility type (SIC) (see Figure 4.18) can be viewed in tabular format on the Daily Use menu.

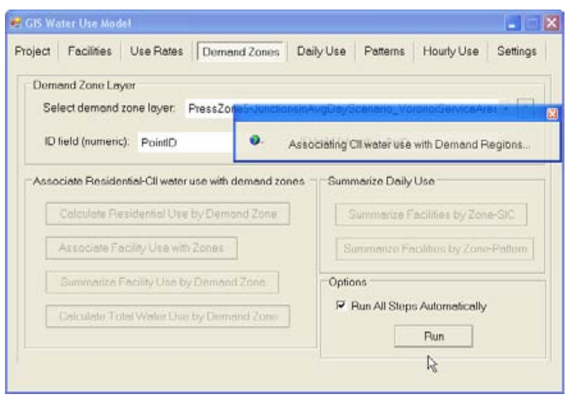


Figure 4.13. The Demand Zones menu allows the user to execute the method on a step-by-step basis or automatically execute all steps without user interaction.

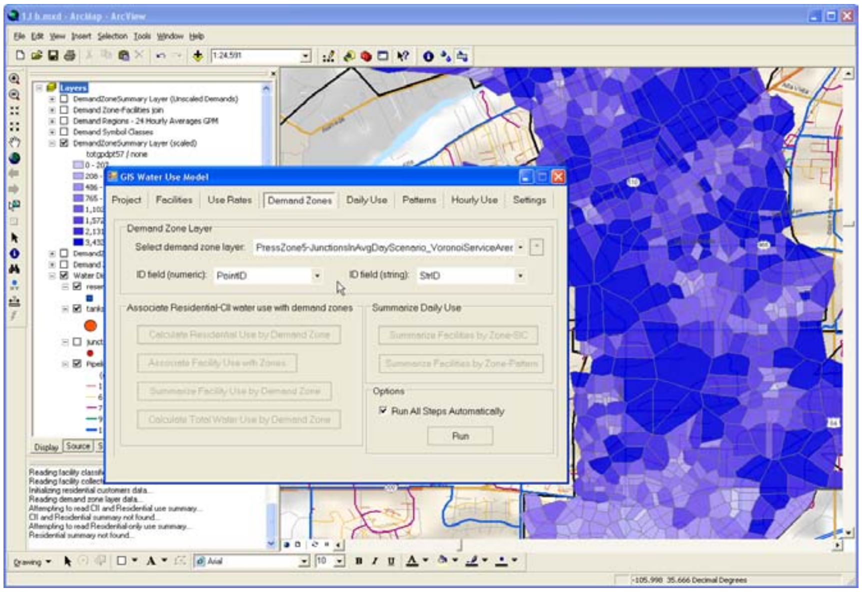


Figure 4.14. The results after executing the method show the total of the daily residential and CII demands by service area. The shade of blue per service area indicates relative water demand, where light-to-dark blue represents low-to-high total daily water demands, respectively.

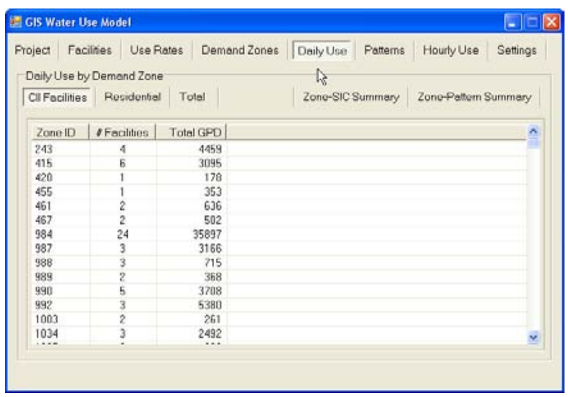


Figure 4.15. The results of the daily CII demands per service area.

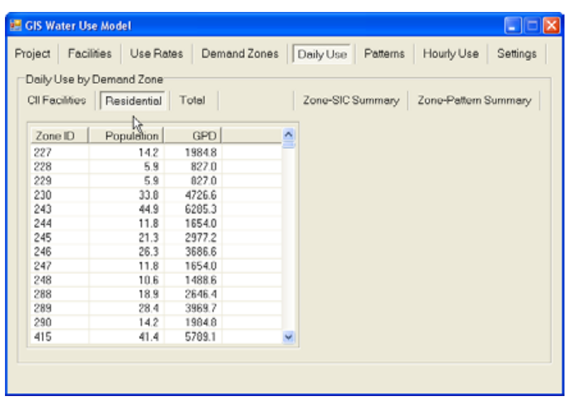
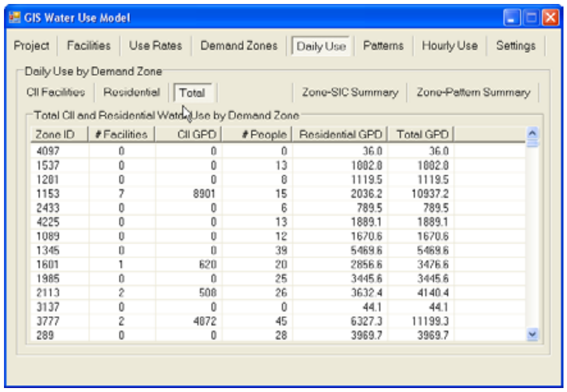
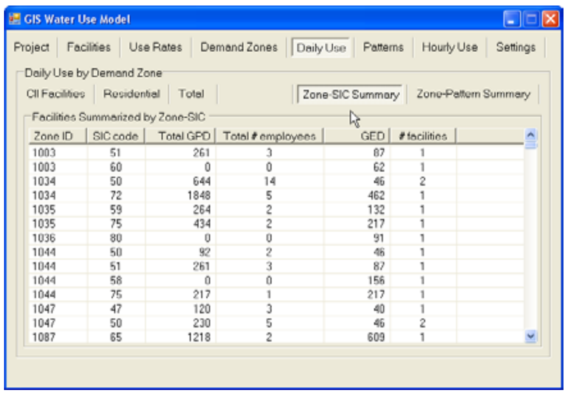


Figure 4.16. The results of the daily residential demands per service area.



Zone ID	# Facilities	CII GPD	# People	Residential GPD	Total GPD
4097	0	0	0	36.0	36.0
1537	0	0	13	1802.8	1802.8
1201	0	0	8	1119.5	1119.5
1153	7	8901	15	2036.2	10937.2
2433	0	0	6	789.5	789.5
4225	0	0	13	1889.1	1889.1
1089	0	0	12	1670.6	1670.6
1345	0	0	39	5469.6	5469.6
1601	1	620	20	2856.6	3476.6
1985	0	0	25	3445.6	3445.6
2113	2	508	26	3632.4	4140.4
3137	0	0	0	44.1	44.1
3777	2	4872	45	6327.3	11199.3
289	0	0	28	3969.7	3969.7

Figure 4.17. The results of total daily residential and CII demands per service area.



Zone ID	SIC code	Total GPD	Total # employees	GED	# facilities
1003	51	261	3	87	1
1003	60	0	0	62	1
1034	50	644	14	46	2
1034	72	1848	5	462	1
1035	59	264	2	132	1
1035	75	434	2	217	1
1036	80	0	0	91	1
1044	50	92	2	46	1
1044	51	261	3	87	1
1044	58	0	0	156	1
1044	75	217	1	217	1
1047	47	120	3	40	1
1047	50	230	5	46	2
1087	65	1218	2	609	1

Figure 4.18. The results of total daily CII demands per facility type (SIC) per service area

Selecting the 24-hour water use patterns (Step 11)

The 24-hour time patterns are used to disaggregate the daily water use at each demand junction to an hourly demand rate. A single use pattern is uniformly applied to disaggregate the residential demands at each demand junction. Each CII facility type has its own use pattern. This allows for very fine-grained modeling of CII demand by applying unique use patterns that correspond with each CII facility type. For this research, only a few use patterns were acquired from the literature. A generic business use pattern – the Haestad Business pattern – is used as the default pattern for most of the CII facility types because specific patterns for these facility types were not available. For the residential demand, a use pattern was obtained from previous research and patterns were derived for the research. The derived residential patterns were computed by subtracting the estimated CII demand from the total empiric demand, on an hour-by-hour basis. Both the acquired and derived patterns are used in the illustrated case.

Step 11. Select the Patterns menu to assign different use patterns for corresponding CII facility types (see Figure 4.19) and a use pattern for residential customers (see Figure 4.20). The Motel pattern (see Figure 4.21) was used for CII facilities categorized as Hotels, rooming houses, camps and other lodging places; the mid-morning peak looks similar to that of a Saturday demand pattern. The Restaurant pattern (see Figure 4.22) was used for CII facilities categorized as Eating and Drinking places; this pattern is characterized by water use, related to lunch and dinner activities, that is shifted later in the day. The Restaurant and Motel patterns were the only patterns obtained from the literature for specific CII facility types. The Haestad Business pattern was used for all remaining CII facilities. The Derived Residential Pattern (#1) was used for all residential demands.

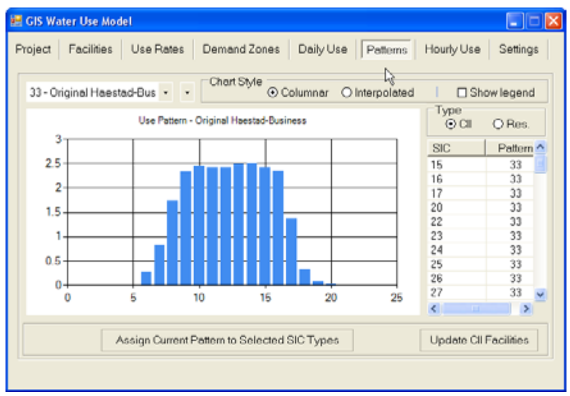


Figure 4.19. The Haestad Business 24-hour use pattern of hourly temporal resolution is used for most of CII the facility types.

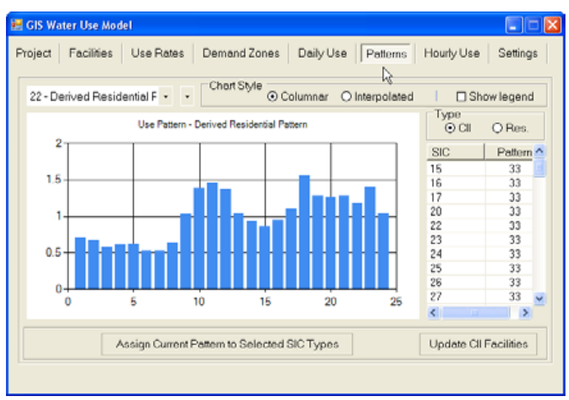


Figure 4.20. The Derived Residential Pattern (#1) 24-hour pattern of hourly temporal resolution is used for the residential customers.

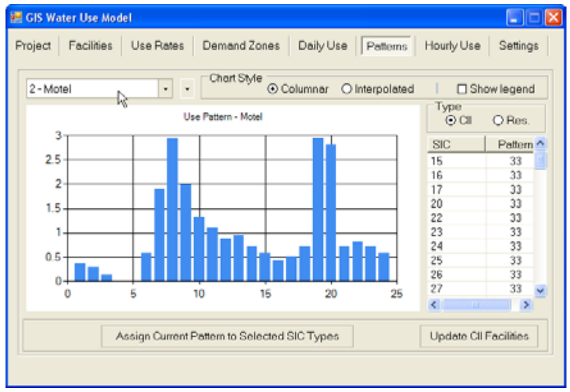


Figure 4.21. The Motel 24-hour use pattern of hourly temporal resolution is used for motels and other lodging facility types.

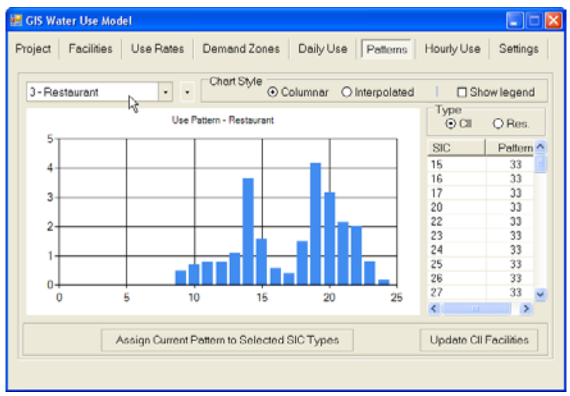


Figure 4.22. The Restaurant 24-hour use pattern of hourly temporal resolution is used for eating and drinking facility types.

Exporting the estimated demand values (Step 12)

Estimating the daily water use was the first of two main parts to estimating demand. This is the second main part, where the daily water use is temporally disaggregated to an hourly rate by applying the residential and CII use patterns. Any service area can have one residential use pattern and many CII use patterns because each CII facility type can have its own corresponding use pattern. By applying Equation (4) from the methods chapter (shown below), the total residential daily demand for all demand junctions is computed. Within the equation, the daily residential demand for one demand junction is calculated by summing across all 24 hourly periods the product of the number of residential persons within the service area and the hourly use rate. The hourly use rate is equal to the daily residential use rate for the demand junction multiplied by the use

pattern factor for that hour. This calculation per demand junction is then summed across all demand junctions to derive the total daily water demand.

Equation (4) from the Methodology chapter: $D_R = \sum_{j=1}^{J}\sum_{t=1}^{24} P_j R_{Rt}$

where D_R is the daily residential demand, J is the total number of junctions in the system. t is the hour, which varies from 1 to 24. P_j is the residential population served by junction j . R_{Rt} is the use rate at hour t for each residential person.

The calculation of the total daily CII water demand, including the CII use patterns, is similar to that for residential demand. However, the differences are that each CII facility type can have its own use pattern, its own number of persons (i.e., employees), and its own daily use rate (per CII facility type). Further, any demand junction can serve many CII facility types. Using Equation (7) from the methods chapter (shown below), the total CII demand is calculated. Examining the CII demand for one CII facility type, for one demand junction, the daily CII water use is calculated by summing the product of the daily CII water use for the CII facility type, the number of persons (i.e., employees) working at that CII facility type, and the hourly use pattern factor across all 24 hourly periods. This approach is then applied for all CII facility types represented by a demand junction. Lastly, this procedure is applied for all demand junctions to derive the total daill CII demand.

Equation (7) from the Methodology chapter: $D_{CII} = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{24} E_{jk} R_{CII\,kt}$

where D_{CII} is the daily CII demand. J is the total number of junctions in the system. K is the total number of CII facility types. t is the hour and varies from 1 to 24. E_{jk} is the number of employees working for facilities of type k within the service area served by junction j . $R_{CII\,kt}$ is the use rate per employee for facilities of type k at hour t .

Step 12. With the daily CII and residential demand estimated per demand zone, the last step is to temporally disaggregate the daily usage to 24 one-hour periods using the assigned CII and residential use patterns. Select the Hourly Use menu (see Figure 4.23), select the Output folder and Output filename (where the results will be written) and enter a Demand Scale Factor of 0.5777. The demand scale factor uniformly scales all demands by this factor. The scale factor was derived to ensure that the total estimated demand for a calibration case equaled the overall empiric demand. Under the Export Demands area, select EPANET Inp File Section to export the demands to a format compatible with the EPANET software package, or select Junctions Demand Table to export to a text file in columnar table format. The Junctions Demand Table format can be readily imported into ArcMap for use with the demand junctions or demand zones layers.

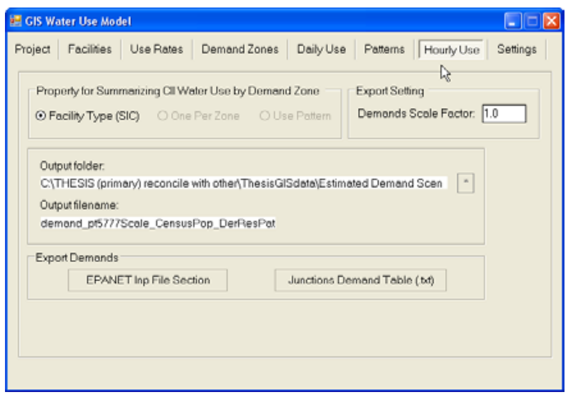


Figure 4.23. The Hourly Use menu is used to export residential and CII demands at hourly temporal resolution using daily demands and selected 24-hour use patterns.

Visualizing the estimated water demand (Step 13)

The last step shows how the estimated demand can be visualized in the ArcMap GIS environment.

Step 13. With the demand estimate completed, the results can be visualized by demand zone (service area) for each of the 24 one-hour periods. Figure 4.24 shows the total CII and residential demands by service area for the period from 12:00am to 1:00am. Figure 4.25 shows the estimated demand for four one-hour periods over the 24-hour period, including the peak demand period at 10:00am to 11:00am.

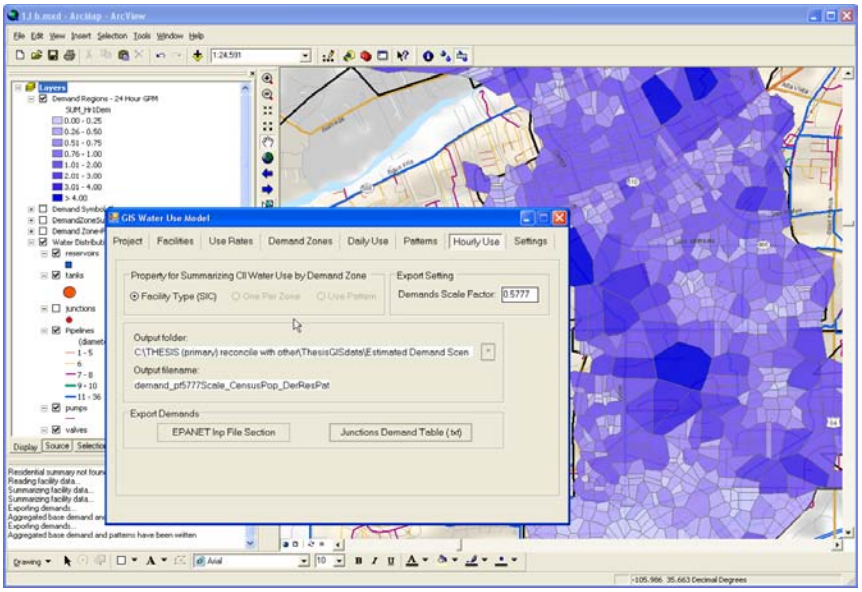


Figure 4.24. Shown are the estimated total of residential and CII demands per service area as an average for the period from 12:00am to 1:00am.

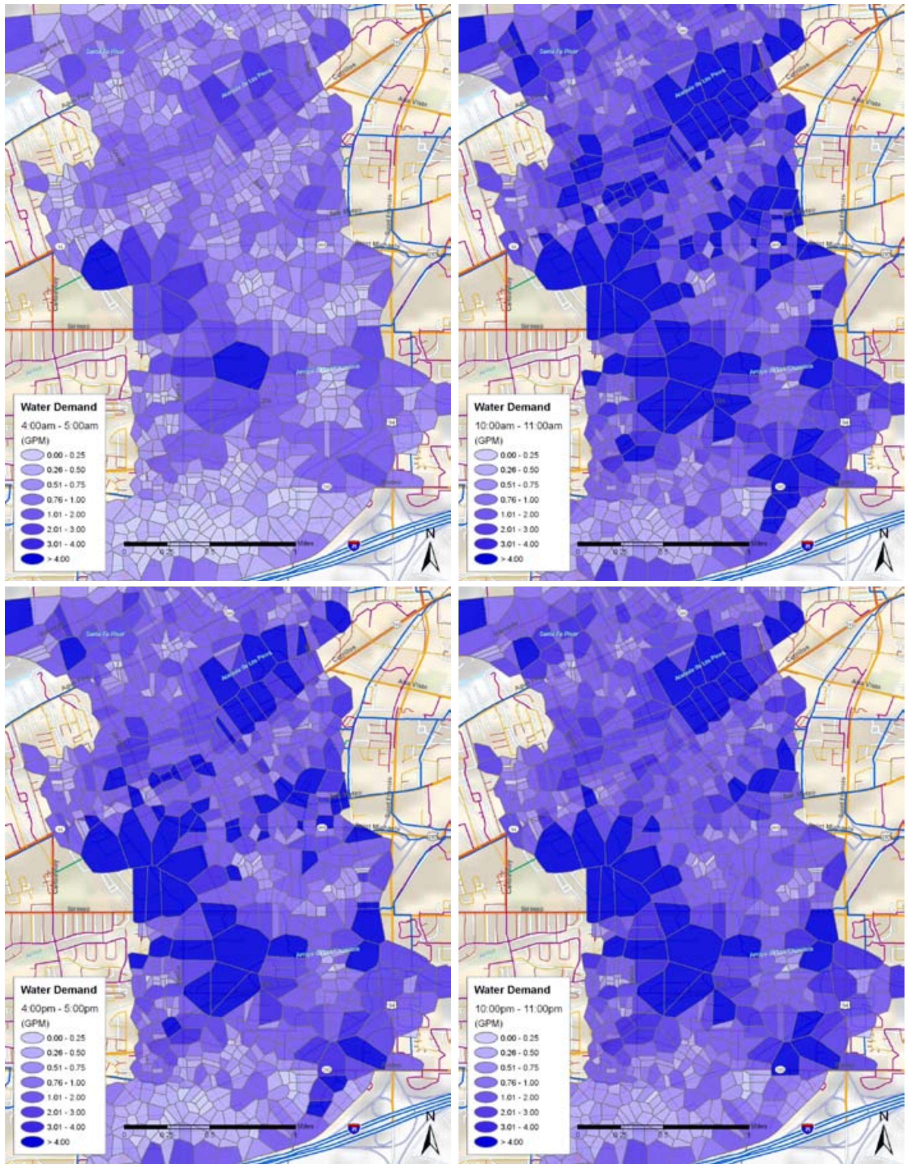


Figure 4.25. Shown are the estimated total of residential and CII demands per service area for four one-hour periods. The hourly water demand averages are shown for 4:00am-5:00am (top left), 10:00am-11:00am (top right), 4:00pm-5:00pm (bottom left), and 10:00pm-11:00pm (bottom right). The peak demand occurs from 10:00am-11:00am.

Other features of the GWUM application are designed to increase usability. All of the input parameter values of the GWUM application are stored on the computer and retrieved the next time the application is used. Similarly, the Settings menu saves and restores user preferences from one session to the next session.

4.2 Calibrating the Method

This section describes the process of calibrating the research method. The introductory material of the section provides background information about model calibration and details of the calibration region, followed by a summary of the results of one calibration case. The final subsection presents a summary of the results of all the calibration cases.

4.2.1 Model Calibration

The purpose of the calibration process is to explore and understand the response of the model to varying inputs, with an overarching goal of finding the best fit between empiric measurements and simulated calculations. The best fit is assessed using statistical metrics. When estimating demand for a water distribution system, there are many potential spatial and temporal units to consider. However, for calibration purposes, these may be limited by the empiric data that are available. For the research, the empiric data were provided by the City of Santa Fe Water Division and the consulting firm Brown and Caldwell. The empiric demand data were obtained from a calibrated hydraulic and demand model built by Brown and Caldwell for the City of Santa Fe's 2009 Master Plan. The calibrated hydraulic and demand model was developed using system data, including system measurements such as pressures, tank levels, and flows, as well as, customer usage records.

Ideally, the process of calibration for the research would compare simulated calculations with measured values. However, the accepted practice employed by Brown and Caldwell for developing the calibrated demand representation (referred to within this research as the "empiric" water demand) involves adjusting customer usage data because of unaccounted-for losses in a system (Haested 2003). The approach for establishing the demand model for the calibrated system entailed scaling the recorded customer usage so that it matched the measured system-wide water production (i.e., the outflows, such as customer usage and filling tanks, equal the inflows, such as those provided by well fields, reservoirs, and draining tanks). This operation addressed the issue of unknown system losses by equating the total customer usage to the total system-wide water production (See Appendix E for more details on the approach used by Brown and Caldwell).

Additionally, individual customer usage is recorded for a billing period, such as a month, whereas this research focuses on estimating demand for a 24-hour period. For the 2009 Master Plan, the system-wide water production, which is recorded daily, was used as the basis for determining the minimum, maximum and average daily scenarios, where the specific day for each scenario is selected appropriately from different seasons of the year (e.g., the minimum-production day occurs during winter).

4.2.2 Details of the Calibration Region

The steps outlined in the methodology chapter were followed to estimate water demand for the calibration cases using the representation of the City of Santa Fe's water distribution system provided by the 2009 Master Plan. The service territory of the Santa Fe system (see Figure 3.4) was used to define the outer boundary of the analysis region. The 11 pressure zones within the service territory were characterized by land use type (see Table 3.2) and compared to the land use characterization of the overall service territory (see Table 3.1). Pressure zone 5 was chosen as the geographic region to use for all calibration cases because its land use characteristics closely resemble the aggregate land use characteristics within the entire water system service territory.

Within pressure zone 5, there are 973 demand junctions on the pipeline network and 973 corresponding neighborhood-scale service areas. The total use rate for the Empiric Average Day Scenario is 1,191 GPM or 1,715,040 GPD. The empiric demand provided by the 2009 Master Plan study for the 973 demand junctions will be used to calibrate the estimated demand.

A qualitative assessment of the land use classification of the empiric water customers can be made to gain an understanding of customer types within pressure zone 5. The 2009 Master Plan data provided the geographic point location, base demand, street address, and gelocation method (i.e., parcel, geocode, etc.) for every water customer on the Santa Fe water system. These are referred to as *empiric customers*. Each empiric customer location can represent a residential or CII water customer. For residential customers, empiric customers can represent households such as single-family houses or apartments. The CII customers can represent facilities such as commercial businesses, government offices, and public schools. Because of privacy issues, the

specific customer names, such as person name for residential customers and company name for CII customers, were removed from the empiric customer dataset. Unfortunately, no other attribute in the dataset indicated whether a water customer was residential or CII. An attribute like this would have enabled further analysis at the service territory, pressure zone, or service area scales.

There are 6,659 empiric customers within pressure zone 5. Of these 6,659 customers, 5,991 are within one of the four residential land use regions, while 605 of the customers fall within one of the CII land use regions. The remaining 63 customers are within the open space and park land use regions.

For the CII water demand estimation, there were 2,043 Dun and Bradstreet CII facilities within pressure zone 5. Of these 2,043 CII facilities, it was estimated that 833 facilities would be open on Saturday and 776 facilities would be closed on Saturday (see Appendix B for the assumptions on which facility types are open or closed on Saturday). The remaining 434 facilities could not be classified within a specific business type category using their North American Industry Classification System (NAICS) code. The 434 facilities were classified with either an unknown classification or had an untranslatable classification identifier. Therefore, the 434 facilities could not be assigned an associated water use rate and were excluded from consideration. Within pressure zone 5, 833 CII facilities were considered.

4.2.3 Summary of One Calibration Result

Next, a summary of the results from calibration Case 1J are presented. Case 1J was presented in a previous section on using the GWUM application to estimate water demand, which shows more details on the input parameters and the mathematical underpinnings of the method. The case is described, the input parameter values are listed, and the results and error analysis in tabular and graphical formats are shown. Case 1J was selected as the best-fit calibration case and was used in the validation section. Summaries for all calibration cases are provided in Appendix F.

Description. Case 1J is based on using the baseline parameter values and a demand scale factor (these are the input parameter values for Case 1A), and enhances this by using a derived residential use pattern instead of the default residential pattern. The demand scale

factor is a multiplier that is applied to all estimated demands so that the total estimated demand equals the total empiric demand. Because the predominant demand of the system is residential, creating an improved residential pattern is expected to result in a better fit between the estimated and empiric demand. The residential use pattern was derived using the following steps:

1) Use the estimated CII demand of Case 1A and the empiric demand.
2) Subtract the estimated aggregate CII demand from the empiric demand for each of the 24 hours.
3) Calculate the average of the estimated CII demand subtracted from the average empiric demand for the 24-hour period.
4) Divide the result for Step 2 for each hour by the value calculated in Step 3. These are the 24 hourly dimensionless multipliers of the newly derived residential pattern.

The input parameters are summarized in Table 4.1. The results and error analysis are portrayed in Figure 4.26, Table 4.2, Figure 4.27, and Figure 4.28.

Input Parameters

Table 4.1. Parameter values for Calibration Case 1J.

Case 1J Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Derived New Residential Pattern
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	0.5777
Residential Population	Census

Results and Error Analysis

The estimated demand matches closely with the empiric demand, using the chosen metrics. The slight relative error of 0.1% is due to an issue whereby the 24 hourly factors for the empiric use pattern do not sum to 24 (or have an average value of 1), which appears to be a discrepancy with the empiric use pattern. The 24 hourly factors of the empiric use pattern sum to 23.98. This introduces a small error when comparing the estimated demands (where the use patterns for the 24 hourly factors sum to 24) to the empiric demands. The close match of estimated and empiric demand is expected because the residential demand is predominant within pressure zone 5. Further, the derived

residential pattern is custom-fitted to equal the aggregate hourly empiric demand for this pressure zone. Figure 4.26 illustrates the close match of the estimated and empiric demand. The diurnal shape of the graph reflects the mid-morning and early-evening peak use times of the day. The mid-morning timing of the peak is indicative of a Saturday, whereas, a weekday peak would occur earlier in the morning.

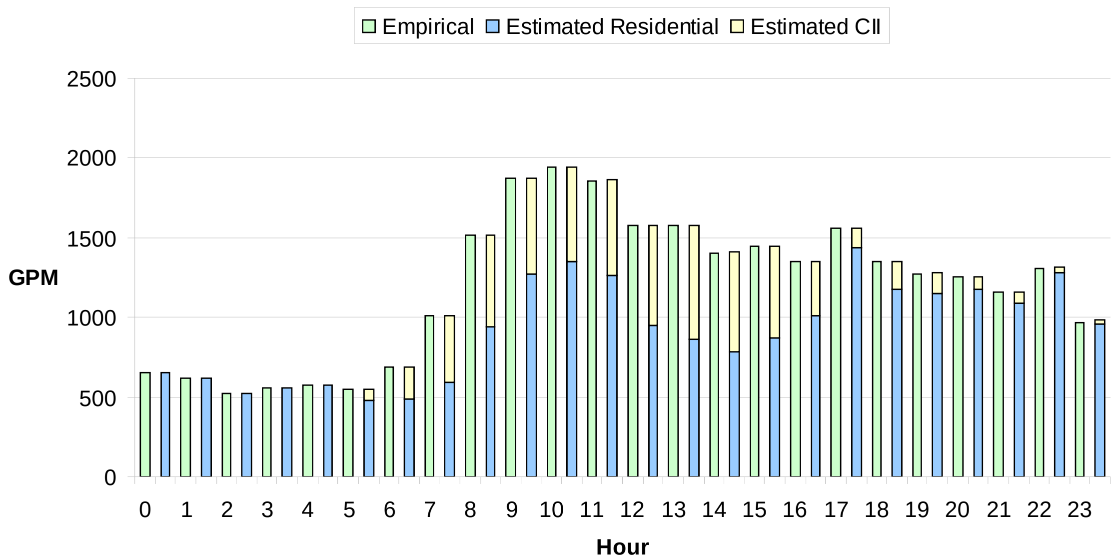


Figure 4.26. The total empiric and estimated Case 1J hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table 4.2. Results and error measures for Calibration Case 1J. The demand units are GPD. The percentage contributions of the estimated residential and CII components to the total estimated demand are shown in the right column.

Case 1J Error Metrics		
(Demand and RMSE units are GPM)		
Total Estimated Demand	1191	
Total Empiric Demand	1191	
Total % Difference	0%	
Total Estimated Residential Demand	920	77%
Total Estimated CII Demand	272	23%
Relative Error	0.1%	

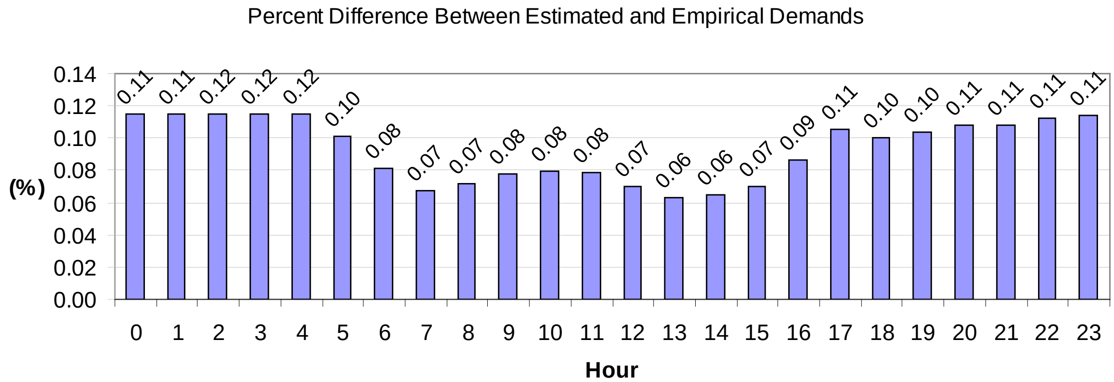


Figure 4.27. The percent difference between the estimated Case 1J and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

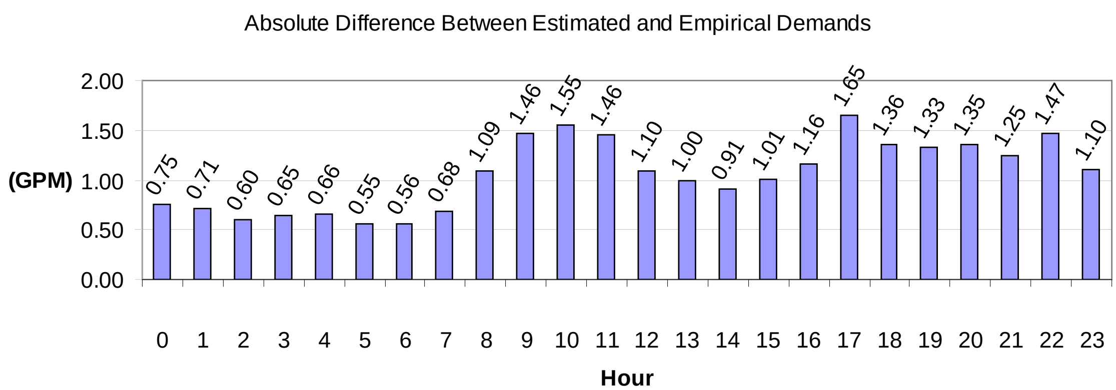


Figure 4.28. The absolute difference in GPM between the estimated Case 1J and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

4.2.4 Summary of Calibration Results

This section presents a summary of the results of all the calibration cases. Fifteen calibration cases were explored. Each case investigates the response of the method to different assumptions and input parameters (see Table 4.3 for the description of each case). For example, the first case – Case 1 – examines the effects of using the baseline or default values provided by the data sources. Each successive case uses what is thought to be reasonable assumptions (implemented through an input parameter set) to test not only the model, but also the GWUM application. The purpose of the cases, collectively, is to

explore and gain some understanding of the importance of the input parameters and how they affect the response of the method.

Because the residential component is predominant in the overall water demand of the system, most of the cases focus on modifying parameters related to residential demand. These parameters include the residential population, residential daily use rate, and residential use pattern. The parameter adjusted for estimating CII demand is the default business use pattern, which is used by most of the CII facilities.

Each of the calibration cases is described in Table 4.3 and the main input parameter values, results and error analysis are presented in Table 4.4. A graphical comparison of the calibration results of estimated demand with the empiric hourly averages is shown in Figure 4.29.

Case 1 uses the baseline input parameter values established by the method and results in a Percent Difference (PD) of 73% and a Relative Error (RE) of 82%. It is the poorest performing case. Case 1 was then used as the baseline case to derive new calibration cases. For example, Case 1A enhances the Case 1 result by using a scale factor to uniformly scale all service area demands so that the total estimated demand equals the total empiric demand. This case markedly improves the error analysis to a Percent Difference of 0% (the scale factor ensures that the PD value will be 0%) and a Relative Error of 32%. The use of a scale factor, in addition to forcing the PD to 0%, improves the RE. This is true for all cases that utilize a scale factor. This can be seen for the following pairs of cases where the use of the scale factor is the only difference between the initial case and the follow-on case: Cases 1 and 1A (RE improves from 82% to 32%), Cases 1B and 1C (RE improves from 61% to 33%), Cases 1D and 1E (RE improves from 70% to 28%), Cases 1G and 1H (RE improves from 48% to 30%), Cases 1I and 1J (RE improves from 73% to 0.1%), Cases 1K and 1L (RE improves from 14% to 13%), and Cases 1M and 1N (RE improves from 5% to 0.1%). The improvement in the RE is generally inversely proportional to the magnitude of the scale factor. That is, the use of a smaller scale factor value results in a greater change in demand values, which, in turn, produces a greater relative improvement in the RE.

Some of the cases explore the results of additional changes or combinations of changes, such as, reducing the per capita residential water use (e.g., Cases 1B, 1C, 1F, 1G

and 1H), using a different residential population dataset (e.g., Cases 1D, 1E, 1K, 1L, 1M and 1N), reducing the residential population to compensate for the (CII) working population (e.g., Cases 1G and 1H), modifying the general CII use pattern (e.g., Cases 1F, 1G and 1H), and deriving new residential use patterns (e.g., Cases 1I through 1N). Two main categories of changes can be identified: changes that adjust the magnitude of the residential water use (i.e., the base residential demand) and changes that adjust the 24-hour use pattern (i.e., the temporal distribution of the base demand over a 24-hour period). The cases that alter the per capita residential water use rate or employ a different residential population dataset result in a change in magnitude of the residential demand component (which is the primary demand component of the water system). All of these cases use the Loureiro residential 24-hour use pattern, which is the default residential pattern, provided by previous research (Loureiro *et al.* 2006). Cases 1G and 1H also reduce the magnitude of the residential demand but only for the block of time deemed to be during business working hours. If these cases are considered, and the cases that apply a scale factor and/or introduce a derived residential use pattern are excluded (i.e., Cases 1I through 1N), Cases 1B and 1D remain. The PDs and the REs for both cases are similar in value. The PD and RE values for Case 1B are 47% and 61%, respectively. For case 1D, the PD and RE values for Case 1D are 61% and 70%, respectively. The error values are not that unlike the baseline result for Case 1, which has a PD of 73% and an RE of 82%. Employing a scale factor for Case 1B (i.e., this is Case 1C) improves the error values to a PD of 0% and an RE of 33%. Similarly, applying a scale factor to Case 1D (i.e., this is Case 1E) improves the PD and RE error values to 0% and 28%, respectively. The PD and RE values for the baseline case (i.e., Case 1) with a scale factor (i.e., Case 1A) are 0% and 32%, respectively.

While the use of a lower residential use rate and the LANL daytime residential population dataset (which also has the effect of reducing the base residential demand) do result in lower error values, the improvements are not dramatic. For Case 1F, the use of the modified CII water use pattern with the lower residential use rate without a scale factor produces a moderate improvement, with a PD of 47% and an RE of 60%. Case 1G improves upon Case 1F by also reducing the daytime residential population to account for the working population (i.e., people who are not at their residence during working

hours). The result is a PD of 36% and an RE of 48%. Case 1G produces the lowest error values for any case that does not use a scale factor and does not use a derived residential pattern. Case 1H enhances Case 1G through the use of a scale factor. The PD and RE values for Case 1G are 0% and 30%, respectively. For all of the above cases that do not use a derived residential pattern, the REs for the cases that use a scale factor only range in value from 28% to 33%. It is apparent for these cases that no significant difference in efficacy was revealed by modifying the available parameters, short of altering the residential use pattern. For these cases, the general shape of the estimated 24-hour water demand is the same, as shown in Figure 4.29. The exceptions are the cases that reduce the residential population during work hours (e.g., Cases 1G and 1H) and the cases that use the adjusted CII use pattern to serve customers during non-business hours (e.g., Cases 1F, 1G, and 1H).

Examining the 24-hour pattern for the empiric water demand in Figure 4.29 leads one to understand that the best fit for the estimated demand would require replicating the 24-hour pattern of the empiric demand. Cases 1I through 1N explore the use of derived residential use patterns. By using detailed knowledge of the empiric demand, that is the 24 hourly demand values of the empiric data, new residential use patterns can be derived. For Cases 1I through 1L, a new residential use pattern is derived – Derived Pattern #1. The derived pattern is based on the use of Census population data. While Case 1I produces error values of 73% for both the PD and RE, use of the scale factor for Case 1J results in the best fit of all of the calibration cases. The PD and RE for Case 1J are 0% and 0.1%, respectively. The other cases that use the Derived Residential Pattern #1, employ the LANL daytime population. These two cases – Case 1K and Case 1L – do not perform as well. Substituting the LANL population data into a case that was formulated using the Census population data, alters the shape of the 24-hour pattern, and results in a pattern that will not replicate the empiric use pattern and, therefore, will not result in near-zero error values.

Cases 1M and 1N are based on the use of a newly derived residential use pattern – Derived Residential Pattern #2. These cases use the LANL daytime population dataset and, similar to Case 1J, result in a PD of 0% and an RE of 0.1%, when a scale factor is applied. What is apparent from these cases is that deriving and applying a residential use

pattern based on a specific population dataset and the empiric demand enables the estimate to very closely resemble the empiric demand. While the scale factor enables the overall estimated base demand to align with the empiric demand, the residential use pattern is critical for fine-tuning the estimated demand so that it closely emulates the behavior of the empiric demand.

The details of the calibration cases, including the graphs of the demand and the errors (as were shown in the previous section on calibration Case 1J), are shown in Appendix F.

Both Case 1J and Case 1N, decidedly, result in the minimum errors using the Relative Error metric. However, Case 1J was selected as the preferred calibration case for two reasons: the Census population dataset, which provides a standardized and accepted dataset for research, was used for Case 1J; and, the case resulted in a higher percentage of total estimated residential demand, which is more representative of the demands on the Santa Fe water system.

Table 4.3. The table provides a description of each calibration case.

Case	Description
1	This is the baseline case, where the default parameter values provided by the data sources are used. This case is the basis for all of the subsequent cases (hence the preceding “1” for all case names). The baseline or default values include a daily residential use rate of 140 GPM (USGS); the Loureiro residential use pattern; the Restaurant use pattern for CII facility types of eating and drinking establishments; the Motel use pattern for CII facility types of lodging facilities; CII daily use rates provided by the Dziegielewski *et al.* study (2000); 2005 Census residential population data; and the Dun and Bradstreet commercial dataset for CII facilities.
1A	This case employs the baseline parameters of Case 1 and enhances this by using a demand scale factor to scale all demands (at every demand junction for every hour) so that the total estimated demand equals the empiric demand. The demand scale factor ensures that the total estimated demand equals the total empiric demand. The scale factor is 0.5777.
1B	The premise for this case is that the baseline residential daily use rate could be adjusted to improve the estimated demand. The baseline rate of 140 GPM (estimated using the USGS data) is higher than the rates reported for the 2009 Master Plan. A new residential daily rate was calculated by examining the empiric use rates for customers wholly within land use regions defined as residential. The derived residential daily rate is 113 GPM. All other parameter values are the same as for Case 1.
1C	The case is identical to Case 1B with the addition of the use of a demand scale factor of 0.6788.
1D	The premise for this case is that the residential population could be reduced during the work hours of 8:00am – 5:00pm by the number of people who are working. The working population would not be consuming water at home but instead would be consuming water at work. It was assumed that 50% of the employees working within pressure zone 5 also live in the same pressure zone. This number of employees was removed from the residential population during work hours. The case employs a daytime residential population dataset that was developed at LANL. All other parameter values are the same as for Case 1.

Case	Description
1E	This case is identical to Case 1D with the addition of the use of a demand scale factor equal to 0.95.
1F	The premise for the case is that the default CII use pattern (i.e., the Haestad Business pattern), which is applied for most of the CII facilities, does not supply water during non-business hours of before 6:00am or after 7:00pm. It is expected that some amount of demand would take place during non-business hours, such as for landscaping. The derived business pattern modifies the Haestad Business pattern by distributing s small percentage of the demand during the non-business hour periods. The case is based on Case 1B.
1G	This case is based on Case 1F. In addition to using the modified business use pattern, the (Census) residential population is reduced by 50% of the working population during the working hours of 8:00am – 5:00pm, as was performed for Case 1D. This is done to decrease the residential demand to compensate for the working people who are consuming water at work and not at their residence.
1H	This case is identical to Case 1G but includes a demand scale factor of 0.7379.
1I	The premise of the case is that deriving a new residential use pattern using the empiric data would result in small errors. This case is based on Case 1, with the addition of the derived residential use pattern. The residential use pattern was, in principle, derived by subtracting the estimated CII demand from the empiric demand.
1J	This case is identical to Case 1I but includes a demand scale factor of 0.5777. Estimating demand using the derived residential use pattern with the scale factor results in errors of, essentially, 0.
1K	This case is based on Case 1I but uses the LANL daytime residential population dataset.
1L	This is identical to Case 1K but uses a demand scale factor of 0.95.
1M	The case is based on Case 1D with the addition of the derivation of a new residential use pattern. This case is similar to Case 1I but the LANL daytime residential population dataset is used instead of Census population data.
1N	The case is identical to Case 1M but uses a demand scale factor of 0.95.

Table 4.4. The table summarizes the calibration cases and includes a brief description, main parameter values and values of error metrics. For the cases where the total estimated demand is scaled to equal the total empiric demand, the total percentage difference is zero. These cases have a scale factor; the non-scaling cases do not have a scale factor. The code for residential population sources is: C for Census and L for LANL. All cases are for pressure zone 5. The total empiric demand for pressure zone 5 is 1191 GPM. The percentage contributions of residential demand and CII demand for the empiric demand is not known.

Case	Description	Scale Factor	Res. GPD	Res. Population	Res. Use Pattern	Total % Diff.	Relative Error (%)	Total Est. Base Demand (GPM)	Est. Res./CII Demand %s
1	Base case	-	140	C	Loureiro	73	82	2062	77 / 23
1A	Scale base case to empiric	.58	140	C	Loureiro	0	32	1191	77 / 23
1B	Reduce residential GPD	-	113	C	Loureiro	47	61	1755	73 / 27
1C	Reduce res. GPD, scale to empiric	.68	113	C	Loureiro	0	33	1191	73 / 27
1D	LANL daytime res. pop.	-	140	L	Loureiro	61	70	1922	76 / 24
1E	LANL daytime res. pop., scale	.61	140	L	Loureiro	0	28	1191	76 / 24
1F	Modified general CII pattern	-	113	C	Loureiro	47	60	1755	73 / 27
1G	Mod. CII pat., reduce res. pop.	-	113	C	Loureiro	36	48	1615	71 / 29
1H	Mod. CII pat, reduce res pop, scale	.74	113	C	Loureiro	0	30	1191	71 / 29
1I	Derive res. pat., base case	-	140	C	Derived1	73	73	2062	77 / 23
1J	Derive res. pat., base case, scale	.58	140	C	Derived1	0	0.1	1191	77 / 23
1K	Derive res. pat., LANL pop.	-	140	L	Derived1	5	14	1253	62 / 38
1L	Derive res. pat., LANL pop., scale	.95	140	L	Derived1	0	13	1191	62 / 38
1M	Derive res. pat. 2, LANL pop.	-	140	L	Derived2	5	5	1253	62 / 38
1N	Derive res. pat. 2, LANL pop., scale	.95	140	L	Derived2	0	0.1	1191	62 / 38

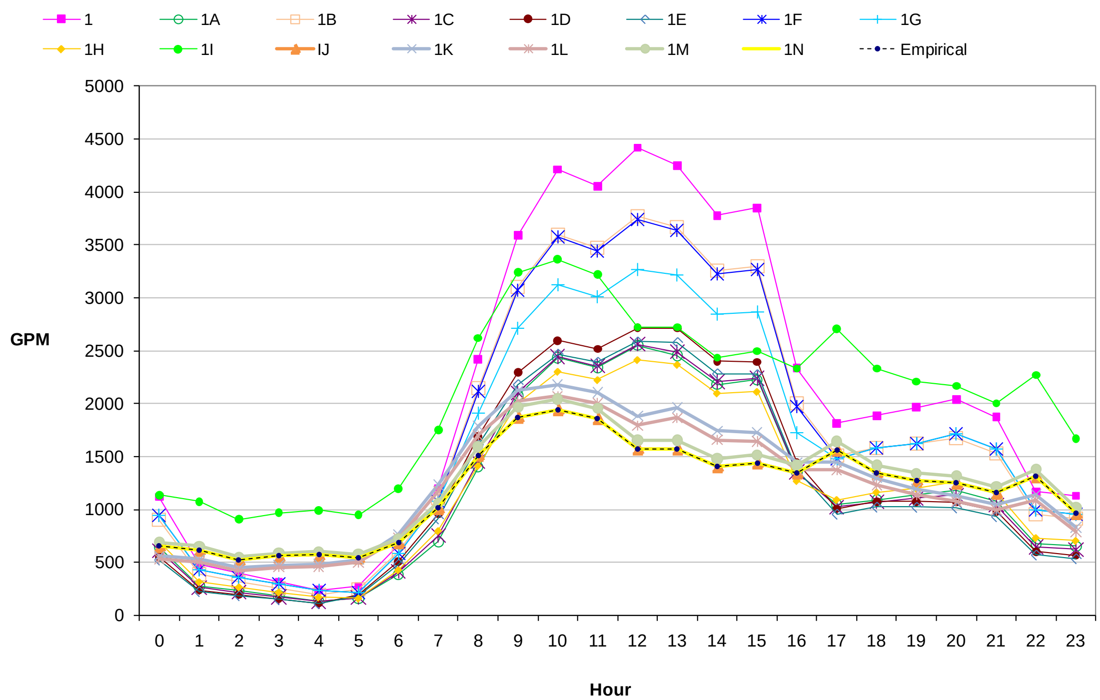


Figure 4.29. The 24-hour water demand estimates for all of the calibration cases are shown with the empiric water demand. Calibration Cases 1J and 1N closely overlay the empiric water demand for all the hourly values.

4.3 Validating the Method

This section describes the process of validating the research method. Background information about model validation is provided first, followed by details about the validation regions. Finally, a summary of the results of the validation cases is presented.

4.3.1 Model Validation

Model validation applies a calibrated method to a system or, in this case, a subsystem within a geographic region, which is independent or different from that used to calibrate the method. The validation section assesses how well the calibrated method performs on the independent dataset(s) and provides an indication of the applicability of the method for other purposes. All of the validation cases were calculated using the GWUM application. The same error metrics used for the calibration cases and described in the methodology chapter are used for validation. The empiric demand data used to

error-check the validation cases were obtained from the calibrated hydraulic and demand data provided by the City of Santa Fe's 2009 Master Plan.

4.3.2 Details of the Validation Regions

Three regions within the Santa Fe water distribution system were selected for validation. The regions, corresponding to three of the eleven pressure zones within the water distribution system, were selected because they are geographically distributed within the utility service territory, have varying underlying land use characteristics and were not used to calibrate the method. The three pressure zones used for validation were pressure zones 6, 8 and 2. The values for input parameters to the method were provided by calibration Case 1J and calibration Case 1A, both of which were described in the calibration section.

4.3.3 Summary of Validation Results

This section summarizes the results of the validation cases. Two sets of validation results were explored. The use of calibration Case 1J for validation demonstrates the efficacy of using detailed empiric data, while the use of calibration Case 1A for validation demonstrates a more generalized approach (without the use of detailed empiric demand data).

Validation with a derived residential water use pattern

The use of calibration Case 1J is examined first. The results and error analysis are presented in Table 4.5. Graphical comparisons of the estimated and empiric hourly average demands for each of the three validation cases are shown in Figures 4.30, 4.31, and 4.32, along with the graph for calibration Case 1J (see Figure 4.33). Each of the graphs shows the contributions of the estimated CII and residential demand portions of the total estimated demand. (See Appendix G for details on each validation case.)

Case 1J-PZ8, which validates the region of pressure zone 8, performs the best of the three validation cases using the selected error metrics. The Percent Difference (PD) between the total estimated demand and total empiric demand is 2% and the Relative Error (RE) is 9%.

Case 1J-PZ6 performs reasonably well with a PD of 15% and an RE of 15%. The error values for this case appear to be larger because the estimated demand for CII facilities has a noticeable influence by restaurant businesses. The restaurant use pattern has peaks at mid-day and early-evening mealtimes. These peaks coincide with notable increases in the estimated CII demand. The water use patterns for restaurant and motel types of facilities (see Figure 4.22 and Figure 4.21) have much different peaking characteristics than the general CII facility use pattern.

Case 1J-PZ2 has the highest error values of the three cases, but still performs reasonably well, with a PD of 22% and an RE of 22%. By examining the graph of estimated and empiric daily water demand for Case 1J-PZ2 (see Figure 4.32), the total modeled demand is underestimated for the period roughly corresponding with a typical workday. It appears that Case 1J-PZ2 underperforms because the estimated residential demand is proportionally higher (i.e., 88%) than that of calibration Case 1J (i.e., 77%), which relies on a higher contribution by CII facilities to total demand. The smaller contribution of the estimated CII demand for Case 1J-PZ2 results in a generally lower estimated total demand during the workday period.

Table 4.5. The summary table of validation results includes a unique case ID, the pressure zone used for the case, error metrics, the total estimated base demand and the total empiric base demand. Calibration Case 1J was used to define the parameters for each validation case. The residential and CII percent contributions for Case 1J are 77% and 23%, respectively.

Validation Case	Validation Pressure Zone	Total % Diff.	Relative Error (%)	Total Estimated Base Demand (GPM)	Total Empiric Base Demand (GPM)	Est. Res./CII Demand %s
	Calibr. case 1J uses base case param. values, scale factor, and derived res. pattern 1					
1J-PZ6	6	15	15	846	737	74 / 26
1J-PZ8	8	2	9	677	664	89 / 11
1J-PZ2	2	22	22	251	321	88 / 12

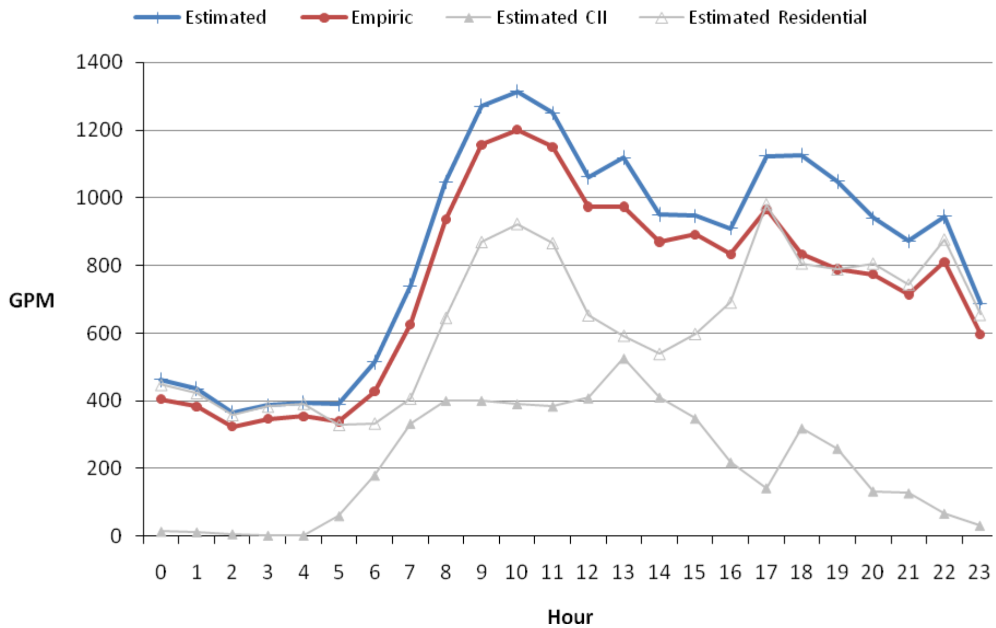


Figure 4.30. The estimated and empiric 24-hour water demand for validation Case 1J-PZ6.

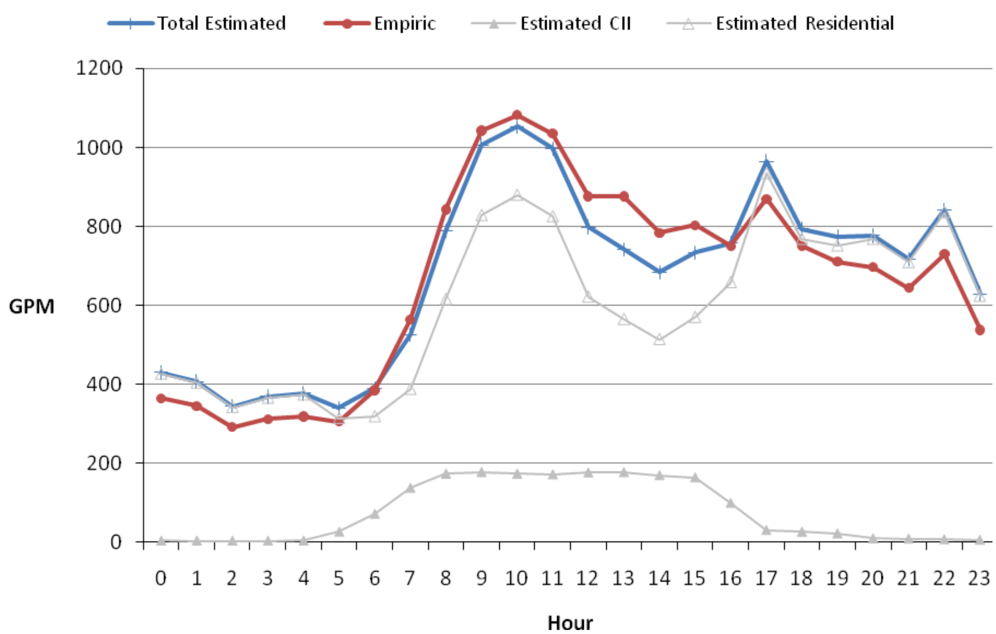


Figure 4.31. The estimated and empiric 24-hour water demand for validation Case 1J-PZ8.

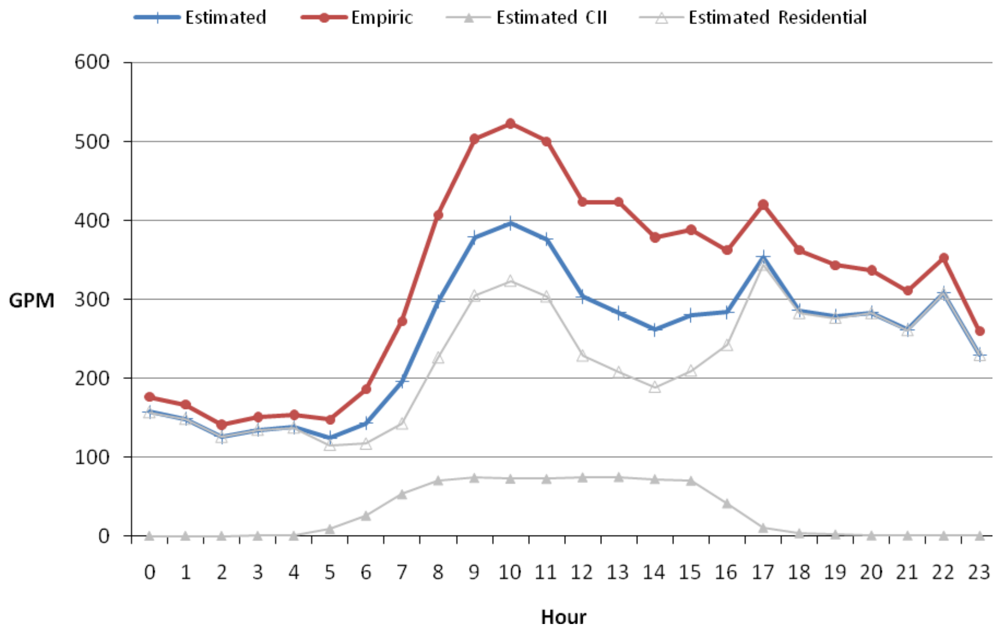


Figure 4.32. The estimated and empiric 24-hour water demand for validation Case 1J-PZ2.

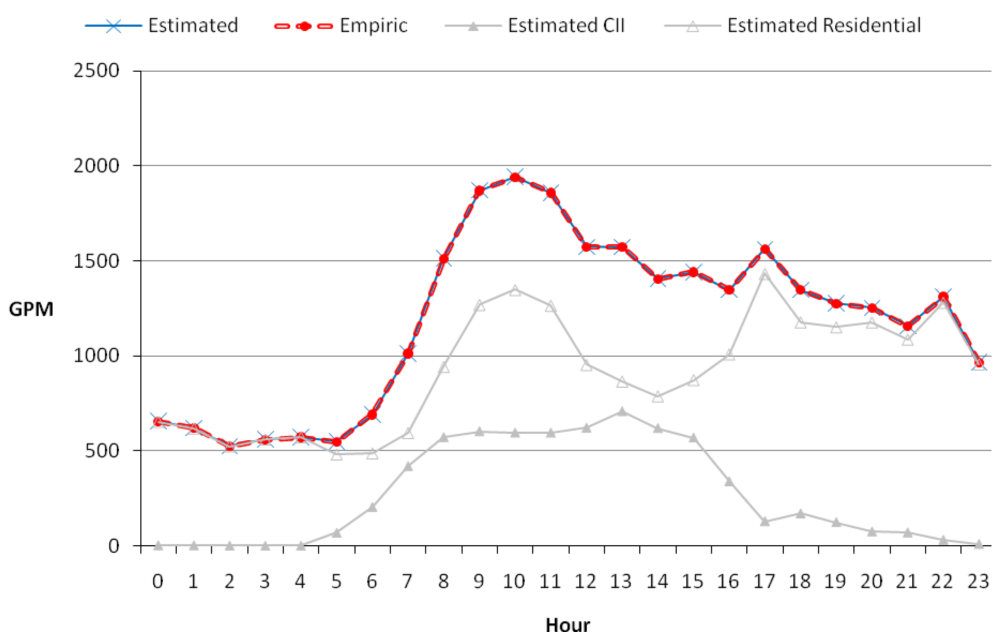


Figure 4.33. The estimated and empiric water demand for calibration Case 1J.

Validation without a derived residential water use pattern

To further explore validation cases, the parameter values of calibration Case 1A were applied to estimate demand for validation pressure zones 6, 8, and 2. The intent here is to use a calibration case that is representative of cases that do not employ a derived residential water use pattern. Calibration Case 1A is the baseline case that does employ a scale factor and performs similar to any of the other calibration cases that do not use a derived residential water use pattern. Using Case 1A for validation demonstrates how well a calibration case that does not use detailed empiric demand data (the cases that derive residential use patterns use detailed empiric demand data) compares with the validation cases that use the parameter values from Case 1J. Table 4.6 shows the results of using Case 1A to estimate demand for the three validation pressure zones.

Table 4.6. The summary table of validation results includes a unique case ID, the pressure zone used for the case, error metrics, the total estimated base demand and the total empiric base demand. Calibration Case 1A was used to define the parameters for each validation case. The residential and CII percent contributions for Case 1A are 77% and 23%, respectively. Case 1A does not use a derived residential use pattern.

Validation Case	Validation Pressure Zone	Total % Diff.	Relative Error (%)	Total Estimated Base Demand (GPM)	Total Empirical Base Demand (GPM)
	Calibr. case 1A uses base case parameter values and scale factor				
1A-PZ6	6	15	36	846	737
1A-PZ8	8	3	32	684	664
1A-PZ2	2	22	30	251	321

While the PD of the validation sets based on using calibration Cases 1J and 1A are essentially the same, the REs are different. The REs for the validation cases based on Case 1J are 15%, 9%, and 22%, while the validation results based on Case 1A are 36%, 32%, and 30%. Both sets of results are for pressure zones 6, 8, and 2, respectively. Understanding the sensitivity of hydraulic analyses to errors in demand is vital for determining how well a demand estimate may perform for hydraulic analysis applications. The next section examines the effects on hydraulic solutions of using a series of cases that explore the use of progressively *worse* demand representations.

Specifically, the result from the baseline demand case is compared to cases where the demand is increased by 5% to 50%. Accepted engineering guidelines are used as metrics to grade the results and help establish which validation set is most likely to provide better demand estimates for real-world hydraulic analyses. This is especially relevant for the application phase of this research.

The applicability of the model validation results for hydraulic analyses

Next, a series of hydraulic analyses are performed to better understand the sensitivity of the water level in a tank to the deviations in demand from a baseline case. The purpose of this analysis is to determine a threshold for the acceptable error in demand for a hydraulic model. More specifically, the threshold of error is the percentage change in demand for a calibrated model that still enables the model to reach a hydraulic solution within the acceptable tolerances of calibration. Comparing observed and simulated tank levels is one of the approaches used to calibrate hydraulic models. For small and large systems, the accepted fluctuation in tank level height is 3-6 feet (Haestad 2003). A series of hydraulic models was created by artificially increasing the demand uniformly for all demand junctions within a water distribution model. The percent increases from the baseline case were 5%, 10%, 15%, 20%, 22%, 25%, 30%, and 50%. The hydraulic model used for analysis represents a New Jersey water distribution system that is predominantly residential, and a tank (i.e., Tank #5867) within the model was selected to study. (It should be noted that the original intent of the research was to use the empiric hydraulic model of Santa Fe, solely. However, because the empiric model was not usable within the EPANET software package, the New Jersey system was employed for this section of the research. See Appendix H for an explanation of this data issue.) The goal is to help determine if either or both validation cases could be applied, in a defensible manner, to estimate demands.

Table 4.7 shows the results of performing the hydraulic analyses using seven different EPANET models. The seven models are identical except that each has a different uniform increase (indicated by the percent change) in demand from the baseline model. An indicator that a case is hydraulically acceptable is that the water level of the selected tank will deviate only from 3-6 feet from the baseline case. The table shows that

the cases with 5%, 10%, 15%, 20%, and 22% result in an acceptable deviation of tank level heights from the baseline case. The cases with a higher percent increase in demand from the baseline case result in unacceptable deviations in tank level heights (as indicated by the red cells in Table 4.7).

Table 4.7. The table shows the difference in tank level heights between the baseline hydraulic model and models for which the demands have been artificially increased by 5%, 10%, etc. From general guidance on calibrating models (Haestad 2003), the red cells represent problems because the tank level heights have deviated beyond the acceptable range of 3-6 feet. The hydraulic calculation represents an extended period simulation over 48 hours.

Difference in tank level height (ft) from baseline case to modified-demand case versus time (hour)								
		Case (% indicates increase in total demand from baseline case)						
Hour	5%	10%	15%	20%	22%	25%	30%	50%
0:00:00	0	0	0	0	0	0	0	0
1:00:00	0.07	0.13	0.19	0.26	0.29	0.33	0.4	0.71
2:00:00	0.13	0.26	0.42	0.5	0.57	0.66	0.78	1.34
3:00:00	0.16	0.33	0.54	0.67	0.73	0.8	1.02	1.73
4:00:00	0.17	0.35	0.57	0.71	0.78	0.85	1.09	1.84
5:00:00	0.19	0.38	0.61	0.77	0.84	0.92	1.17	1.97
6:00:00	0.2	0.4	0.64	0.81	0.89	0.97	1.23	2.08
7:00:00	0.22	0.44	0.7	0.88	0.96	1.06	1.33	2.24
8:00:00	0.23	0.47	0.74	0.94	1.04	1.14	1.44	2.42
9:00:00	0.25	0.51	0.81	1.03	1.13	1.25	1.56	2.63
10:00:00	0.27	0.55	0.86	1.1	1.21	1.34	1.68	2.82
11:00:00	0.29	0.58	0.92	1.18	1.29	1.44	1.79	3
12:00:00	0.31	0.63	0.98	1.26	1.38	1.53	1.9	3.19
13:00:00	0.33	0.66	1.03	1.33	1.46	1.62	2.01	3.37
14:00:00	0.34	0.69	1.07	1.38	1.52	1.69	2.1	3.52
15:00:00	0.36	0.72	1.12	1.45	1.59	1.77	2.19	3.68
16:00:00	0.55	1.72	2.35	2.69	2.84	3.03	3.46	5.01
17:00:00	1.54	2.66	3.37	3.87	4.07	4.38	4.85	6.45
18:00:00	1.39	2.45	3.22	3.9	4.14	4.45	4.94	6.59
19:00:00	1.41	2.49	3.28	3.97	4.21	4.53	5.04	6.76
20:00:00	1.42	2.52	3.33	4.04	4.28	4.62	5.14	6.93
21:00:00	1.44	2.56	3.38	4.11	4.37	4.71	5.25	7.11
22:00:00	1.47	2.6	3.44	4.18	4.44	4.8	5.36	7.28
23:00:00	1.47	2.62	3.48	4.24	4.5	4.87	5.44	7.43
24:00:00	1.5	2.66	3.53	4.3	4.58	4.95	5.54	7.59

Difference in tank level height (ft) from baseline case to modified-demand case versus time (hour)								
		Case (% indicates increase in total demand from baseline case)						
Hour	5%	10%	15%	20%	22%	25%	30%	50%
25:00:00	1.31	2.33	3.15	3.91	4.19	4.57	5.22	7.67
26:00:00	1.18	2.12	2.98	3.69	3.98	4.34	5.05	7.82
27:00:00	1.13	1.99	2.84	3.6	3.86	4.3	5.02	8.02
28:00:00	1.14	2.01	2.87	3.64	3.9	4.36	5.09	8.13
29:00:00	1.16	2.04	2.91	3.69	3.96	4.42	5.16	8.26
30:00:00	1.17	2.06	2.94	3.74	4.01	4.47	5.23	8.37
31:00:00	1.18	2.09	2.99	3.8	4.07	4.55	5.32	8.52
32:00:00	1.2	2.13	3.05	3.87	4.16	4.64	5.43	8.71
33:00:00	1.22	2.17	3.11	3.96	4.25	4.75	5.56	8.92
34:00:00	1.24	2.21	3.16	4.03	4.33	4.84	5.67	9.11
35:00:00	1.26	2.24	3.22	4.11	4.42	4.94	5.78	9.29
36:00:00	1.27	2.28	3.27	4.17	4.49	5.02	5.88	9.47
37:00:00	1.29	2.31	3.32	4.25	4.57	5.11	5.99	9.65
38:00:00	1.31	2.35	3.38	4.31	4.64	5.2	6.09	9.81
39:00:00	1.33	2.38	3.42	4.38	4.72	5.28	6.19	9.97
40:00:00	1.37	2.5	3.61	4.64	5.03	5.76	6.75	10.59
41:00:00	1.3	2.46	3.66	4.93	5.41	6.19	7.87	11.76
42:00:00	1.27	2.5	3.72	5.02	5.51	6.31	8.54	12.28
43:00:00	1.28	2.53	3.76	5.07	5.58	6.39	8.63	11.65
44:00:00	1.31	2.57	3.82	5.15	5.66	6.48	8.75	10.94
45:00:00	1.32	2.6	3.87	5.22	5.73	6.57	8.85	10.23
46:00:00	1.34	2.64	3.92	5.29	5.81	6.65	8.95	9.58
47:00:00	1.36	2.67	3.97	5.35	5.88	6.73	8.97	8.97
48:00:00	1.37	2.7	3.94	5.37	5.92	6.81	8.38	8.38

The conclusion from this assessment is that the use of parameter values from calibration Case 1J for estimating water demand would be decidedly more defensible. The chief reason is that the RE values for Case 1J (i.e., 15%, 9%, and 22%) are in-agreement with the above hydraulic analysis and evaluation with respect to tank levels. The acceptable cases for the hydraulic analysis range from a uniform 5% to 22% increase in demand. Because the RE is a composite assessment of error that incorporates the aggregate system demand for each of the 24 one-hour periods, it more closely represents the uniform scaling of all demand junctions, as is the assumption for the cases studied

above. Based on this assessment, Case 1J will be used for the application of the method to a real-world problem, which is described next.

4.4 Applying the Method to a Real-World Problem

4.4.1 Summary of Application Cases

The four cases where the method was applied to estimate water demand are described next. All cases are based on the City of Santa Fe water distribution system. The validated parameters of Case 1J were applied for this phase of the research. As shown in the previous phase, using the Case 1J parameters results in demand estimates that are within the acceptable tolerance for the calibration of analytical hydraulic models.

Estimated 2008 Baseline. The case uses the calibrated and validated method to estimate the current water demand for the entire municipal water system.

Estimated 2020 Baseline. Using forecasts for the population at 2020 and the business growth at 2018 (to represent business activity at 2020), the water demand at 2020 is estimated.

Estimated 2020 Washer Credit. The case estimates the water demand on the system at 2020 if all residential customers convert from using less efficient top-loading washers to water-conserving front-loading washers. The water demand estimate assumes that only the residential customers are affected and this is implemented by reducing the residential customer's daily use (GPD). The reduced residential GPD is calculated using the following assumptions: 1) 70% of daily residential water use is indoor (Mayer *et al.* 1999), 2) each household has one washer, 3) washers account for 21.7% of the indoor use (Mayer *et al.* 1999); 4) front-loading washers use 50% less water than top-loading washers (EPA 2008). Using these assumptions, the reduced residential GPD was calculated as:

Daily water savings per residential person = 0.7 (indoor water use) * 140 (residential GPD) * 0.217 (washer use portion of indoor use) * 0.5 (water savings of front-loading washer) = 10.6333 GPD

Revised residential daily use = 140 – 10.6333 = 129.367 GPD

The reduced residential daily use (GPD) results in a 7.6% decrease in the total residential water use for this case when compared to the 2020 Baseline case.

Estimated 2020 Toilet Credit. The case estimates the water demand at 2020 if all residential customers and CII facilities convert from less-efficient toilets to dual-flush toilets. The case assumes that both residential customers and CII facilities will reduce their water use through this credit. To implement the residential water use reduction, the following assumptions are used, 1) 70% of daily residential water use is indoor (Mayer *et al.* 1999), 2) toilets account for 26.7% of the indoor use (Mayer *et al.* 1999), and 3) dual-flush toilets use 60% less water than less-efficient toilets (EPA 2008). Using these assumptions, the reduced residential GPD was calculated as:

Daily water savings per residential person = 0.7 (indoor water use) * 140 (residential GPD) * 0.267 (toilet portion of indoor use) * 0.6 (water savings of dual-flush toilet) = 15.7 GPD

Revised residential daily use = 140 – 15.7 = 124.3 GPD

The reduced residential daily use (GPD) represents an 11.2% decrease in the total residential water use compared to the 2020 Baseline case.

The reduction in water use by CII facilities was implemented using the following assumptions: 1) each employee will use the toilet at work three times, and 2) the water saved per flush is 2.2 gallons (Mayer *et al.* 2000). The water savings per CII facility per employee is was defined to be:

Daily water savings per facility per employee = 3 (toilet use per day per employee) * 2.2 (gallons saved per flush) = 6.6 GPD

This water savings was incorporated into the calculation of daily water demand for each facility. The daily employee water use at a facility was reduced by 6.6 GPD for each employee.

Estimated 2020 Washer + Toilet Credit. The case combines the water savings of both converting to front-loading washers and converting to dual-flush toilets. The same approach as implemented by the above case for the toilet credit alone was used to reduce the estimated demand for the CII facilities. An assumption is that the washer credit was not applied to the CII facilities. The residential daily rate was reduced by the daily water conserved by both the toilet and washer credit cases. The daily residential use rate was defined as:

Revised residential daily use = 140 – 10.633 – 15.7 = 113.667 GPD

4.4.2 Application Results

This section presents the results of applying the calibrated and validated method to estimate water demand for the five cases related to water conservation policy (see Figure 4.34 and Table 4.8). The first case estimates water demand for the current 2008 system as the baseline scenario. (Incidentally, comparing this estimate with the empiric demand for the entire system resulted in, both, a percent difference and relative error of 20.5%. Additionally, the relative error between the empiric and estimated demand for the one-hour period of 10:00am to 11:00am when considering all 5,162 demand junction service areas was 20.06%. These errors are within the tolerance of the previous analysis based on tank levels, which indicates a more defensible demand estimate.) The 2020 baseline case represents a 18.4% increase in total demand over the 2008 baseline case, with a 9.1% increase in the CII demand component and a 23.4% increase in the residential demand component. Because the service areas within the system have varying

percentages of residential and CII customers, with varying forecasted demand growth rates, the service area regions are estimated to grow at different rates (see Figure 4.35). By estimating the potential water savings achieved by having customers upgrade to more-efficient washers and toilets, the remaining three cases examine scenarios where water is conserved.

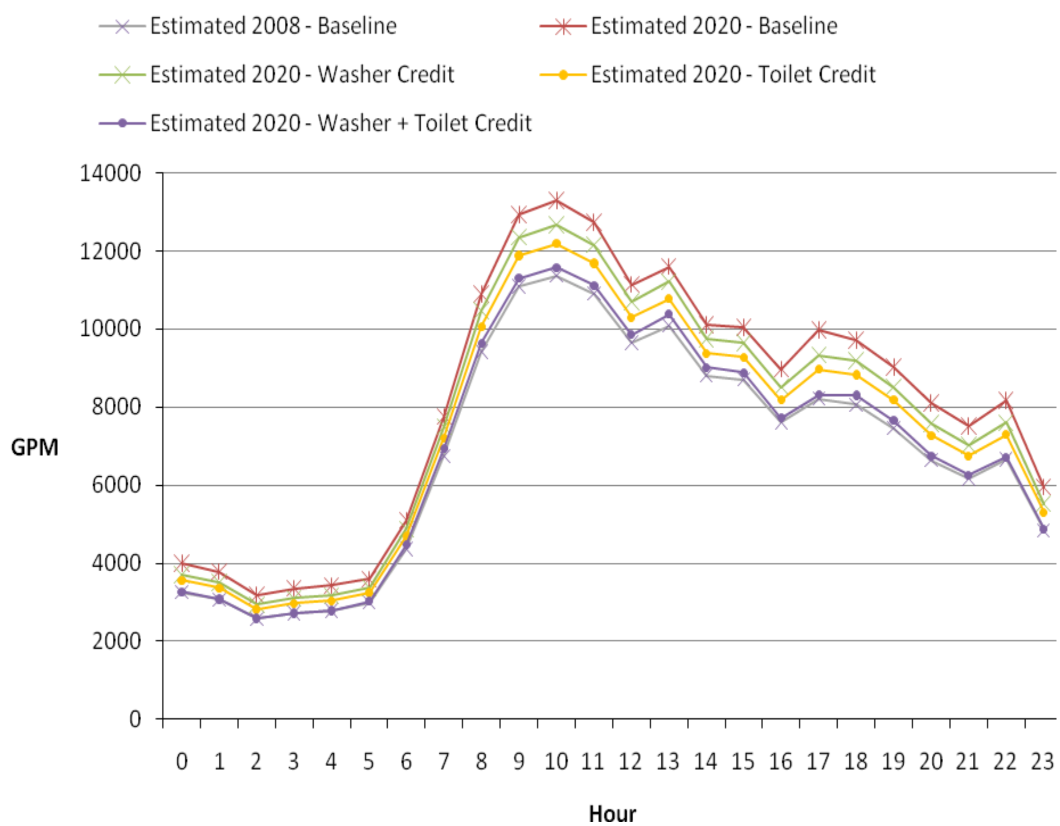


Figure 4.34. Total estimated hourly demands over 24-hour period for the five application cases.

Table 4.8. Summary table of the five application cases for estimating water demand.

Case	Estimated Demand (GPM)			
	Total	Residential	CII	Res. % / CII %
Estimated 2008 Baseline	6843	4427	2416	65 / 35
Estimated 2020 Baseline	8099	5464	2635	67 / 33
Estimated 2020 Washer Credit	7684	5049	2635	66 / 34
Estimated 2020 Toilet Credit	7385	4851	2534	66 / 34
Estimated 2020 Washer + Toilet Credit	6970	4436	2534	64 / 36

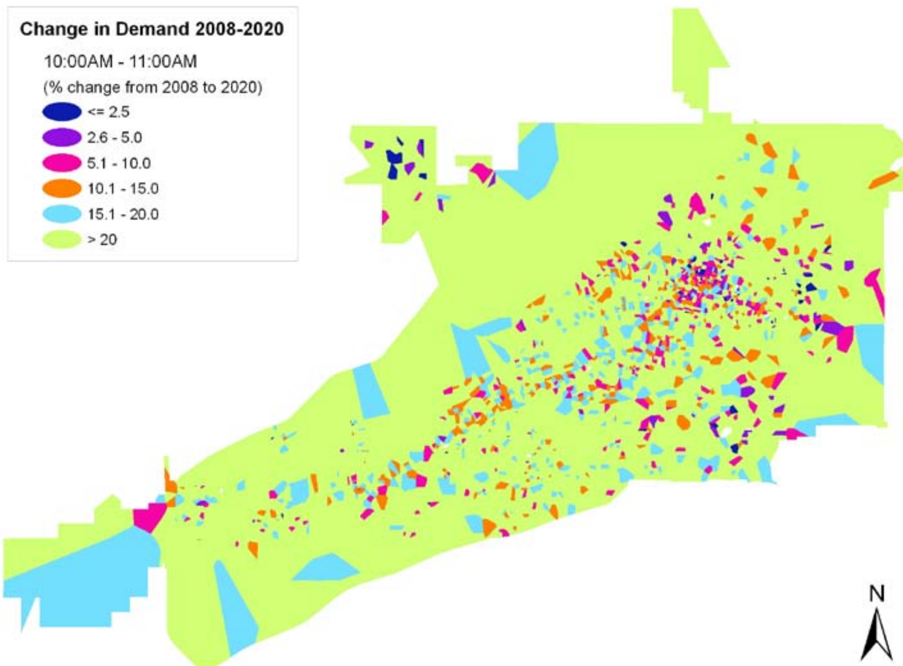


Figure 4.35. The figure shows percent change in estimated water demand from the 2008 baseline case to the 2020 baseline case by service area as an average for the period 10:00am – 11:00am.

The 2020 washer credit case reduces the residential demand from 5,464 GPM for the 2020 baseline case to 5,049 GPM, which is a 7.6% decrease. The case results in a reduction in total demand of 5.1%.While the 2020 washer credit case only affects residential customers, the 2020 toilet credit case reduces water use for both residential and CII customers. The 2020 toilet case reduces the total water demand from 8,099 GPM for the 2020 baseline case to 7,385 GPM. This is a total reduction of 8.8%, with decreases of 11.2% for the residential component and 3.8% for the CII component.

By combining the potential water savings of both the washer and toilet credits, the 2020 washer and toilet credit case results in a reduction in total water demand from the 2020 baseline case of 13.9%. The decrease in demand by component is 18.8% for residential and 3.8% for CII.

4.4.3 Summary of Application Results

The application cases examine the potential change in water demand when credits are used to encourage customers to upgrade to water-efficient washers and toilets. The combined estimated water savings when customers upgrade to these water-efficient appliances is shown to nearly offset the growth in water demand due to the forecasted population and business changes for the period 2008 – 2020. The percent increase in total demand from the baseline 2008 case to the 2020 case that projects the use of both water-efficient toilets and washers is 1.9%. This is compared to the percent increase in total demand from the baseline 2008 case to the baseline 2020 case of 18.4%. Though there are simplifying assumptions used for the approach, the results provide some guidance for utility planning personnel. Additionally, more detailed data, such as empiric data on water use by CII facility type, could be used to tune the approach and presumably produce more focused and relevant results.

4.5 Issues Related to Empiric and Model Data

A number of issues related to the empiric and model data were revealed while conducting the research. A predominant issue was that the engineering consultants Brown and Caldwell questioned the accuracy of the SCADA clock used when collecting measurements from the Santa Fe water system. Further investigation for the research found that the discrepancies were due to a one-hour difference between the SCADA clock and local time (the SCADA clock is not changed for Daylight Saving time) and, more importantly, that the measurements were recorded on a Saturday. The system-wide use pattern for a Saturday, with a mid-morning peak, is markedly different than for a weekday, which has an early-morning peak. Additional issues of the empiric and model data are described in Appendix H.

Chapter 5: **Conclusions**

5.1 Objective

Understanding and characterizing the demand for water on municipal water distribution systems is critical for managing this vital resource. The objective of the research was to develop a method to estimate water demand at a neighborhood-scale spatial resolution and one-hour temporal resolution for any municipal water distribution system in the U.S. using publically available data. These desired spatial and temporal resolutions are commonly used for defensible engineering analyses of pipeline networks. After calibrating and validating the method, the approach would be applied to a real-world problem to explore the potential effects of water-conservation policy. The research complements the existing literature on estimating demand by providing a method to estimate demand that is not based solely on historical or measured data for a specific water system, which has been the predominant approach.

5.2 Results

Using the water distribution pipeline network for the City of Santa Fe, New Mexico as the study system, a series of 15 calibration cases was explored using the method, which was implemented as an ArcGIS ArcMap extension. The initial case used the default model parameter values and resulted in a relative error of 82% when compared with the empiric demand for the calibration region. For all 15 cases, the relative error ranged from 0.1% to 82%. Applying a uniform scale factor significantly improved the demand estimates for all calibration cases, resulting in a maximum relative error of 33%. Additional refinements of the model parameters were made using more detailed empiric data to derive custom residential use patterns. These calibration cases resulted in further improvements, with relative errors of 0.1%, 0.1%, and 13%, when a scale factor was employed. Of the 15 calibration cases, two were selected to perform validation studies. Of these, one case was representative of those that use more general input data, while the other was representative of cases that use more detailed empiric demand data.

In order to select a best-fit validation case, the acceptable errors in water demand were quantified by applying a standard model-calibration metric to study a series of hydraulic models with varying errors in demand using the EPANET hydraulic analysis software. For a sample calibrated hydraulic model, uniform errors in the demand, up to and including 22%, resulted in hydraulic solutions that were within acceptable tolerances for calibrated models. This analysis, combined with the relative errors of the validation cases, led to the selection of Case 1J as the best-fit validation case because it produced a maximum relative error of 22% and was, therefore, within the allowable variance of demand determined by the hydraulic analysis.

The last phase of the research applied the selected validated case to estimate current and future water demand for the Santa Fe system under different water-conservation strategies. The baseline 2008 water demand for the system was estimated, which resulted in a relative error of 20.5% when compared with the empiric demand model. Note that this relative error is within the tolerance determined by the previous hydraulic analysis, indicating that the model results could be acceptable and defensible for engineering studies. Using forecasted economic activity and population change, four additional cases were created to represent the water demand at year 2020 under different assumptions. The baseline 2020 water demand estimate resulted in an 18.4% increase in demand over the baseline 2008 case. The remaining three cases forecasted the savings in water when conservation policies were enacted. Assuming published typical water savings for efficient toilets and washers, the 2020 washer credit case resulted in a 5.1% decrease in demand from the 2020 baseline case. The 2020 toilet credit case resulted in a decrease in demand of 8.8% from the 2020 baseline case. By combining the savings of, both, the washer and toilet credits, the resulting decrease was 13.9% from the 2020 baseline case. With a difference in total demand of only 1.9%, the savings in water that results from enacting both credits was shown to nearly offset the increase in forecasted demand from 2008 to 2020.

5.3 Summary

The method performed reasonably well for estimating the water demand for the Santa Fe water distribution system. Simply using the default baseline parameter values

resulted in a relative error of 82%. Considering that the difference in total water demand between an average day and peak day for a municipal system typically ranges within a factor of 1.2 to 3.0 (Haestad 2003), the estimated demand appears to provide a reasonable initial estimate for the Santa Fe system. The best-fit validation case produced a demand estimate with a relative error of 20.2% for the entire Santa Fe system, which was shown to be within the smaller tolerance of error required for hydraulic analyses for engineering studies. This suggests that the demand estimates produced, based on the best-fit validation case, are more likely to be defensible for hydraulic studies. In the application phase, employing the best-fit validation case demonstrated that enacting water conservation policy to encourage customers to upgrade to water-efficient fixtures could nearly offset the projected increase in water demand from 2008 to 2020.

Because the method uses national datasets, water demand can be estimated for any municipality in the U.S. For the Santa Fe water distribution system, the method was shown to provide a reasonable initial estimate and a more defensible estimate using system-specific empiric data. Understanding how broadly the method can be applied will require more research. It is presumed that using the method for municipalities that are comparable in size and proportion of residential and CII customers as Santa Fe may perform similarly. For municipalities that are dissimilar to Santa Fe, the method may provide a reasonable initial estimate that would be useful for characterizing urban water demand.

There are several broader lessons learned by the research. First, the approach used by the research for developing, calibrating, and validating the model using empiric data is founded on sound and accepted practices. However, issues regarding the empiric data introduced more complexities to the problem, and, in some cases, changed the course of the research. For example, not having a solvable hydraulic model of the Santa Fe system warranted the development of a different approach for calibrating and validating the research method. Rather than using the detailed hydraulic characteristics (e.g., tank levels, pressures, and flows) of the pipeline network as metrics for judging the efficacy of the estimated demand, the empiric demand at the desired spatial and temporal resolutions was used. Still, in discussing these topics with other researchers, it became apparent that having real-world data of reliable quality to calibrate against is not so common.

Additionally, general data issues such as integrity, lineage, spatial and textual inaccuracies, time stamps, even with published data, introduce error into the method. These types of complications required that the researcher be open to new ideas and approaches during the research, and to question and evaluate the data for obvious or not-so-obvious issues that could affect the research.

5.4 Issues and Assumptions

There are a number of assumptions and approximations used within the thesis. For example, the date stamps of the data are not the same. The CII facilities were represented using 2007 Dun and Bradstreet data while the residential population was represented using 2005 Census data and 2005 LANL population data. Both are used to estimate the demand on the Santa Fe water pipeline network for 2008. The CII water use rates were based on research published in 2000, while the residential use rates were derived from data published in 2004. For the application phase, the forecasted economic activity was for 2018 and not the target future year of 2020.

Some data were either missing altogether or missing information that rendered some records unusable. For example, the CII use rates study represented most CII facility categories but some were missing. The facilities that had no data on use rates were ignored.

Additionally, there are typically errors in the geocoded locations of some of the CII facilities represented in the Dun and Bradstreet database. For example, geocoding based on street address has inherent errors because the estimated location is typically an interpolation between addresses. Other errors are introduced because some facility addresses actually represent mailing addresses rather than actual facility locations. A specific example of a misplaced facility was for a Santa Fe high school, which was one of the largest users of water within the calibration region. The location within the Dun and Bradstreet database was not close to its known location, so the water demand was not correctly placed on the pipeline network. The locations of water customers on the Santa Fe system were geocoded for the 2009 Master Plan, which could introduce similar errors. The original intent of the research was to estimate demand for the Santa Fe system, then test the result within the calibrated hydraulic model provided by the 2009 Master Plan

against actual field measurements. However, the hydraulic analysis software used by the consulting firm was unable to export the hydraulic model into a format usable by the EPANET software package. As a result, the estimated demand was compared to the empiric demand model developed for the 2009 Master Plan.

For the application phase, the projections of water demand at 2020 made no assumptions about new CII facilities. That is, CII facilities were neither added to nor removed from the model for the 2020 representation. Instead, employee counts for the existing businesses were modified by using the forecasted change in employment for 2008 – 2018. The application cases also assumed that all residential and CII customers upgraded from low-efficiency fixtures to high-efficiency fixtures.

5.5 Future Work

Future work for the research could include testing the method on different municipal water systems, conducting more detailed analytical assessments with the empiric data, comparing estimated results with field measurements, and obtaining or collecting localized use rates data to employ with the method. Estimates could be made and compared for numerous municipal systems to examine such possible factors as regional differences, varying ratios of residential and CII customers, cost of water, or influence of demand-side management practices. Additional spatial and temporal analysis could be performed to study how well the method is performing on, for example, all or some sample of service areas over various time periods. If more refined local data on CII and residential use rates were available or could be collected for a municipal system, further analysis could evaluate the usefulness of these data within the research method. Similarly, data provided by other studies could be tested.

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Appendix A: NAICS code to SIC code correspondence

Table A.1 shows the correspondence of NAICS codes to SIC codes. The 2007 Dun and Bradstreet CII facilities database includes the NAICS code for each facility. The research method uses a 2-digit SIC code for several steps. Therefore, a lookup table is needed to translate the NAICS code to the SIC code.

The NAICS code values of 990000 and 999990 indicate that the facility type is unknown. Within the table, SIC codes with value 0 indicate the original facility type is unknown, unclassified, or there is no available mapping from the NAICS code to an SIC code.

The table is limited to only the NAICS codes that are assigned to facilities within the City of Santa Fe water distribution system service territory; the table represents a subset of all of the NAICS codes.

The table in Appendix B (Table B.1) shows descriptions of the 2-digit SIC code categories.

Table A.1. The table shows the correspondence of NAICS codes to SIC codes for the Dun and Bradstreet facilities located within the service territory for the City of Santa Fe water distribution system. The source of the NAICS-SIC crosswalk table is the U.S. Census Bureau (www.census.gov).

NAICS Code	SIC Code	2-Digit SIC Code
111199	0119	01
111421	0181	01
111422	0181	01
111998	0139	01
112111	0212	02
112990	0219	02
115112	0711	07
115113	0722	07
115210	0751	07
115310	0851	08
211111	1311	13
211112	1321	13
212311	1411	14
212321	1442	14
212399	1499	14
213111	1381	13
213112	1382	13
221119	4911	49
221210	4923	49
221310	4941	49
236115	1521	15
236116	1522	15
236117	1531	15

NAICS Code	SIC Code	2-Digit SIC Code
236118	1521	15
236210	1531	15
236220	1522	15
237110	1623	16
237210	6552	65
237310	1611	16
237990	1622	16
238110	1771	17
238120	1791	17
238130	1751	17
238140	1741	17
238150	1793	17
238160	1761	17
238190	1791	17
238210	1711	17
238220	1711	17
238310	1742	17
238320	1721	17
238330	1752	17
238340	1743	17
238350	1751	17
238390	1761	17
238910	1081	10
238990	1771	17
311211	2034	20
311320	2066	20
311421	2033	20
311422	2032	20
311520	2024	20
311612	2013	20
311811	5461	54
311812	2051	20
311830	2099	20
311920	2043	20
311991	2099	20
311999	2015	20
312111	2086	20
312113	2097	20
312120	2082	20
312130	2084	20
313320	2295	22
314110	2273	22
314911	2392	23
314912	2394	23
314991	2298	22
314999	2299	22
315191	2253	22

NAICS Code	SIC Code	2-Digit SIC Code
315228	2329	23
315232	2331	23
315233	2335	23
315239	2339	23
315292	2371	23
315299	2329	23
315991	2353	23
315999	2339	23
316999	3131	31
321114	2491	24
321214	2439	24
321911	2431	24
321918	2421	24
321992	2452	24
321999	2421	24
322121	2611	26
322212	2657	26
323110	2752	27
323113	2396	23
323114	2752	27
323117	2732	27
323118	2782	27
323119	2759	27
323121	2789	27
323122	2791	27
324110	2911	29
325120	2813	28
325199	2869	28
325222	2824	28
325314	2875	28
325411	2833	28
325412	2834	28
325510	2851	28
325611	2841	28
325620	2844	28
325998	2819	28
326199	3089	30
326299	3069	30
327112	3262	32
327113	3264	32
327121	3251	32
327122	3253	32
327123	3259	32
327212	3229	32
327215	3231	32
327320	3273	32
327420	3275	32

NAICS Code	SIC Code	2-Digit SIC Code
327991	3281	32
331513	3325	33
331525	3366	33
332212	3421	34
332312	3441	34
332313	3443	34
332323	3446	34
332710	3599	35
332812	3479	34
332993	3483	34
332995	3489	34
332999	3291	32
333294	3556	35
333298	3559	35
333412	3564	35
333512	3541	35
333911	3561	35
334111	3571	35
334112	3572	35
334119	3577	35
334220	3663	36
334290	3669	36
334310	3651	36
334419	3679	36
334511	3812	38
334513	3823	38
334515	3825	38
334516	3826	38
334612	3652	36
334613	3577	35
335110	3641	36
335121	3645	36
335211	3634	36
335228	3639	36
335312	3621	36
335931	3643	36
335999	3629	36
336212	3715	37
336399	3429	34
336413	3728	37
336611	3731	37
336991	3751	37
336992	3711	37
337110	2434	24
337121	2512	25
337122	2511	25
337124	2514	25

NAICS Code	SIC Code	2-Digit SIC Code
337125	2499	24
337127	2531	25
337211	2521	25
337910	2515	25
337920	2591	25
339112	3829	38
339116	8072	80
339911	3479	34
339912	3479	34
339913	3915	39
339914	3172	31
339920	3069	30
339931	3942	39
339944	3955	39
339950	3993	39
339993	3131	31
339999	2499	24
423120	5013	50
423130	5014	50
423140	5015	50
423210	5021	50
423220	5023	50
423310	5031	50
423320	5032	50
423390	5039	50
423420	5044	50
423430	5045	50
423440	5046	50
423450	5047	50
423460	5048	50
423490	5049	50
423510	5051	50
423610	5063	50
423620	5064	50
423690	5065	50
423710	5072	50
423720	5074	50
423820	5083	50
423830	5084	50
423840	5085	50
423850	5087	50
423910	5091	50
423920	5092	50
423930	5093	50
423940	5094	50
423990	5099	50
424120	5112	51

NAICS Code	SIC Code	2-Digit SIC Code
424130	5113	51
424210	5122	51
424310	5131	51
424320	5136	51
424330	5137	51
424340	5139	51
424410	5141	51
424420	5142	51
424430	5143	51
424450	5145	51
424460	5146	51
424470	5147	51
424480	5148	51
424490	5149	51
424520	5154	51
424590	5159	51
424690	5169	51
424710	5171	51
424720	5172	51
424810	5181	51
424820	5182	51
424910	5191	51
424920	5192	51
424930	5193	51
424950	5198	51
424990	5199	51
441110	5511	55
441120	5521	55
441210	5561	55
441221	5571	55
441222	5551	55
441310	5013	50
441320	5014	50
442110	5021	50
442210	5023	50
442291	5714	57
442299	5719	57
443111	5064	50
443112	5064	50
443120	5045	50
443130	5946	59
444110	5031	50
444120	5231	52
444130	5072	50
444190	5032	50
444220	5153	51
445110	5141	51

NAICS Code	SIC Code	2-Digit SIC Code
445120	5411	54
445210	5144	51
445220	5146	51
445230	5148	51
445291	5461	54
445292	5145	51
445299	5143	51
445310	5181	51
446110	5122	51
446120	5087	50
446130	5995	59
446191	5122	51
446199	5047	50
447190	5541	55
448110	5136	51
448120	5137	51
448130	5137	51
448140	5651	56
448150	5611	56
448190	5136	51
448210	5139	51
448310	5094	50
448320	5948	59
451110	5091	50
451120	5092	50
451130	5131	51
451140	5736	57
451211	5192	51
451212	5994	59
451220	5099	50
452111	5311	53
452112	5311	53
452910	5399	53
452990	5331	53
453110	5992	59
453210	5044	50
453220	5199	51
453310	5932	59
453910	5149	51
453920	5999	59
453930	5271	52
453991	5194	51
453998	5085	50
454113	5961	59
454210	5962	59
454312	5171	51
454319	5989	59

NAICS Code	SIC Code	2-Digit SIC Code
454390	5142	51
481111	4512	45
481219	4522	45
482111	4011	40
483112	4481	44
484110	4212	42
484121	4213	42
484210	4212	42
484220	4212	42
484230	4213	42
485111	4111	41
485112	4111	41
485113	4111	41
485210	4131	41
485310	4121	41
485320	4119	41
485510	4141	41
485999	4111	41
488111	4581	45
488119	4581	45
488190	4581	45
488210	4013	40
488410	7549	75
488510	4731	47
488991	4783	47
488999	4729	47
491110	4311	43
492110	4215	42
493110	4225	42
493120	4222	42
493130	4221	42
493190	4226	42
511110	2711	27
511120	2721	27
511130	2731	27
511140	2741	27
511191	2771	27
511199	2741	27
511210	7372	73
512110	7812	78
512120	7822	78
512131	7832	78
512191	7819	78
512199	7819	78
512230	2731	27
512240	7389	73
512290	7389	73

NAICS Code	SIC Code	2-Digit SIC Code
515112	4832	48
515120	4833	48
515210	4841	48
517110	4813	48
517210	0	0
517911	0	0
517919	0	0
518210	7374	73
519110	7383	73
519120	7829	78
522110	6021	60
522120	6035	60
522130	6061	60
522220	6141	61
522291	6141	61
522292	6111	61
522293	6081	60
522298	5932	59
522310	6163	61
522320	6099	60
522390	6099	60
523110	6211	62
523120	6211	62
523130	6099	60
523910	6153	61
523920	6282	62
523930	6282	62
523991	6091	60
523999	6211	62
524113	6311	63
524126	6331	63
524127	6361	63
524210	6411	64
524291	6411	64
524298	6411	64
525120	6371	63
525910	6722	67
525920	6733	67
525990	6371	63
531110	6513	65
531120	6512	65
531130	4225	42
531190	6515	65
531210	6531	65
531311	6531	65
531320	6531	65
531390	6531	65

NAICS Code	SIC Code	2-Digit SIC Code
532111	7514	75
532120	7513	75
532210	7359	73
532220	7299	72
532230	7841	78
532292	7999	79
532299	7359	73
532310	7359	73
532412	7353	73
532490	7352	73
533110	6792	67
541110	8111	81
541191	6541	65
541199	7389	73
541211	8721	87
541213	7291	72
541214	7819	78
541219	8721	87
541310	8712	87
541320	781	7
541330	8711	87
541340	7389	73
541350	7389	73
541370	7389	73
541380	8734	87
541410	7389	73
541420	7389	73
541430	7336	73
541490	7389	73
541511	7371	73
541512	7373	73
541513	7376	73
541519	7379	73
541611	8742	87
541612	7361	73
541613	8742	87
541614	4731	47
541618	8748	87
541620	8999	89
541690	781	7
541711	0	0
541712	0	0
541720	8732	87
541810	7311	73
541820	8743	87
541840	7313	73
541860	7331	73

NAICS Code	SIC Code	2-Digit SIC Code
541890	5199	51
541910	8732	87
541921	7221	72
541922	7335	73
541930	7389	73
541940	741	7
541990	4499	44
551111	6712	67
551112	6719	67
561110	8741	87
561210	8744	87
561311	0	0
561312	0	0
561320	7363	73
561410	7338	73
561421	7389	73
561422	7389	73
561431	7389	73
561439	7334	73
561440	7322	73
561450	7323	73
561491	7389	73
561492	7338	73
561499	7389	73
561510	4724	47
561520	4725	47
561591	7389	73
561599	4729	47
561611	7381	73
561612	7381	73
561613	7381	73
561621	7382	73
561622	7699	76
561710	4959	49
561720	4581	45
561730	782	7
561740	7217	72
561790	1799	17
561910	7389	73
561920	7389	73
561990	7299	72
562211	4953	49
562219	4953	49
562920	4953	49
562991	7359	73
562998	4959	49
611110	8211	82

NAICS Code	SIC Code	2-Digit SIC Code
611310	8221	82
611420	8243	82
611511	7231	72
611512	8249	82
611519	8243	82
611610	7911	79
611620	7999	79
611630	8299	82
611691	8299	82
611692	8299	82
611699	7999	79
611710	8299	82
621111	8011	80
621112	8011	80
621210	8021	80
621310	8041	80
621320	8042	80
621330	8049	80
621340	8049	80
621391	8043	80
621399	8049	80
621410	8093	80
621420	8093	80
621492	8092	80
621498	8093	80
621511	8071	80
621512	8071	80
621610	8082	80
621910	4119	41
621991	8099	80
621999	8099	80
622110	8062	80
622210	8063	80
622310	8069	80
623110	8051	80
623210	8051	80
623220	8361	83
623311	8051	80
623312	8361	83
623990	8361	83
624110	8322	83
624120	8322	83
624190	8322	83
624221	8322	83
624230	8322	83
624310	8331	83
624410	8351	83

NAICS Code	SIC Code	2-Digit SIC Code
711110	5812	58
711130	7929	79
711190	7929	79
711211	7941	79
711219	7948	79
711310	6512	65
711410	7389	73
711510	7383	73
712110	8412	84
712120	8412	84
712190	7999	79
713120	7993	79
713910	7992	79
713940	7991	79
713950	7933	79
713990	7911	79
721110	7011	70
721191	7011	70
721199	7011	70
721211	7033	70
721214	7032	70
721310	7021	70
722110	5812	58
722211	5812	58
722212	5812	58
722213	5461	54
722310	4789	47
722320	5812	58
722330	5963	59
722410	5813	58
811111	7538	75
811112	7533	75
811113	7537	75
811118	7539	75
811121	7532	75
811122	7536	75
811191	7549	75
811192	7542	75
811198	7534	75
811211	7622	76
811212	7378	73
811213	7622	76
811219	7629	76
811310	7623	76
811411	7699	76
811412	7623	76
811420	4581	45

NAICS Code	SIC Code	2-Digit SIC Code
811430	7251	72
811490	3732	37
812111	7241	72
812112	7231	72
812113	7231	72
812191	7299	72
812199	7299	72
812210	7261	72
812220	6531	65
812310	7215	72
812320	7211	72
812331	7213	72
812332	7218	72
812910	752	7
812921	7384	73
812930	7299	72
812990	4899	48
813110	8661	86
813211	6732	67
813212	8399	83
813219	8399	83
813319	8399	83
813410	8641	86
813910	8611	86
813920	8621	86
813930	8631	86
813940	8651	86
813990	6531	65
921110	9111	91
921120	9121	91
921130	9311	93
921140	9131	91
921190	9199	91
922110	9211	92
922120	9221	92
922130	9222	92
922140	9223	92
922150	8322	83
922160	9224	92
922190	9229	92
923110	9411	94
923120	9431	94
923130	9441	94
923140	9451	94
924110	9511	95
924120	9512	95
925110	9531	95

NAICS Code	SIC Code	2-Digit SIC Code
926110	9611	96
926120	9621	96
926130	9631	96
926140	9641	96
926150	9651	96
928110	9711	97
928120	9721	97
990000	0	0
999990	0	0

Appendix B: Assumptions on whether businesses are open or closed on Saturday

This appendix describes the assumptions about which facility types are open or closed on a Saturday, based on two-digit Standard Industrial Classification (SIC) Codes (see Table B.1). This information is used to include a business (if it is open on Saturday) or exclude a business (if it is closed on Saturday) when estimating demand. General rules were used for these assumptions, such as those shown below.

- Retail – open on Saturday
- Manufacturing – closed
- Food services – open
- General services – open
- Government – closed
- Schools – closed

Table B.1. The table shows the two-digit SIC code and the corresponding description of each SIC category, and the assumption about whether the businesses within the SIC category are generally open or closed on Saturday. The single-digit SIC categories represent the broad categories of classification. The two-digit SIC categories show subsectors within each broad group.

SIC Code	SIC Category Description	Open on Saturday
0	Agriculture, forestry, and fisheries	-
01	Agricultural production- crops	Yes
02	Agricultural production- livestock	Yes
07	Agricultural services	Yes
08	Forestry	No
09	Fishing, hunting, and trapping	No
1	Mineral and Construction Industries	-
10	Metal mining	No
12	Coal mining	No
13	Oil and gas extraction	No
14	Nonmetallic minerals, except fuels	No
15	General building contractors	No
16	Heavy construction contractors	No
17	Special trade contractors	No
2	Manufacturing	-
20	Food and kindred products	No
21	Tobacco manufactures	No
22	Textile mill products	No
23	Apparel and other textile products	No
24	Lumber and wood products	No
25	Furniture and fixtures	No
26	Paper and allied products	No
27	Printing and publishing	No
28	Chemicals and allied products	No
29	Petroleum and coal products	No

SIC Code	SIC Category Description	Open on Saturday
30	Rubber and miscellaneous plastics products	No
31	Leather and leather products	No
32	Stone, clay, glass, and concrete products	No
33	Primary metal industries	No
34	Fabricated metal products	No
35	Industrial machinery and equipment	No
36	Electrical and electronic equipment	No
37	Transportation equipment	No
38	Instruments and related products	No
39	Miscellaneous manufacturing industries	No
4	Transportation, Communication, and Utilities	-
41	Local and interurban passenger transit	Yes
42	Motor freight transportation and warehousing	Yes
43	U.S. Postal Service	Yes
44	Water transportation	Yes
45	Transportation by air	Yes
46	Pipelines, except natural gas	No
47	Transportation services	Yes
48	Communications	No
49	Electric, gas, and sanitary services	No
5	Wholesale and Retail Trade	-
50	Wholesale trade--durable goods	Yes
51	Wholesale trade--nondurable goods	Yes
52	Building materials, hardware, garden supply, & mobile	Yes
53	General merchandise stores	Yes
54	Food stores	Yes
55	Automotive dealers and gasoline service stations	Yes
56	Apparel and accessory stores	Yes
57	Furniture, home furnishings and equipment stores	Yes
58	Eating and drinking places	Yes
59	Miscellaneous retail	Yes
6	Finance, Insurance, and Real Estate	-
60	Depository institutions	Yes
61	Nondepository credit institutions	No
62	Security, commodity brokers, and services	No
63	Insurance carriers	No
64	Insurance agents, brokers, and service	Yes
65	Real estate	Yes
67	Holding and other investment offices	No
7	Service Industries	-
70	Hotels, rooming houses, camps, and other lodging place	Yes
72	Personal services	Yes
73	Business services	No
75	Automotive repair, services, and parking	Yes
76	Miscellaneous repair services	Yes
78	Motion pictures	No

SIC Code	SIC Category Description	Open on Saturday
79	Amusement and recreational services	Yes
8	Service Industries	-
80	Health services	Yes
81	Legal services	No
82	Educational services	No
83	Social services	No
84	Museums, art galleries, botanical & zoological garden	Yes
86	Membership organizations	No
87	Engineering and management services	No
88	Private households	No
89	Miscellaneous services	No
9	Public Administration	-
91	Executive, legislative, and general government	No
92	Justice, public order, and safety	No
93	Finance, taxation, and monetary policy	No
94	Administration of human resources	No
95	Environmental quality and housing	No
96	Administration of economic programs	No
97	National security and international affairs	No
99	Unknown	No

Appendix C: CII facility daily use rates per employee

This appendix shows the Commercial, Industrial and Institutional daily use rates by two-digit Standard Industrial Classification (SIC) Code (see Table C.1). The data were obtained through prior research (Dziegielewski *et al.* 2000).

Table C.1. The table shows SIC code and the corresponding description of each SIC category, and the assumption about whether the business within the SIC category are generally open or closed on Saturday. The single-digit SIC categories represent the broad categories of classification. The 2-digit SIC categories

SIC Code	SIC Category Description	Daily use rate (GPD)
0	Agriculture, forestry, and fisheries	
01	Agricultural production- crops	-
02	Agricultural production- livestock	-
07	Agricultural services	-
08	Forestry	-
09	Fishing, hunting, and trapping	-
1	Mineral and Construction Industries	
10	Metal mining	-
12	Coal mining	-
13	Oil and gas extraction	-
14	Nonmetallic minerals, except fuels	-
15	General building contractors	118
16	Heavy construction contractors	20
17	Special trade contractors	25
2	Manufacturing	
20	Food and kindred products	469
21	Tobacco manufactures	-
22	Textile mill products	784
23	Apparel and other textile products	26
24	Lumber and wood products	49
25	Furniture and fixtures	36
26	Paper and allied products	2614
27	Printing and publishing	37
28	Chemicals and allied products	267
29	Petroleum and coal products	1045
30	Rubber and miscellaneous plastics products	119
31	Leather and leather products	148
32	Stone, clay, glass, and concrete products	202
33	Primary metal industries	178
34	Fabricated metal products	194
35	Industrial machinery and equipment	68
36	Electrical and electronic equipment	95
37	Transportation equipment	84
38	Instruments and related products	66

SIC Code	SIC Category Description	Daily use rate (GPD)
39	Miscellaneous manufacturing industries	36
4	Transportation, Communication, and Utilities	
41	Local and interurban passenger transit	26
42	Motor freight transportation and warehousing	85
43	U.S. Postal Service	5
44	Water transportation	353
45	Transportation by air	171
46	Pipelines, except natural gas	-
47	Transportation services	40
48	Communications	55
49	Electric, gas, and sanitary services	51
5	Wholesale and Retail Trade	
50	Wholesale trade--durable goods	46
51	Wholesale trade--nondurable goods	87
52	Building materials, hardware, garden supply, & mobile	35
53	General merchandise stores	45
54	Food stores	100
55	Automotive dealers and gasoline service stations	49
56	Apparel and accessory stores	68
57	Furniture, home furnishings and equipment stores	42
58	Eating and drinking places	156
59	Miscellaneous retail	132
6	Finance, Insurance, and Real Estate	
60	Depository institutions	62
61	Nondepository credit institutions	361
62	Security, commodity brokers, and services	1240
63	Insurance carriers	136
64	Insurance agents, brokers, and service	89
65	Real estate	609
67	Holding and other investment offices	290
7	Service Industries	
70	Hotels, rooming houses, camps, and other lodging place	230
72	Personal services	462
73	Business services	73
75	Automotive repair, services, and parking	217
76	Miscellaneous repair services	69
78	Motion pictures	110
79	Amusement and recreational services	429
8	Service Industries	
80	Health services	91
81	Legal services	821
82	Educational services	117
83	Social services	106
84	Museums, art galleries, botanical & zoological garden	208
86	Membership organizations	212
87	Engineering and management services	58

SIC Code	SIC Category Description	Daily use rate (GPD)
88	Private households	-
89	Miscellaneous services	73
9	Public Administration	
91	Executive, legislative, and general government	155
92	Justice, public order, and safety	18
93	Finance, taxation, and monetary policy	-
94	Administration of human resources	87
95	Environmental quality and housing	101
96	Administration of economic programs	274
97	National security and international affairs	112
99	Unknown	-

Appendix D: ArcGIS Geoprocessing models for processing estimated demand

Several ArcGIS Geoprocessing models were developed to automate processing the results of the estimation method. The geoprocessing models, shown in the figures below, perform the following functions.

1) Summarize Estimated Demands (see Figure D.1). This geoprocessing model creates four summary tables using the estimated demand. The following summary tables are created:
    - Total demand per hour (result shown in one table row)
    - Total demand per hour by Residential and CII categories (result shown in two table rows)
    - Total demand per junction per hour
    - Total demand per junction per hour by Residential and CII categories
2) Add Diff Fields (see Figure D.2). This model adds 24 fields to a results table, where each field is calculated to be the difference between the empiric demand and estimated demand values.
3) Calc Diff Fields (see Figure D.3). This model calculates the difference between the empiric and estimated demands for all 24 hours.
4) Add Junction Summary Field (see Figure D.4). This geoprocessing model adds and calculates a new field that is used when summarizing results of the estimated demands.

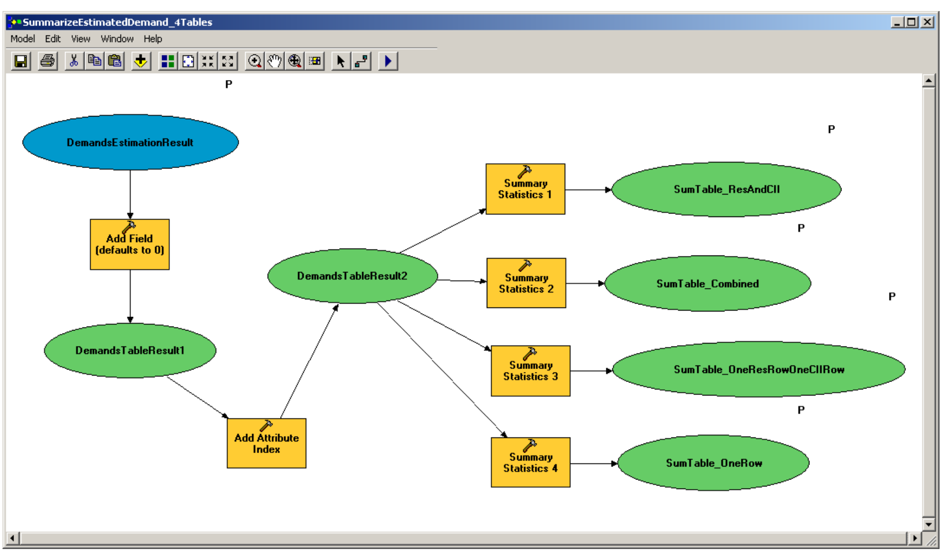

Figure D.1. Summarize Estimated Demands – ArcGIS geoprocessing model for summarizing estimated demand to four summary tables. The model automates the creation of tables summarizing on: residential and CII separately for all demand junctions/service areas, residential and CII combined for all demand junctions/service areas, and each of the above but summed across all junction demands/service areas.

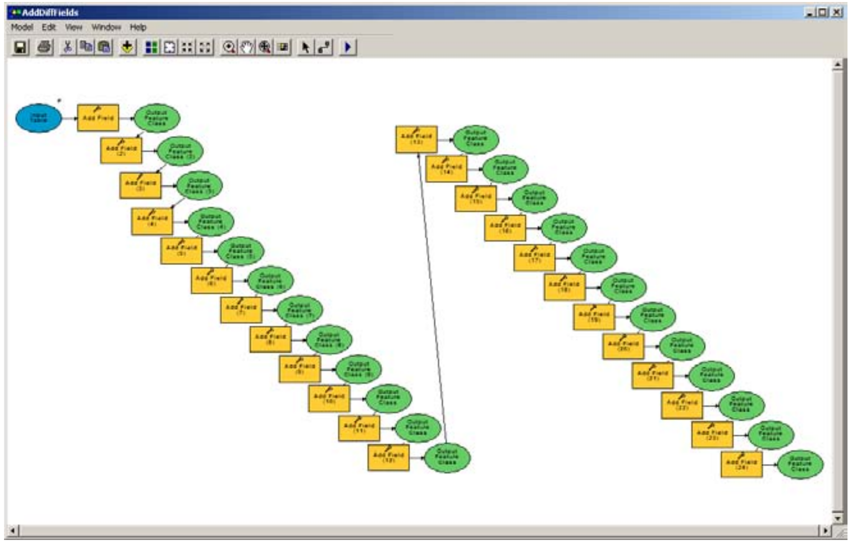

Figure D.2. Add Diff Fields model – ArcGIS geoprocessing model for adding fields used to contain the difference between the estimated water demand and the empiric water demand for the 24 hourly periods.

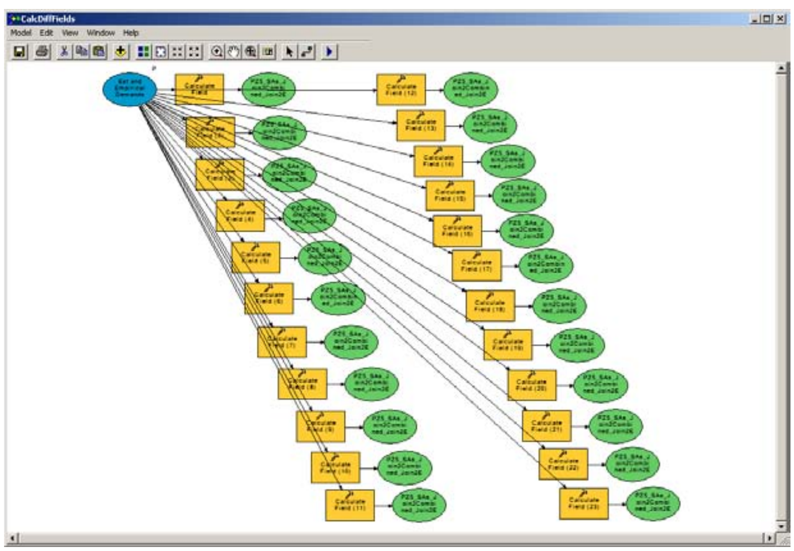

Figure D.3. Calc Diff Fields – ArcGIS geoprocessing model for calculating the difference between the estimated water demand and the empiric water demand for the 24 hourly periods.

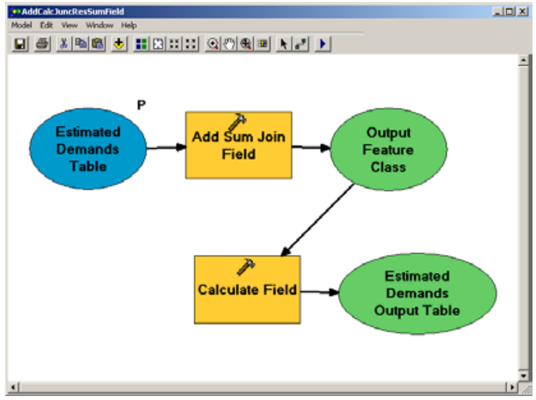

Figure D.4. Add Junction Summary Field – ArcGIS geoprocessing model for adding and calculating a new field on the table of estimated results to combine the junction ID field and residential flag field. The new field is used when summarizing the estimated results.

Appendix E: Overview of method for creating empiric demand

This appendix provides an overview of the method used by the Brown and Caldwell consulting firm to create the empiric water demand.

The empiric water demand for the City of Santa Fe water system was developed by Brown and Caldwell for the 2009 Master Plan (Brown and Caldwell 2009). Accurately representing water demand is an integral part of a calibrated hydraulic model. The process of associating water demand with the pipeline network involves linking customer accounts and corresponding water usage to the pipeline network over a 24-hour period. The steps below were provided in the 2009 Master Plan.

The pipeline network component where demand is connected into the water system is a demand junction. Each demand junction has an associated service area that is notionally the area served by that junction.

1. Obtain billing data including addresses for each customer and calculate the MMD, ADD and MDD for each customer.

   [MMD refers to the average of the minimum month demand; ADD refers to the average of the average day demand; MDD refers to the average of the maximum day demand. For the Master Plan, the billing records for 2007 were used. The minimum month base allocation was obtained from November records, the maximum month allocation was based on August, and the average day scenario was based on the average demand for the 12 months.]

2. Geocode (locate geographically) each of the customers either by matching the customer to a parcel or by street address.

3. Flag each junction in the model as a demand junction or non-demand junction. Non-demand junctions will not have a demand, such as on a transmission pipeline or at a pump station.

4. Calculate the total demand at each demand junction as the sum of the demand for the customers closest to each junction.

   [The closest junction to a customer is represented by the Voronoi or Theissen polygons for a set of points, where the point features in this case are demand junctions.]

5. Scale demands at each junction equally to match total system demand.

   [Because there are losses and other unaccountable water usage, the summation of customer water demand is scaled up to equal the system-level daily water production.]

Appendix F: Calibration results

This appendix presents the results of the calibration cases. Each case is described and the input parameters are shown. Graphical results at an hourly temporal resolution are shown for total empiric and estimated demands, and for percentile and absolute differences between empiric and estimated demands.

Case 1

Description: This is the baseline case, where the default parameter values provided by the data sources are used. This case is the basis for all of the subsequent cases (hence the preceding "1" for all case names). The baseline or default values include a daily residential use rate of 140 GPM (USGS); the Loureiro residential use pattern; the Restaurant use pattern for CII facility types of eating and drinking establishments; the Motel use pattern for CII facility types of lodging facilities; CII daily use rates provided by the Dziegielewski *et al.* study (2000); 2005 Census residential population data; and the Dun and Bradstreet commercial dataset for CII facilities.

Table F.1. Parameter values for Calibration Case 1.

Case 1 Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	-
Residential population	Census

Results and Error Analysis

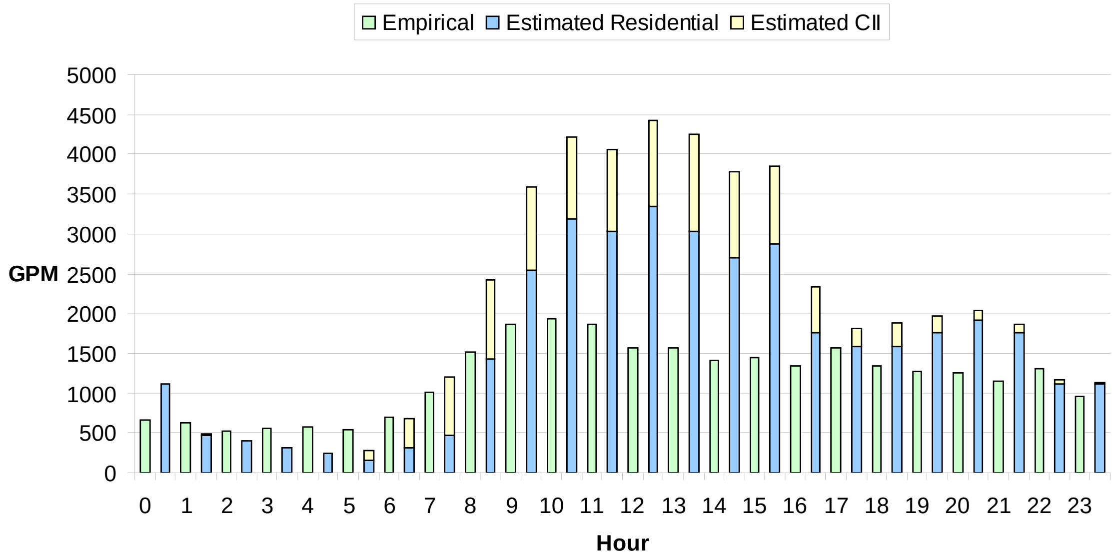

Figure F.1. The total empiric and estimated Case 1 hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.2. Results and error measures for Calibration Case 1. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1 Error Metrics (Demand units are GPM)		
Total Estimated Demand	2062	
Total Empiric Demand	1191	
Total % Difference	73%	
Total Estimated Residential Demand	1592	77%
Total Estimated CII Demand	470	23%
Relative Error	82%	

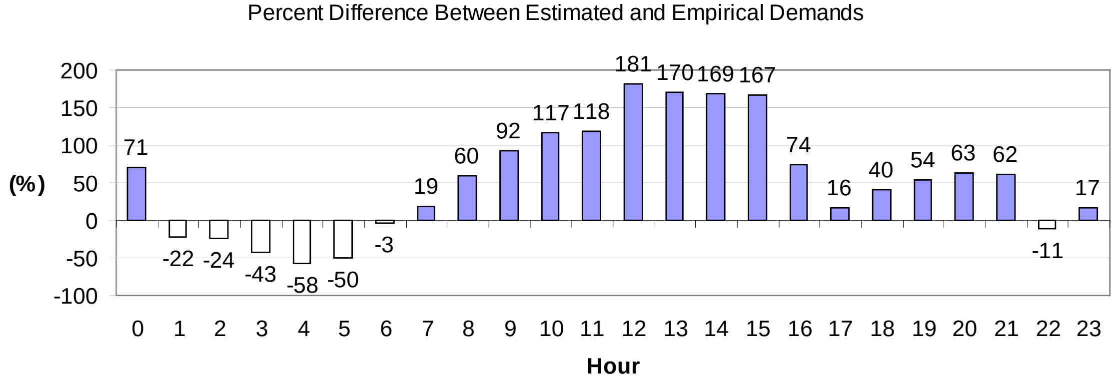

Figure F.2. The percent difference between the empiric and estimated Case 1 hourly demands for pressure zone 5 is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

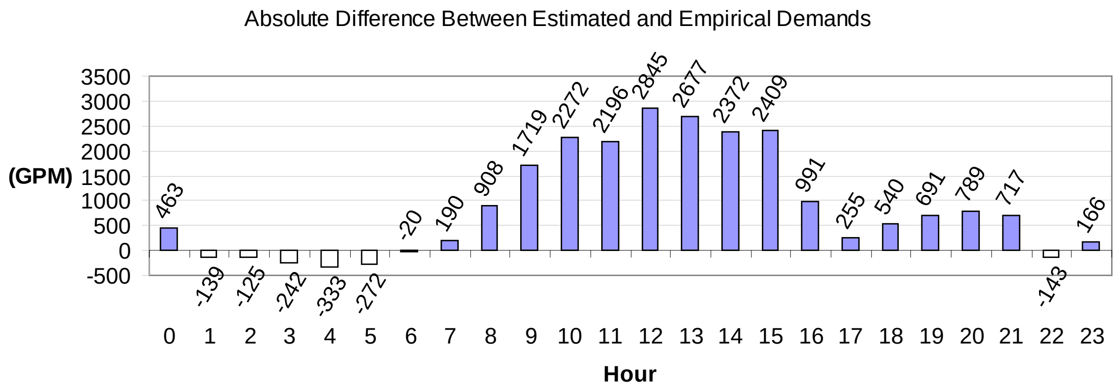

Figure F.3. The absolute difference in GPM between the estimated Case 1 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1A

Description: This case builds on the Case 1 approach by using a scale factor to ensure that the total estimated demand equals the total empiric demand. The scale factor is derived by dividing the estimated demand for Case 1 by the empiric demand, as shown below.

Total empiric demand: 1191.4895
Total estimated demand for Case 1: 2062.3616
Scale factor = 2062.3616 / 1191.4895 = 0.5777

The scale factor is applied uniformly to all of the estimated demand rates for all demand junctions. After applying the factor, the total estimated demand equals the total empiric demand.

Table F.3. Parameter values for Calibration Case 1A.

Case 1A Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	0.5777
Residential Population	Census

Results and Error Analysis

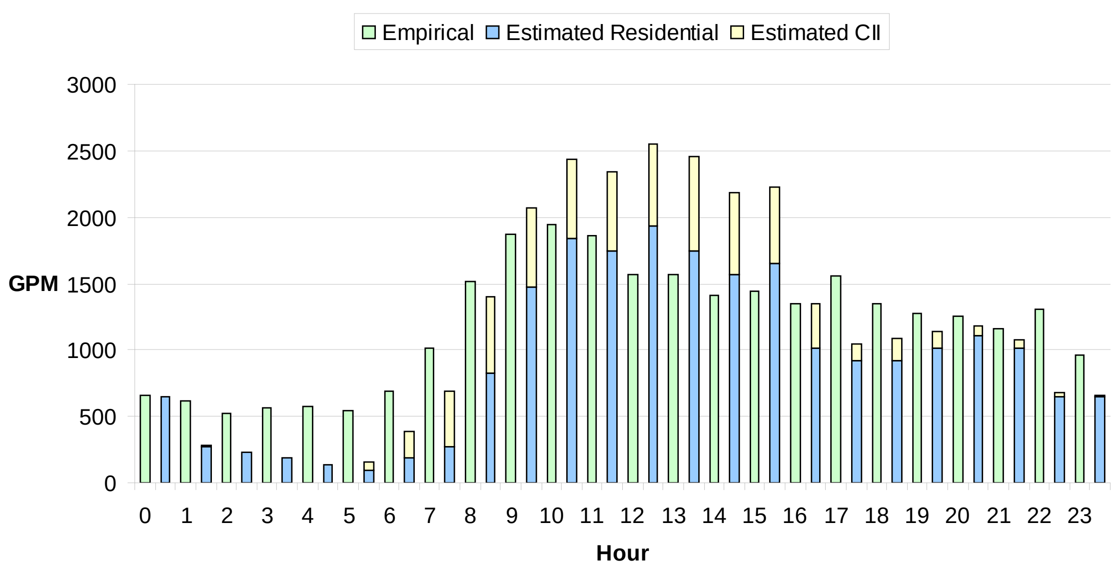

Figure F.4. The total empiric and estimated Case 1A hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.4. Results and error measures for Calibration Case 1A. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1A Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1191	
Total Empiric Demand	1191	
Total % Difference	0%	
Total Estimated Residential Demand	920	77%
Total Estimated CII Demand	272	23%
Relative Error	32%	

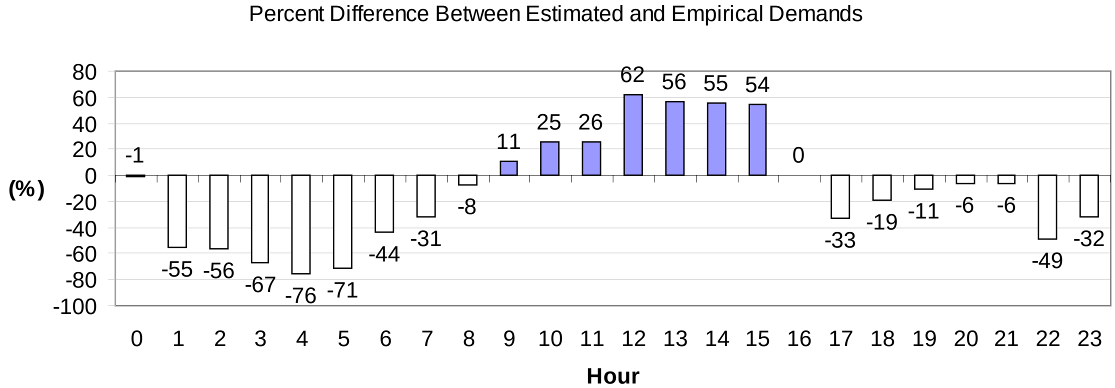

Figure F.5. The percent difference by hourly time interval between the estimated Case 1A and the empiric hourly demands for pressure zone 5 is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

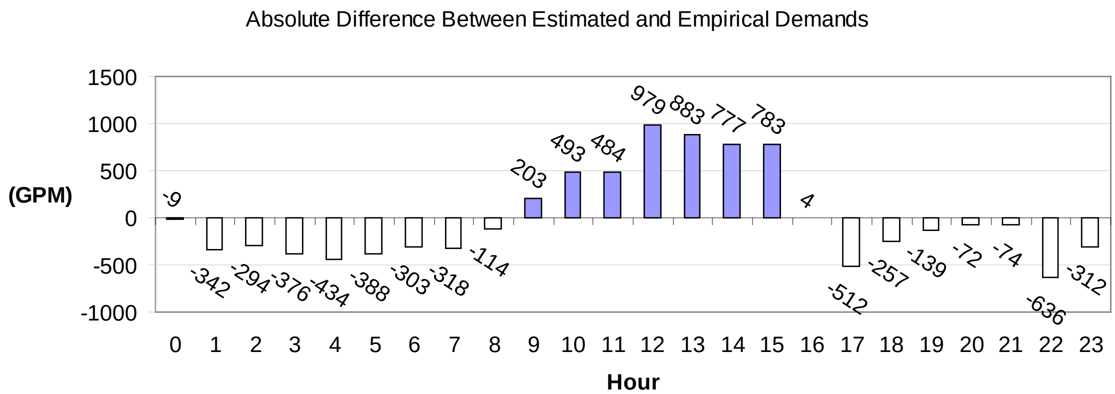

Figure F.6. The absolute difference in GPM between the estimated Case 1A and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1B

Description: The premise for this case is that the baseline residential daily use rate could be adjusted. The baseline rate of 140 GPD (estimated using the USGS data) is higher than the rates reported for the Santa Fe water system in the 2009 Master Plan. A new residential daily rate was calculated by examining the empiric use rates for customers wholly within land use regions defined as residential. The derived residential daily rate is 113 GPD. All other parameter values are the same as for Case 1.

There were 436 demand junction service areas that were completely contained by one of the four residential land use regions. The percent difference between the empiric and estimated demand across all demand junctions was examined. The estimated residential demand was, on average, 124% of the empiric demand. The daily residential GPD was then scaled by 100/124 or 0.8065 to equal approximately 113 GPM (i.e., 140 * 0.8065).

Table F.5. Parameter values for Calibration Case 1B.

Case 1B Parameter Values	
Residential Use Rate	113 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	-
Residential Population	Census

Results and Error Analysis

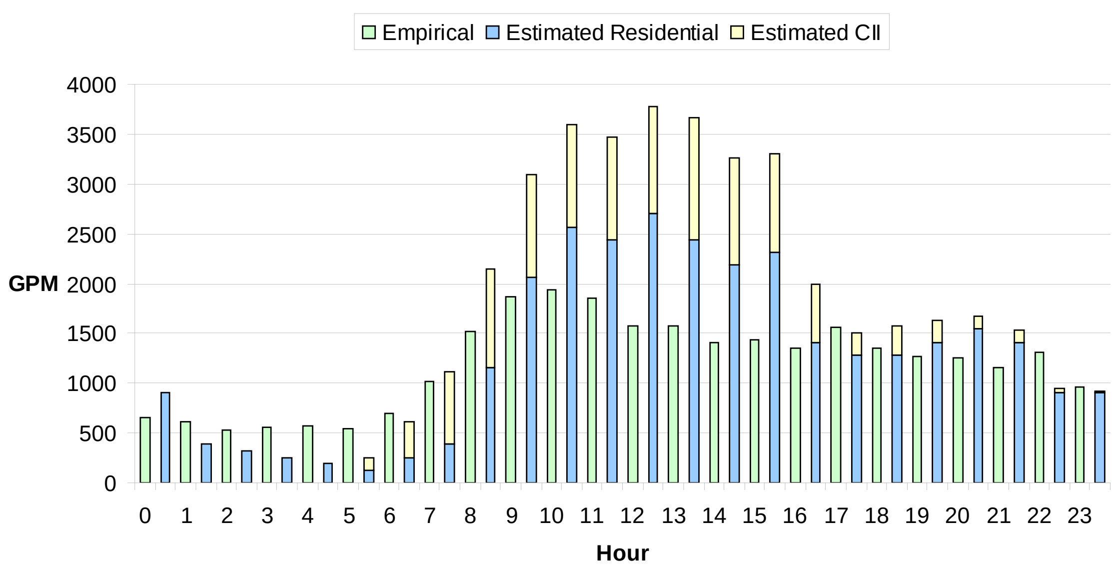

Figure F.7. The total empiric and estimated Case 1B hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.6. Results and error measures for Calibration Case 1B. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1B Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1755	
Total Empiric Demand	1191	
Total % Difference	47%	
Total Estimated Residential Demand	1285	73%
Total Estimated CII Demand	470	27%
Relative Error	61%	

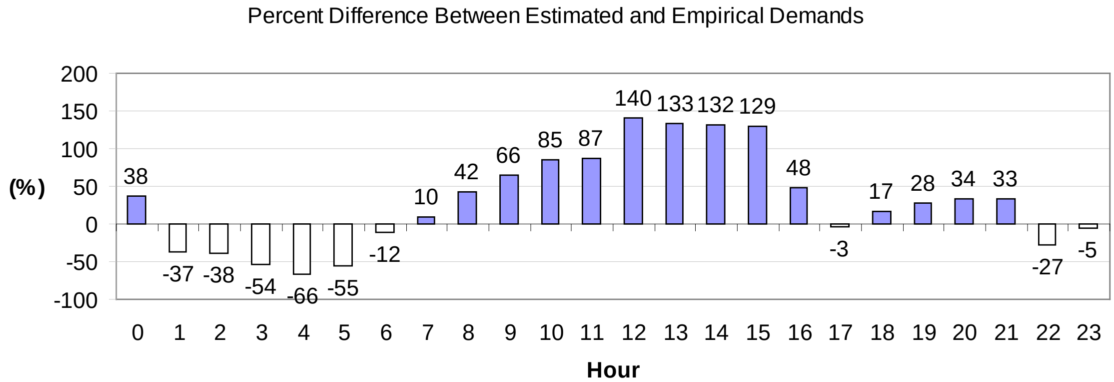

Figure F.8. The percent difference between the estimated Case 1B and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

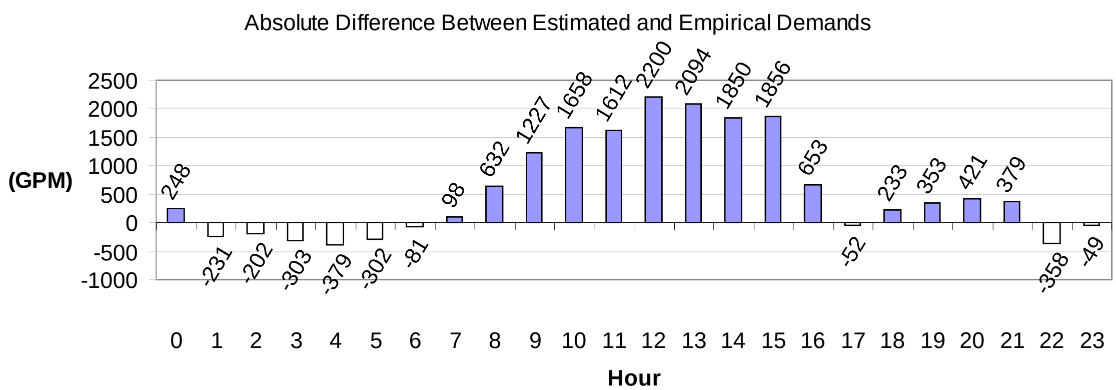

Figure F.9. The absolute difference in GPM between the estimated Case 1B and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1C

Description: The case is identical to Case 1B with the addition of the use of a demand scale factor of 0.6788. The demand scale factor is calculated by dividing the total empiric demand by the total estimated demand, as shown below.

Estimated base demand: 1755.2993
Empiric base demand: 1191.4895
Scale Factor = 1191.4895 / 1755.2993 = 0.6788

Table F.7. Parameter values for Calibration Case 1C.

Case 1C Parameter Values	
Residential Use Rate	113 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	0.6788
Residential Population	Census

Results and Error Analysis

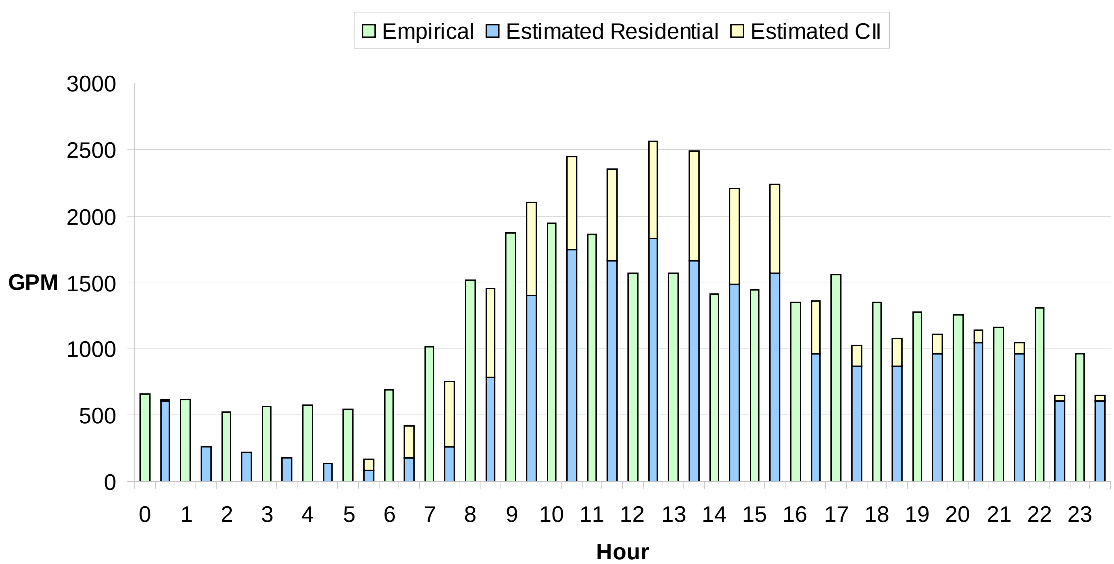

Figure F.10. The total empiric and estimated Case 1C hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.8. Results and error measures for Calibration Case 1C. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1C Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1191	
Total Empiric Demand	1191	
Total % Difference	0%	
Total Estimated Residential Demand	872	73%
Total Estimated CII Demand	319	27%
Relative Error	33%	

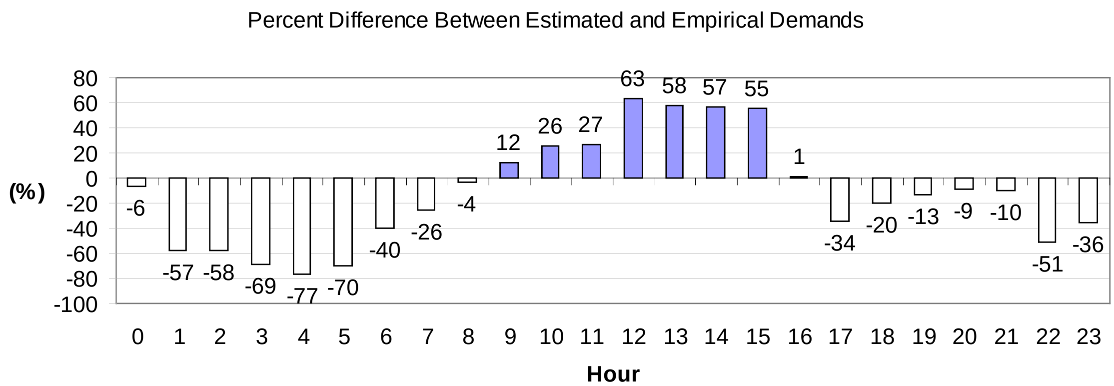

Figure F.11. The percent difference between the estimated Case 1C and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

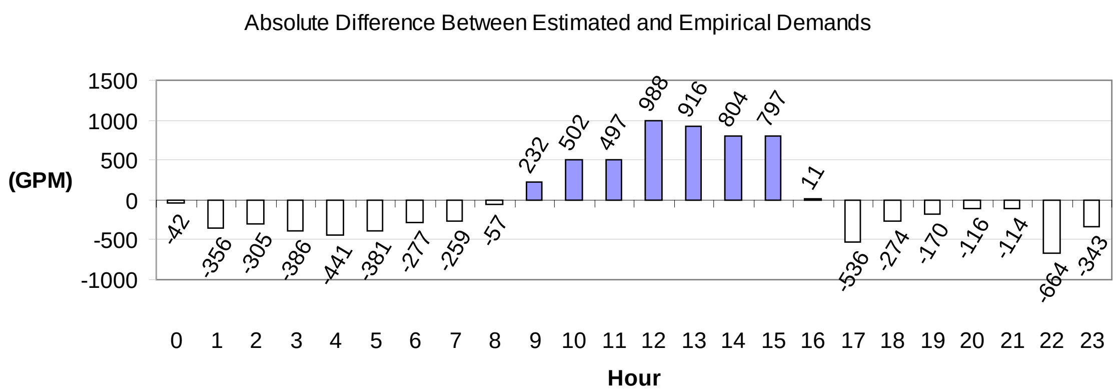

Figure F.12. The absolute difference in GPM between the estimated Case 1C and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1D

Description: The premise for this case is that the residential population could be reduced during the work hours of 8:00am – 5:00pm by the number of people who are working. The working population would not be consuming water at home but instead would be consuming water at work. It was assumed that 50% of the employees working within pressure zone 5 also live in the same pressure zone. This number of employees was removed from the residential population during work hours.

To implement this in the method, the residential population was reduced by 50% of the working population during working hours. There were an estimated 4649 employees in working on Saturday in pressure zone 5. The amount of base demand to be subtracted from the original base demand was calculated to be 50% of 4649 employees multiplied by the residential daily use rate of 140 GPD. This resulted in a base demand value of 225 GPM. This base demand value was then multiplied by the residential use pattern factor for each of the working hours, and subtracted from the original base demand. The resulting total base demand was 1922 GPM.

The case employs a daytime residential population dataset that was developed at LANL. All other parameter values are the same as for Case 1.

Table F.9. Parameter values for Calibration Case 1D.

Case 1D Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	-
Residential Population	LANL Daytime Residential Pop.

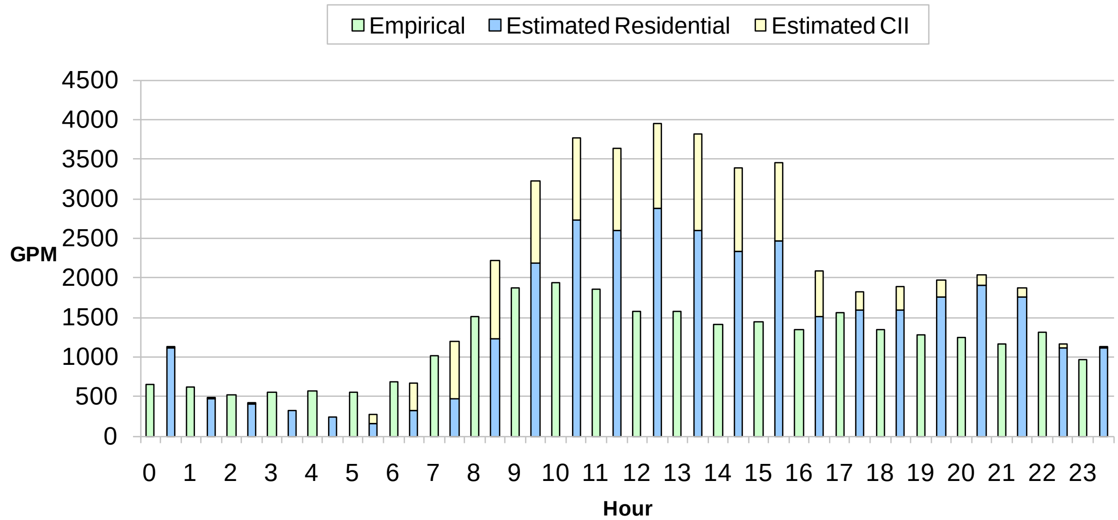

Figure F.13. The total empiric and estimated Case 1D hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.10. Results and error measures for Calibration Case 1D. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1D Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1922	
Total Empiric Demand	1191	
Total % Difference	61%	
Total Estimated Residential Demand	1452	76%
Total Estimated CII Demand	470	24%
Relative Error	70%	

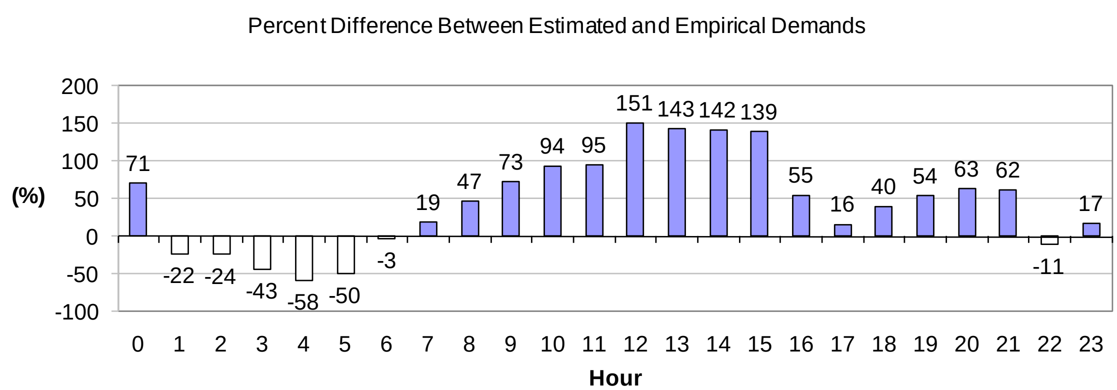

Figure F.14. The percent difference between the estimated Case 1D and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the

demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

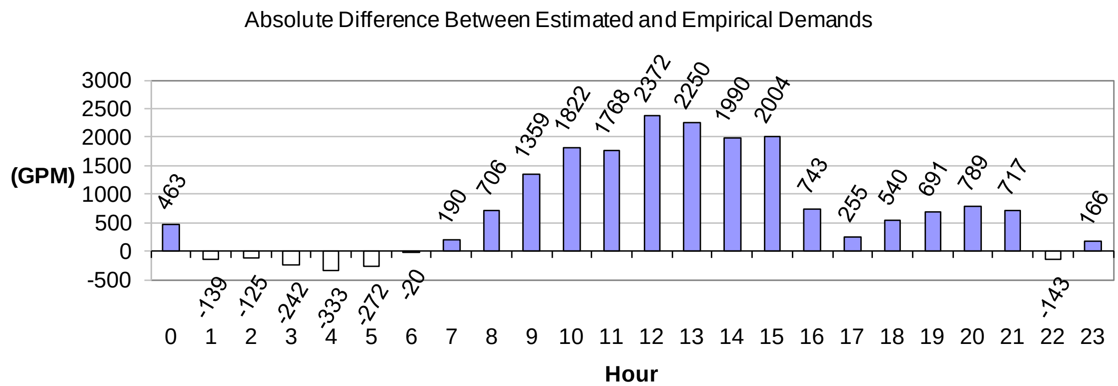

Figure F.15. The absolute difference in GPM between the estimated Case 1D and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1E

Description: This case is identical to Case 1D with the addition of the use of a demand scale factor equal to 0.61, which is calculated below.

Total Empiric Base Demand = 1191.4895
Total Estimated Base Demand = 1921.85
Scale Factor = Empiric / Estimated = 1191.4895/1921.85= 0.610

Table F.11. Parameter values for Calibration Case 1E.

Case 1E Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	0.61
Residential Population	LANL Daytime Residential Pop.

Results and Error Analysis

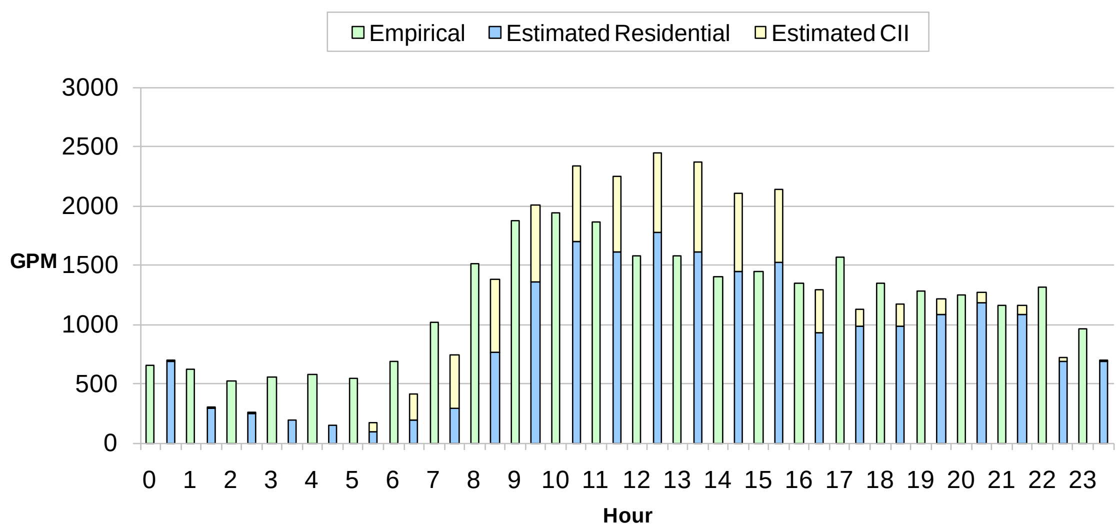

Figure F.16. The total empiric and estimated Case 1E hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.12. Results and error measures for Calibration Case 1E. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1E Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1191	
Total Empiric Demand	1191	
Total % Difference	0%	
Total Estimated Residential Demand	900	76%
Total Estimated CII Demand	292	24%
Relative Error	28%	

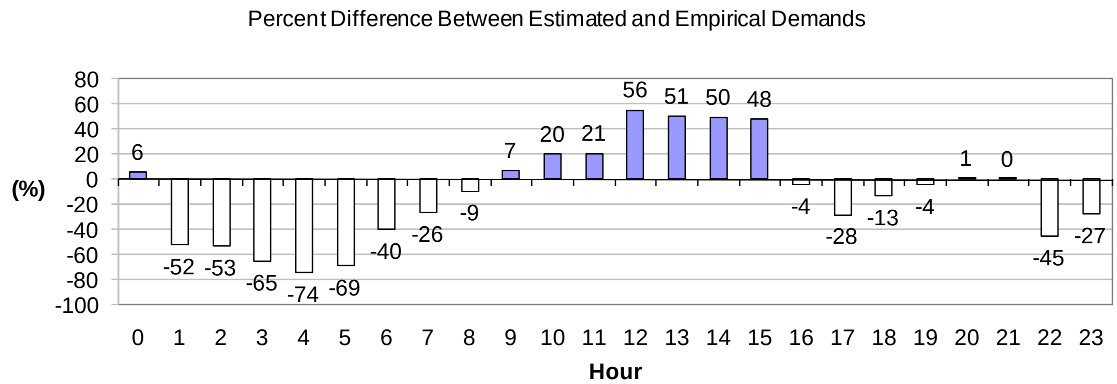

Figure F.17. The percent difference between the estimated Case 1E and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

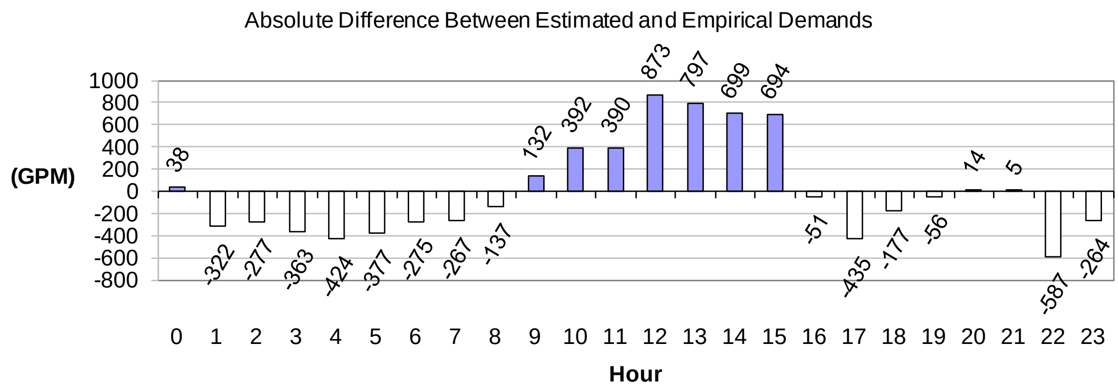

Figure F.18. The absolute difference in GPM between the estimated Case 1E and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1F

Description: The premise for the case is that the default CII use pattern (i.e., the Haestad Business pattern), which is applied for most of the CII facilities, does not supply water during the non-business hours of before 6:00am or after 7:00pm. It is known by first-hand observation that some amount of demand takes place during non-business hours. For example, St. Michael's High School irrigates its sports fields (i.e., football, soccer, etc.) in the evening, as late as 10:00pm. This case creates a revised general purpose CII water use pattern that serves off-hours demand at a minimal but non-zero level.

The derived business pattern modifies the Haestad Business pattern by distributing a small percentage of the demand to the non-business hours. The case is based on Case 1B.

Table F.13. Parameter values for Calibration Case 1F.

Case 1F Parameter Values	
Residential Use Rate	113 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Modified Haestad Business Pattern
Scale Factor	-
Residential Population	Census

Results and Error Analysis

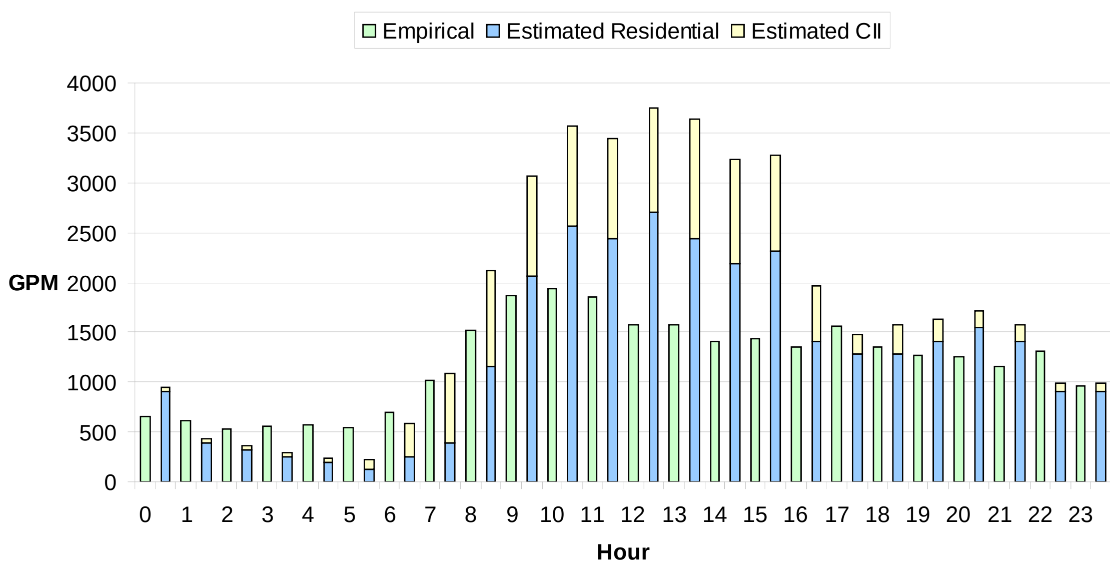

Figure F.19. The total empiric and estimated Case 1F hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.14. Results and error measures for Calibration Case 1F. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1F Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1755	
Total Empiric Demand	1191	
Total % Difference	47%	
Total Estimated Residential Demand	1285	73%
Total Estimated CII Demand	470	27%
Relative Error	60%	

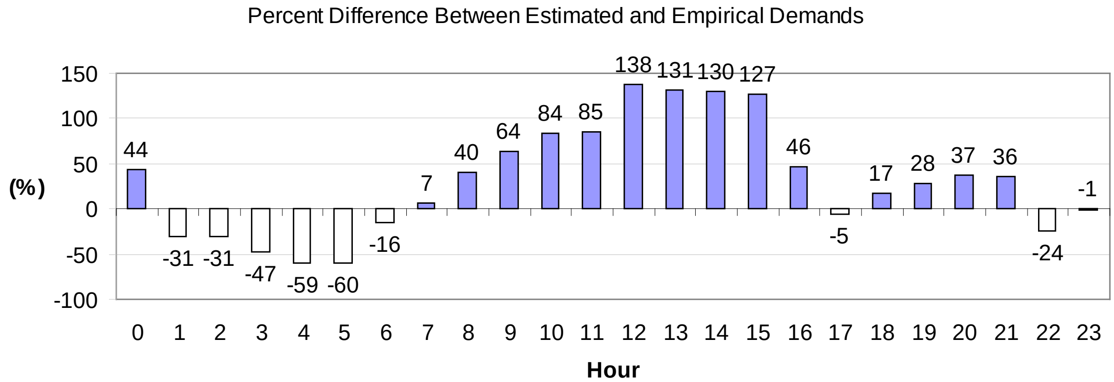

Figure F.20. The percent difference between the estimated Case 1F and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

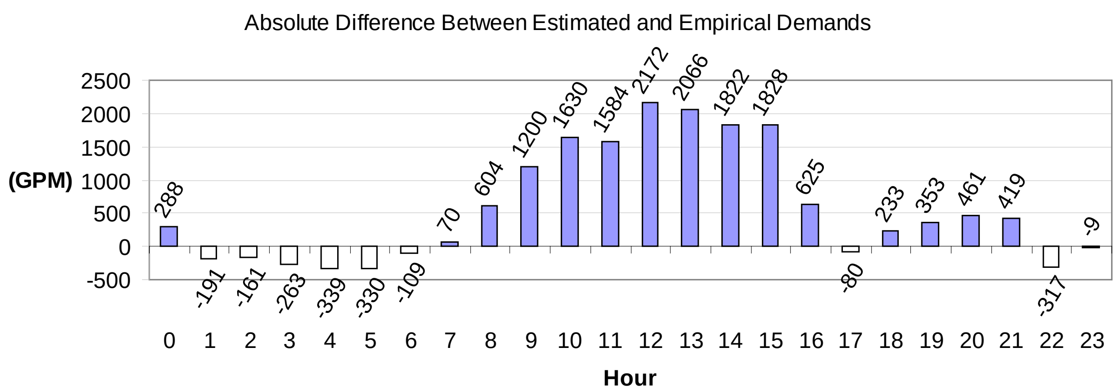

Figure F.21. The absolute difference in GPM between the estimated Case 1F and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1G

Description: This case is based on Case 1F, but also reduces the (Census) residential population by 50% of the working population during the working hours of 8:00am – 5:00pm, as was performed for Case 1D. This is done to reduce the residential demand to compensate for the working people who are using water at work and not at their residence.

Table F.15. Parameter values for Calibration Case 1G.

Case 1G Parameter Values	
Residential Use Rate	113 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Modified Haestad Business Pattern
Scale Factor	-
Residential Population	Census

Results and Error Analysis

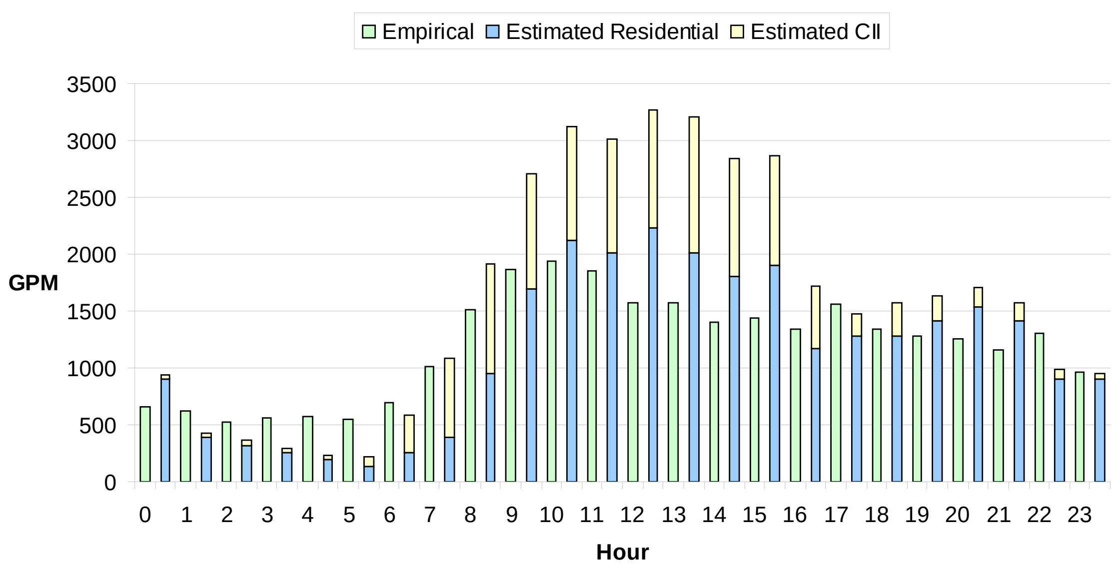

Figure F.22. The total empiric and estimated Case 1G hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.16. Results and error measures for Calibration Case 1G. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1G Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1615	
Total Empiric Demand	1191	
Total % Difference	36%	
Total Estimated Residential Demand	1144	71%
Total Estimated CII Demand	470	29%
Relative Error	48%	

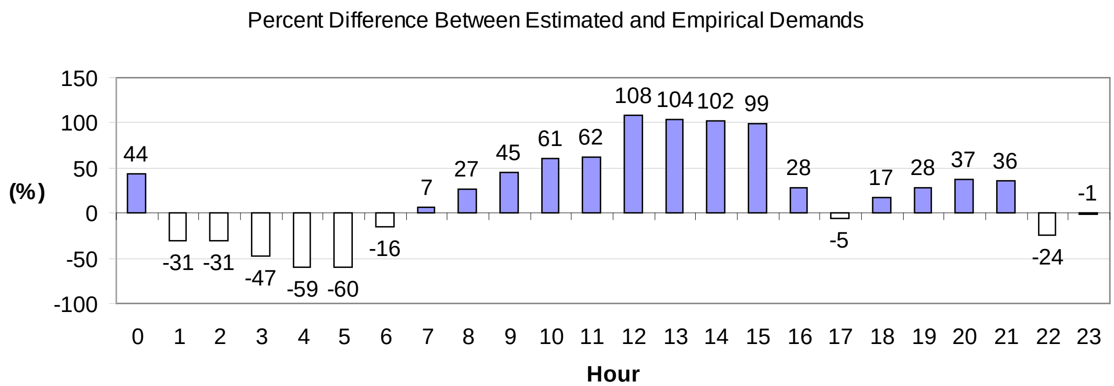

Figure F.23. The percent difference between the estimated Case 1G and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

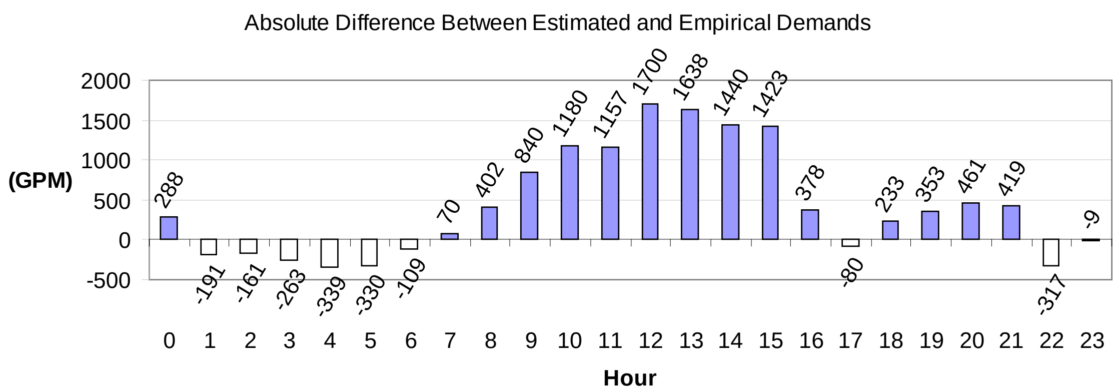

Figure F.24. The absolute difference in GPM between the estimated Case 1G and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1H

Description: This case is identical to Case 1G but includes a demand scale factor of 0.7379, which is calculated below.

Total estimated base demand: 1614.7879
Total empiric base demand: 1191.4895
Scale factor: 1191.4895/1614.7879 = 0.7379

Table F.17. Parameter values for Calibration Case 1H.

Case 1H Parameter Values	
Residential Use Rate	113 GPD
Residential Use Pattern	Loureiro-Residential-Saturday
Primary CII Use Pattern	Modified Haestad Business Pattern
Scale Factor	0.7379
Residential Population	Census

Results and Error Analysis

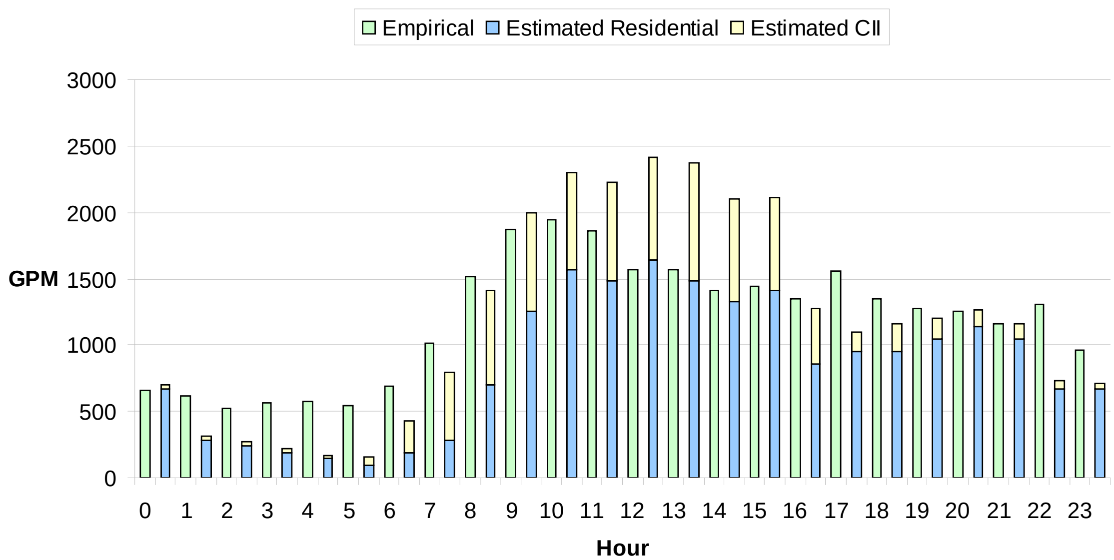

Figure F.25. The total empiric and estimated Case 1H hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.18. Results and error measures for Calibration Case 1H. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1H Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1191	
Total Empiric Demand	1191	
Total % Difference	0%	
Total Estimated Residential Demand	844	71%
Total Estimated CII Demand	347	29%
Relative Error	30%	

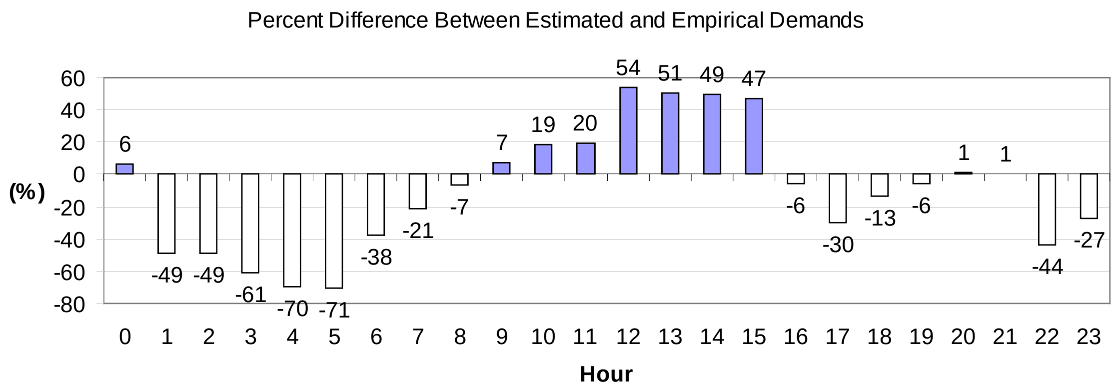

Figure F.26. The percent difference between the estimated Case 1H and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

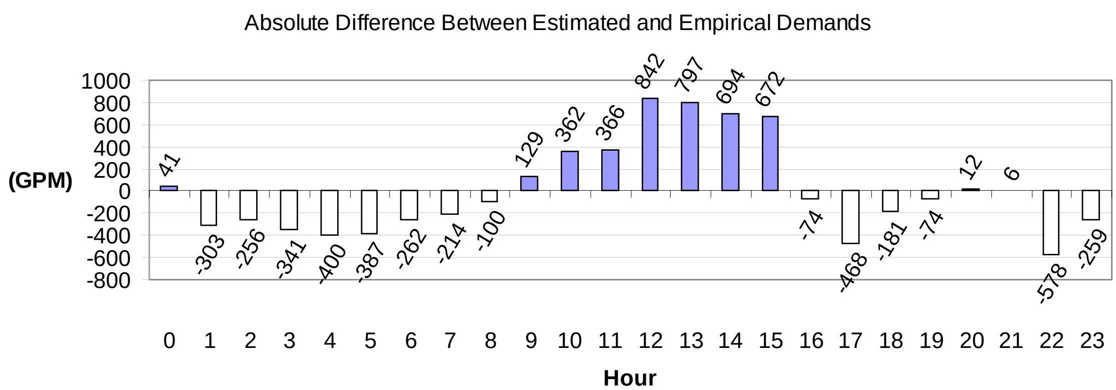

Figure F.27. The absolute difference in GPM between the estimated Case 1H and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1I

Description: The premise of the case is that deriving a new residential use pattern using the empiric data would result in small errors. This case is based on Case 1, with the addition of the derived residential use pattern. The residential use pattern was, in principle, derived by subtracting the estimated CII demand from the empiric demand.

Below are the basic steps used to create the new residential use pattern:

1) Use the estimated CII and residential estimates for each hour from Case 1A
2) Subtract the estimated CII demand from the empiric demand for each hour (this represents the residential demand component)
3) Calculate the average of the adjusted residential demand (i.e., empiric – estimated CII demand) for 24 hours (this represents the base demand of the residential component)
4) Divide each one-hour factor of the adjusted residential demand (i.e., empiric – estimated CII demand) by (3) to get the multiplier for that hour.

The resulting 24 multipliers are the dimensionless multipliers/factors for the new residential use pattern.

Table F.19. Parameter values for Calibration Case 1H.

Case 1I Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Derived Residential Pattern 1
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	-
Residential Population	Census

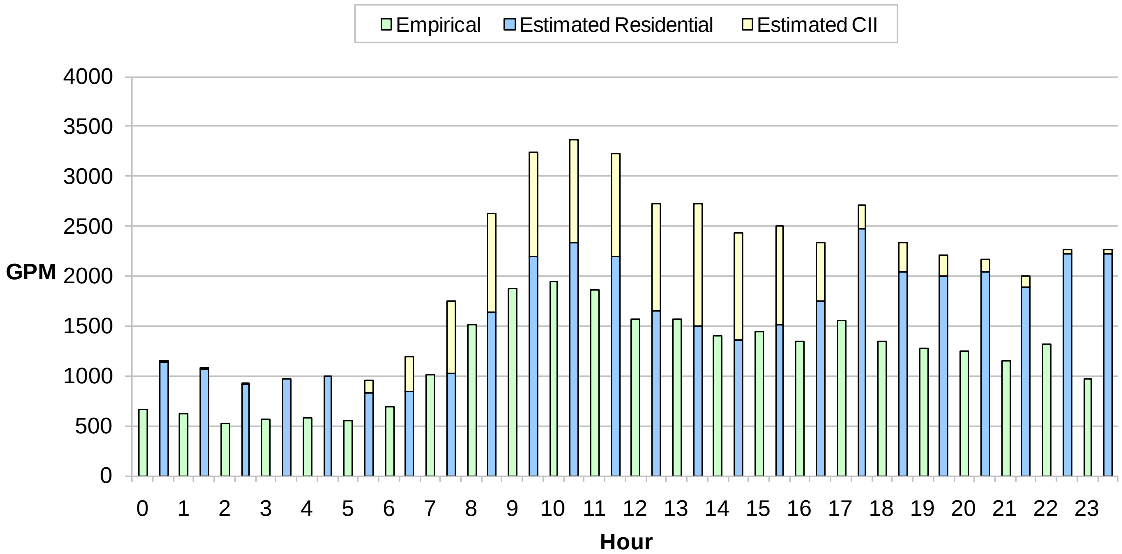

Figure F.28. The total empiric and estimated Case 1I hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.20. Results and error measures for Calibration Case 1I. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1I Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	2062	
Total Empiric Demand	1191	
Total % Difference	73%	
Total Estimated Residential Demand	844	77%
Total Estimated CII Demand	347	23%
Relative Error	73%	

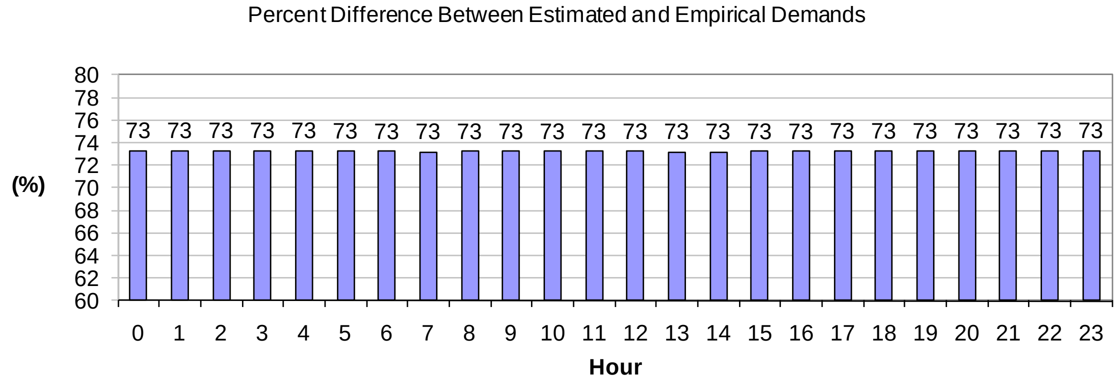

Figure F.29. The percent difference between the estimated Case 1I and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

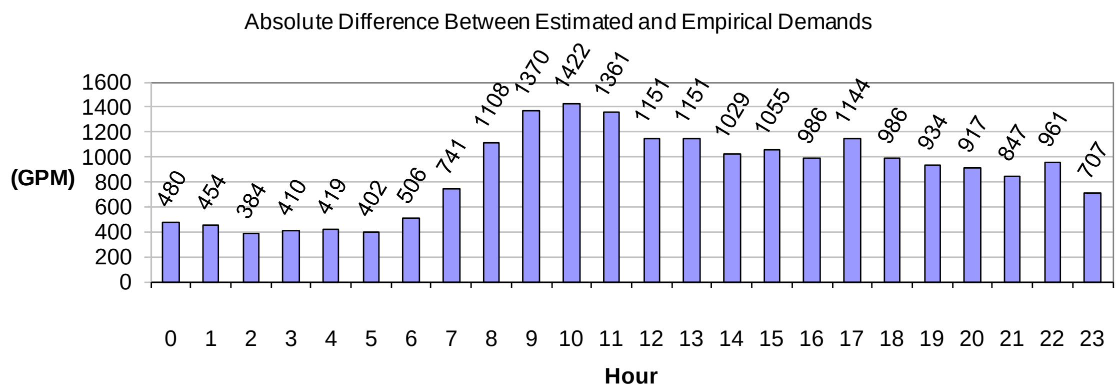

Figure F.30. The absolute difference in GPM between the estimated Case 1I and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1J

Description: This case is identical to Case 1I but includes a demand scale factor of 0.5777. Estimating the water demand with the derived residential use pattern and demand scale factor results in errors of, essentially, 0.

The case was selected as the best-fit case for calibration, and the parameter values were then applied for the validation cases.

Table F.21. Parameter values for Calibration Case 1I.

Case 1J Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Derived Residential Pattern 1
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	0.5777
Residential Population	Census

Results and Error Analysis

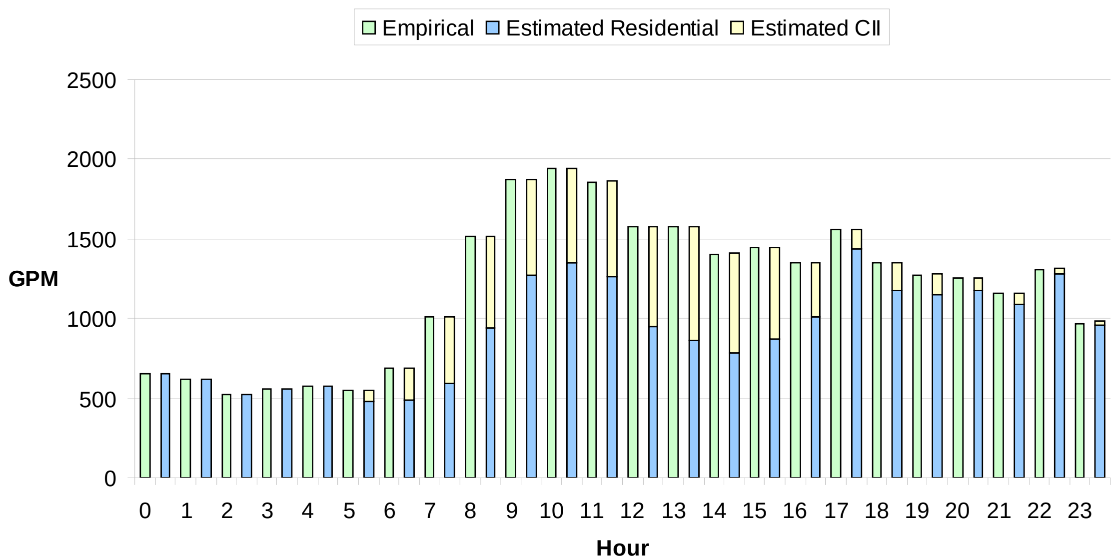

Figure F.31. The total empiric and estimated Case 1J hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.22. Results and error measures for Calibration Case 1J. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1J Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1191	
Total Empiric Demand	1191	
Total % Difference	0%	
Total Estimated Residential Demand	920	77%
Total Estimated CII Demand	272	23%
Relative Error	0.1%	

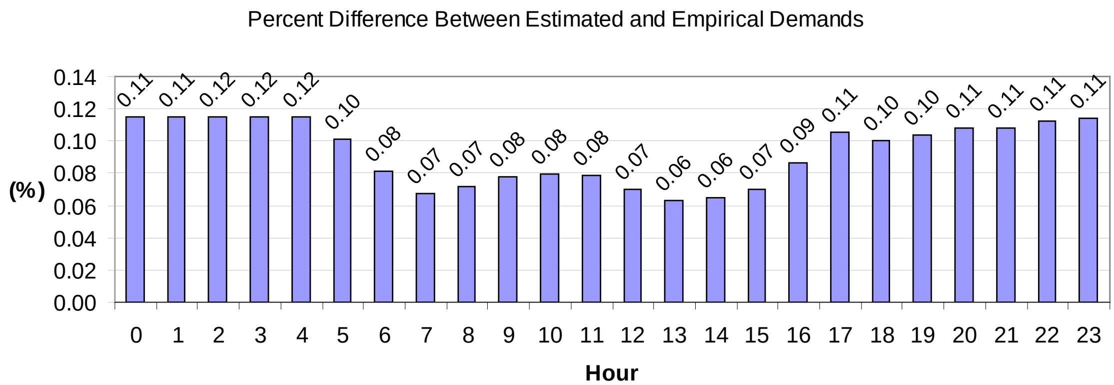

Figure F.32. The percent difference between the estimated Case 1J and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

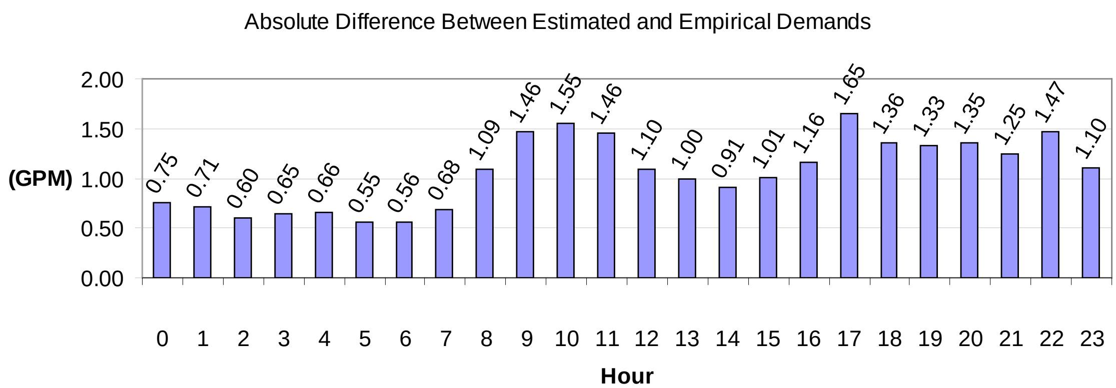

Figure F.33. The absolute difference in GPM between the estimated Case 1J and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1K

Description: This case is based on Case 1I but uses the LANL daytime residential population dataset instead of the Census residential (nighttime) population dataset.

Table F.23. Parameter values for Calibration Case 1K.

Case 1K Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Derived Residential Pattern 1
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	-
Residential Population	LANL Daytime Residential Pop.

Results and Error Analysis

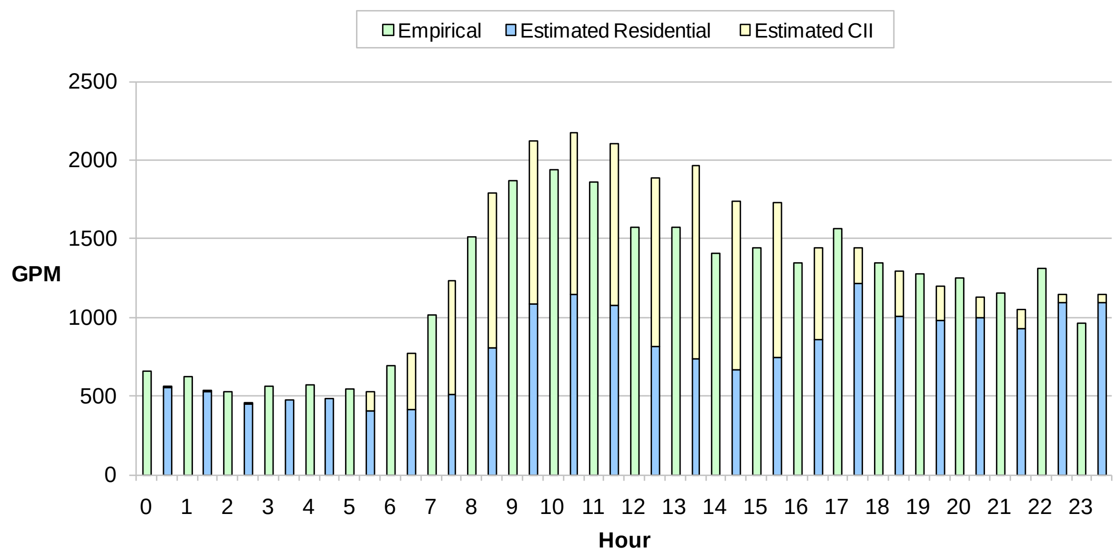

Figure F.34. The total empiric and estimated Case 1K hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.24. Results and error measures for Calibration Case 1K. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1K Error Metrics (Demand units are GPM)		
Total Estimated Demand	1253	
Total Empiric Demand	1191	
Total % Difference	5%	
Total Estimated Residential Demand	783	62%
Total Estimated CII Demand	470	38%
Relative Error	14%	

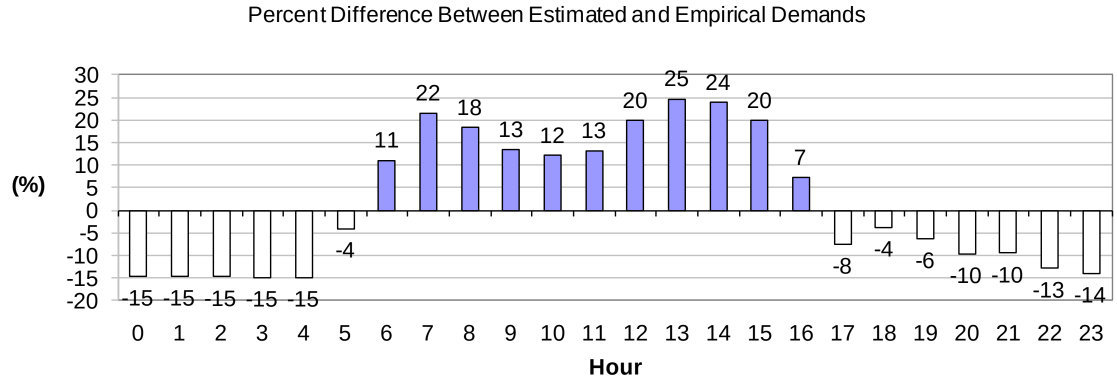

Figure F.35. The percent difference between the estimated Case 1K and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

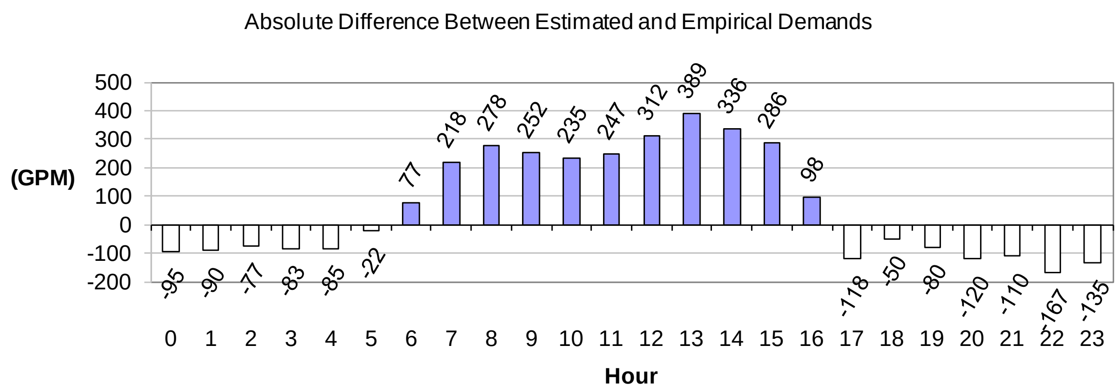

Figure F.36. The absolute difference in GPM between the estimated Case 1K and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1L

Description: This is identical to Case 1K but uses a demand scale factor of 0.95, as calculated below.

Total estimated base demand: 1252.7575
Total empiric base demand: 1191.4895
Scale factor: 1191.4895/1252.7575 = 0.951

Table F.25. Parameter values for Calibration Case 1L.

Case 1L Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Derived Residential Pattern 1
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	0.95
Residential Population	LANL Daytime Residential Pop.

Results and Error Analysis

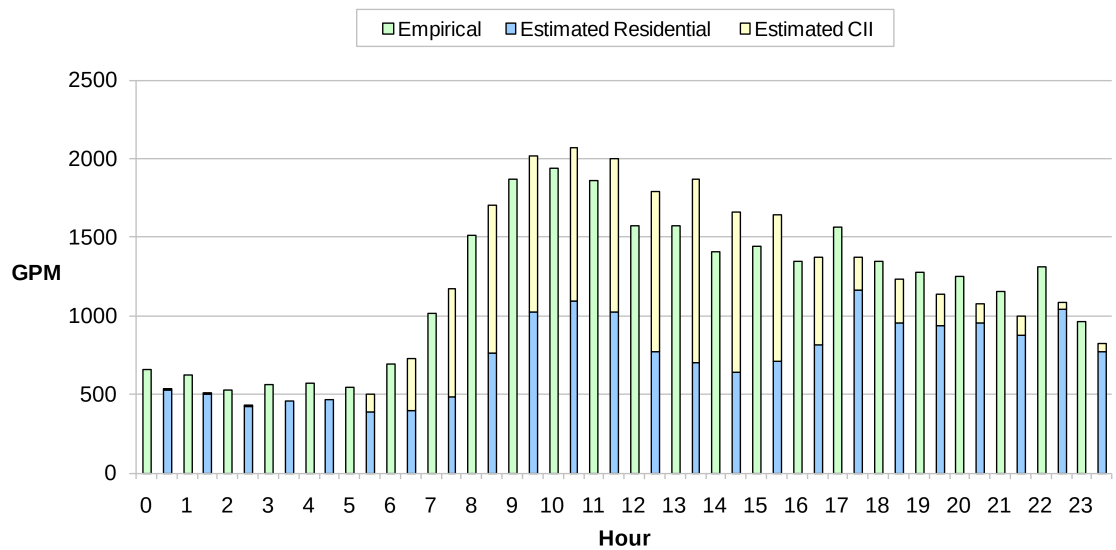

Figure F.37. The total empiric and estimated Case 1L hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.26. Results and error measures for Calibration Case 1L. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1L Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1191	
Total Empiric Demand	1191	
Total % Difference	0%	
Total Estimated Residential Demand	783	62%
Total Estimated CII Demand	470	38%
Relative Error	13%	

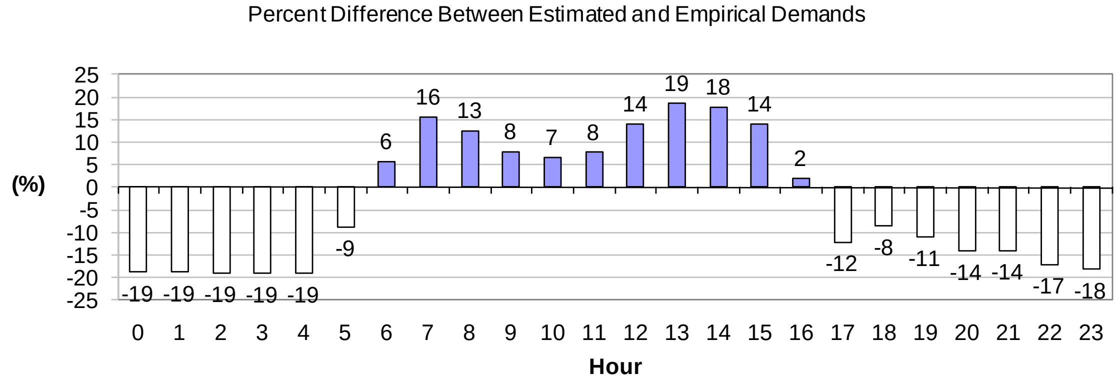

Figure F.38. The percent difference between the estimated Case 1L and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

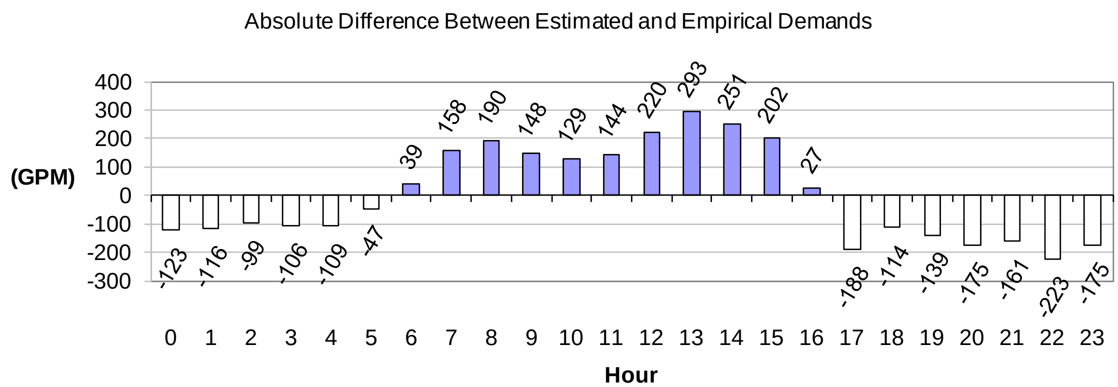

Figure F.39. The absolute difference in GPM between the estimated Case 1L and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1M

Description: The case is based on Case 1D with the addition of a newly derived residential use pattern. This case is similar to Case 1I but the LANL daytime residential population dataset is used instead of Census population data.

Table F.27. Parameter values for Calibration Case 1M.

Case 1M Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Derived Residential Pattern 2
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	-
Residential Population	LANL Daytime Residential Pop.

Results and Error Analysis

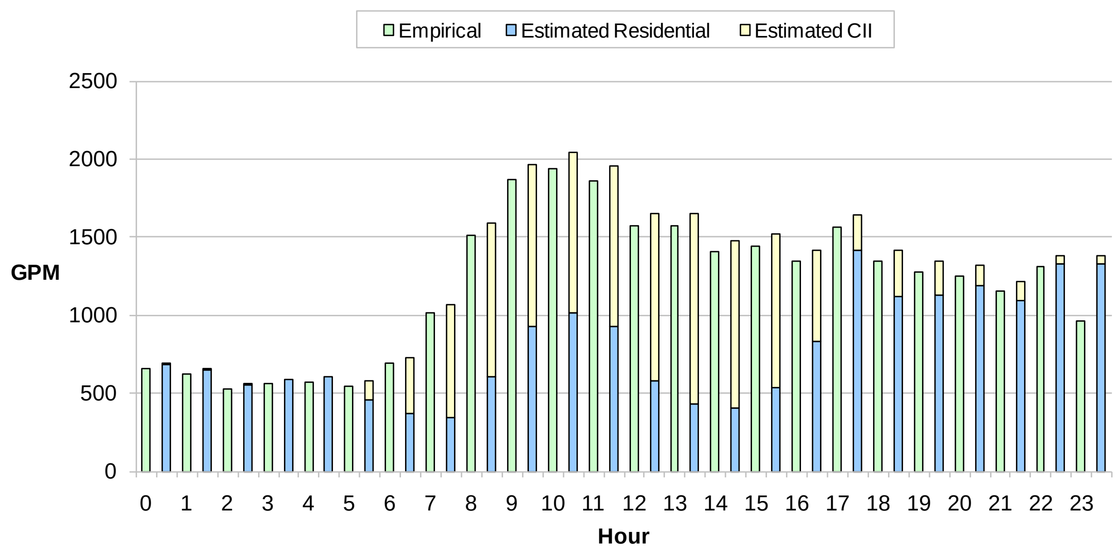

Figure F.40. The total empiric and estimated Case 1M hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.28. Results and error measures for Calibration Case 1M. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1M Error Metrics (Demand units are GPM)		
Total Estimated Demand	1253	
Total Empiric Demand	1191	
Total % Difference	5%	
Total Estimated Residential Demand	783	62%
Total Estimated CII Demand	470	38%
Relative Error	5%	

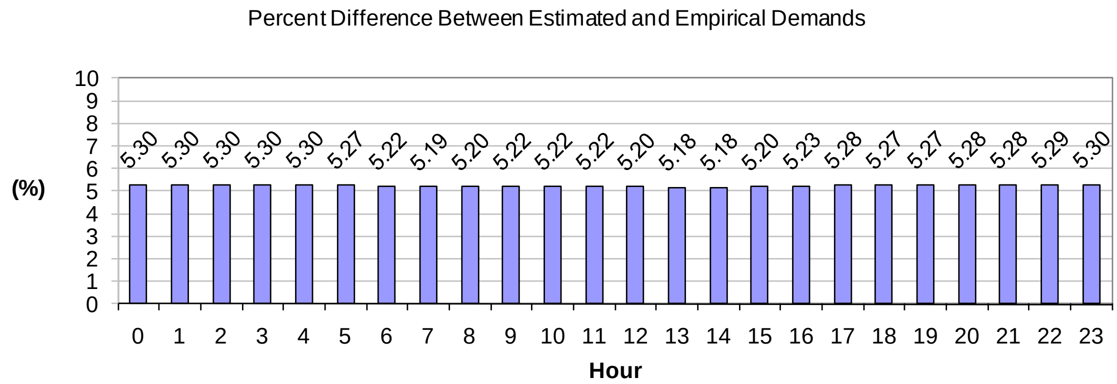

Figure F.41. The percent difference between the estimated Case 1M and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

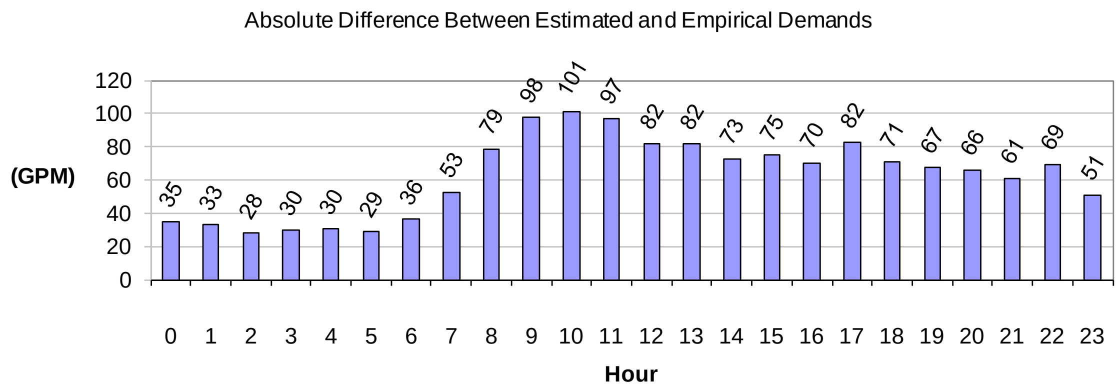

Figure F.42. The absolute difference in GPM between the estimated Case 1M and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1N

Description: The case is identical to Case 1M (with the use of the new Derived Residential Pattern 2) but applies a demand scale factor of 0.95, as calculated below.

Total estimated base demand: 1252.7575
Total empiric base demand: 1191.4895
Scale factor: 1191.4895/1252.7575 = 0.951

Table F.29. Parameter values for Calibration Case 1N.

Case 1N Parameter Values	
Residential Use Rate	140 GPD
Residential Use Pattern	Derived Residential Pattern 2
Primary CII Use Pattern	Haestad Business Pattern
Scale Factor	0.95
Residential Population	LANL Daytime Residential Pop.

Results and Error Analysis

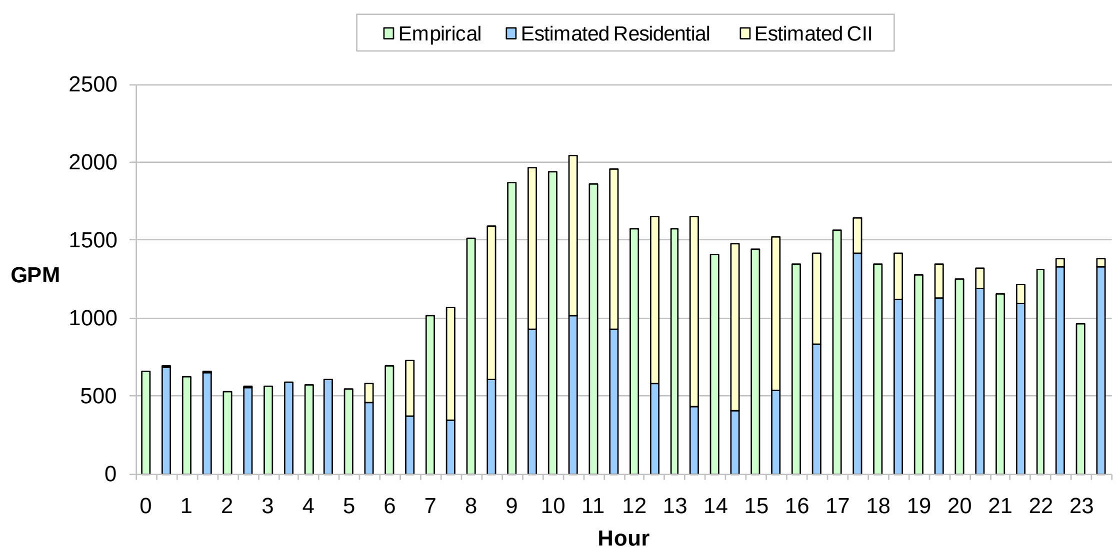

Figure F.43. The total empiric and estimated Case 1M hourly demands for pressure zone 5 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 5 at each one-hour time step.

Table F.30. Results and error measures for Calibration Case 1N. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1N Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	1191	
Total Empiric Demand	1191	
Total % Difference	0%	
Total Estimated Residential Demand	783	62%
Total Estimated CII Demand	470	38%
Relative Error	0.1%	

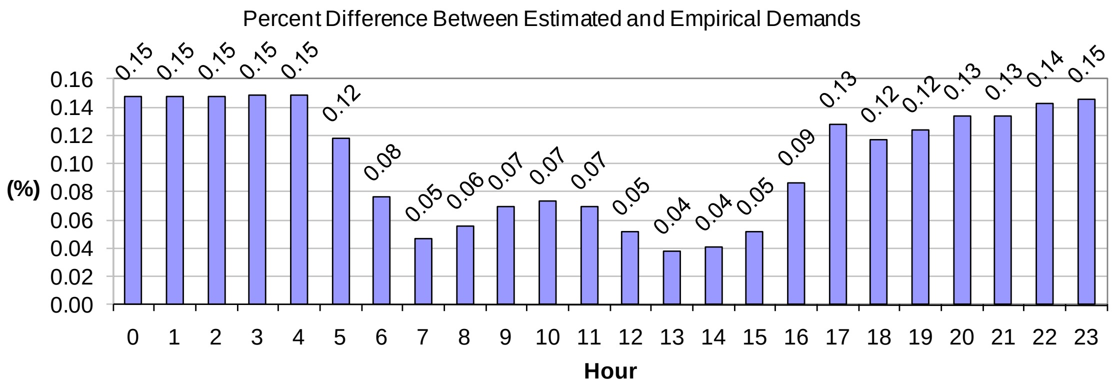

Figure F.44. The percent difference between the estimated Case 1N and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

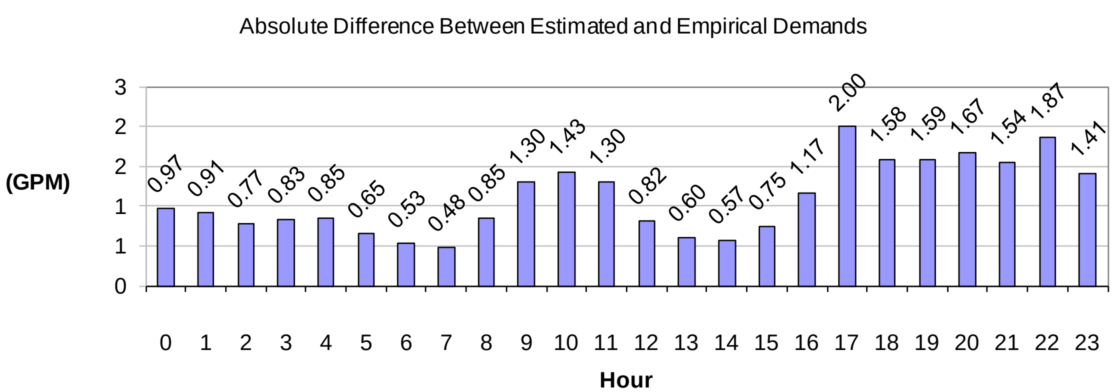

Figure F.45. The absolute difference in GPM between the estimated Case 1N and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Appendix G: Validation results

This appendix presents the results of the validation cases.

Case 1A-PZ6

Description: The case examines the use of the calibration case (Case 1A) to estimate the water demand for pressure zone 6. The input parameters and assumptions are found in the details for calibration Case1A.

Results and Error Analysis

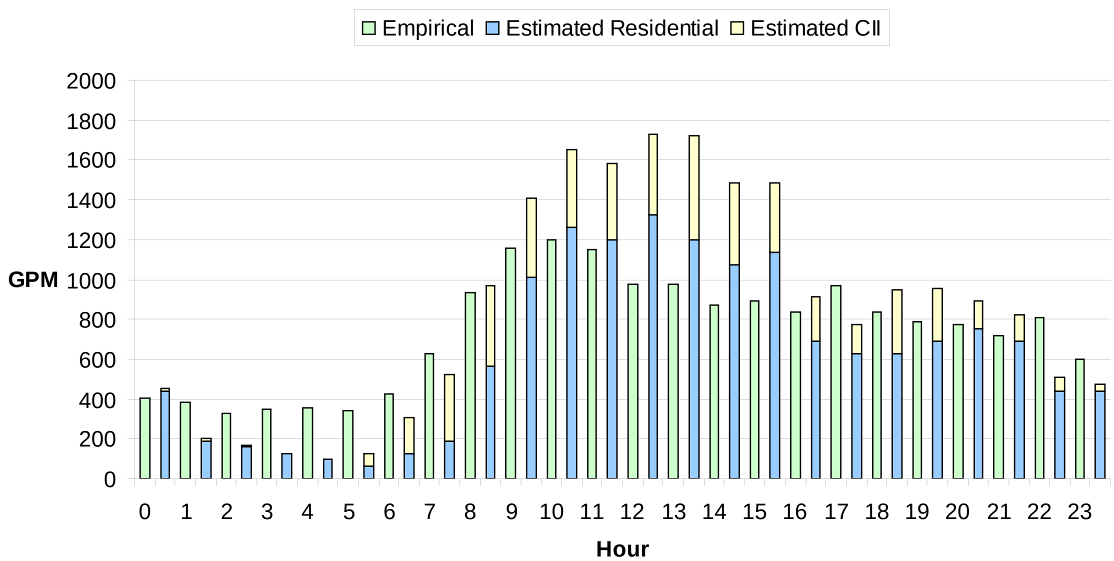

Figure G.1. The total empiric and estimated Case 1A-PZ6 hourly demands for pressure zone 6 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 6 at each one-hour time step.

Table G.1. Results and error measures for Validation Case 1A-PZ6. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1A-PZ6 Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	846	
Total Empiric Demand	737	
Total % Difference	15%	
Total Estimated Residential Demand	630	74%
Total Estimated CII Demand	216	26%
Relative Error	36%	

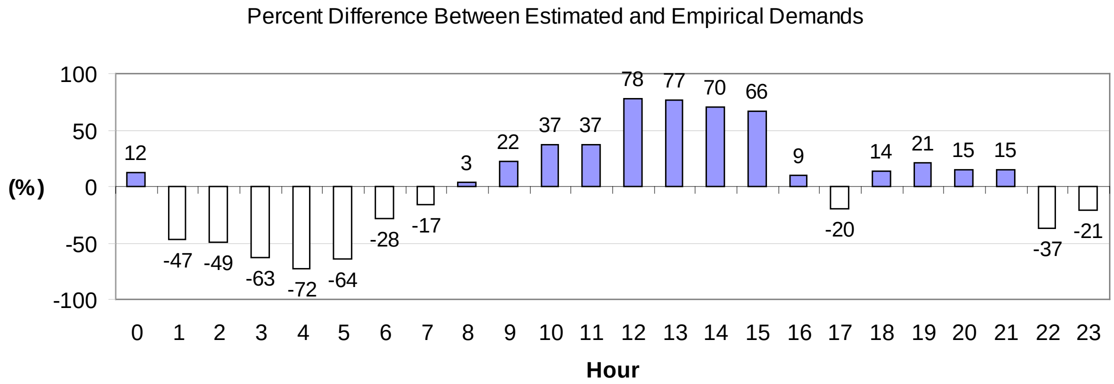

Figure G.2. The percent difference between the estimated Case 1A-PZ6 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

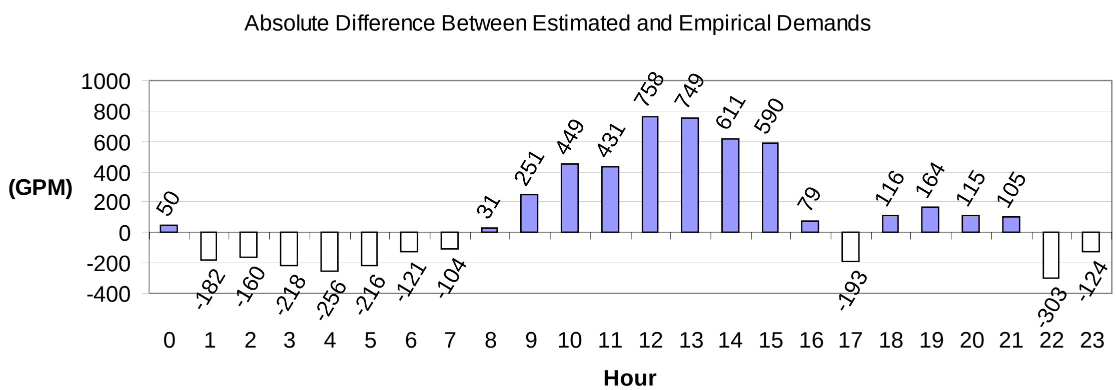

Figure G.3. The absolute difference in GPM between the estimated Case 1A-PZ6 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1A-PZ8

Description: The case examines the use of the calibration case (Case 1A) to estimate the water demand for pressure zone 8. The input parameters and assumptions are found in the details for calibration Case1A.

Pressure zone 8 was selected for validation because it has different land use characteristics than pressure zone 5 or pressure zone 6. There is less residential land use area and more industrial land use area. Applying the calibrated method to this pressure zone could be a more significant test of how well the approach will work because the land use characterization is less similar between the pressure zones 5 and 8.

Results and Error Analysis

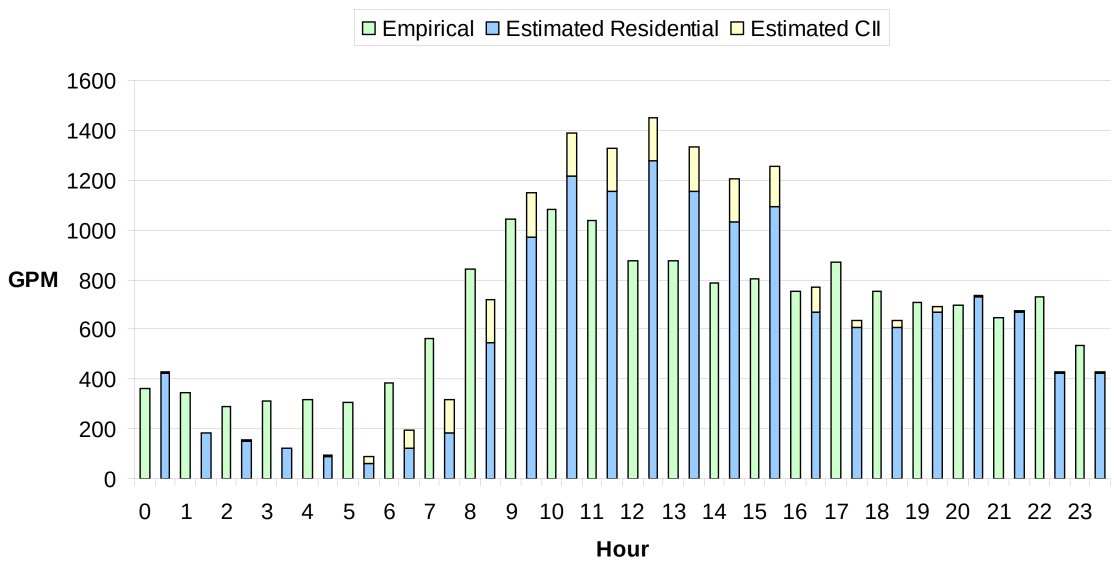

Figure G.4. The total empiric and estimated Case 1A-PZ8 hourly demands for pressure zone 8 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 8 at each one-hour time step.

Table G.2. Results and error measures for Validation Case 1A-PZ8. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1A-PZ8 Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	684	
Total Empiric Demand	663	
Total % Difference	3%	
Total Estimated Residential Demand	607	89%
Total Estimated CII Demand	77	11%
Relative Error	32%	

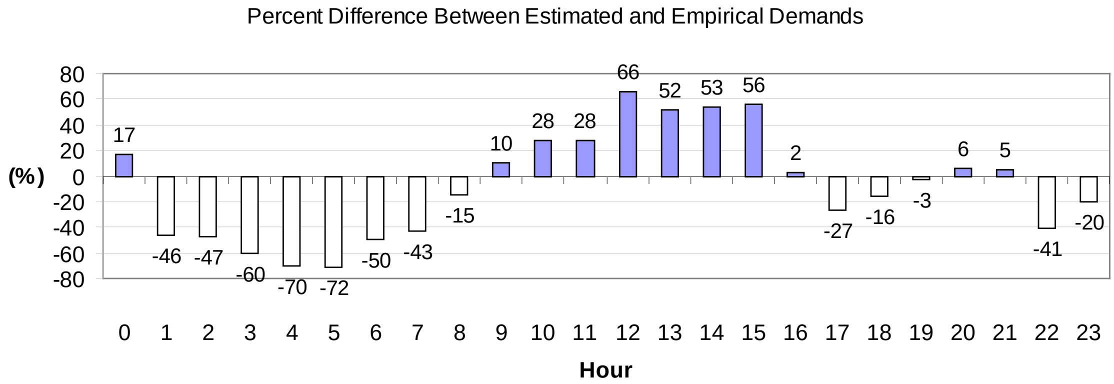

Figure G.5. The percent difference between the estimated Case 1A-PZ8 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

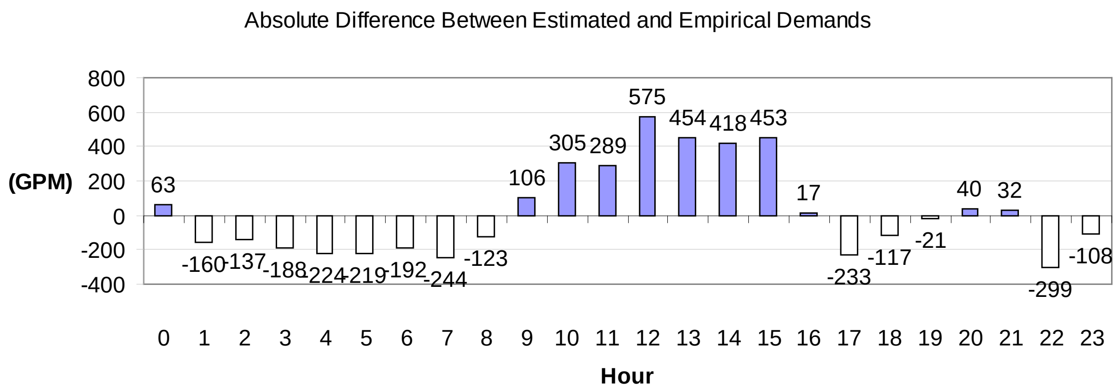

Figure G.6. The absolute difference in GPM between the estimated Case 1A-PZ8 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1A-PZ2

Description: The case examines the use of the calibration case (Case 1A) to estimate the water demand for pressure zone 2. The input parameters and assumptions are found in the details for calibration Case1A.

Pressure zone 2 was selected for validation because it has different land use characteristics than pressure zones 5, 6 or 8. Compare to the calibration pressure zone 5, pressure zone 2 has more residential land use area, more industrial land use area, and much less commercial land use area.

Results and Error Analysis

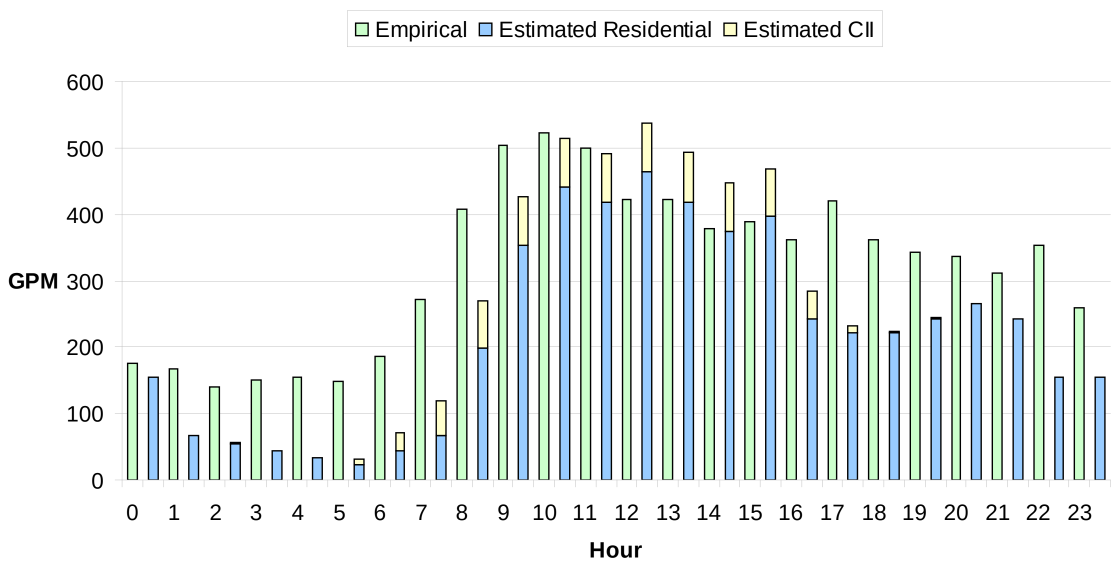

Figure G.7. The total empiric and estimated Case 1A-PZ2 hourly demands for pressure zone 2 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 2 at each one-hour time step.

Table G.3. Results and error measures for Validation Case 1A-PZ2. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1A-PZ2 Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	251	
Total Empiric Demand	320	
Total % Difference	22%	
Total Estimated Residential Demand	221	88%
Total Estimated CII Demand	31	12%
Relative Error	30%	

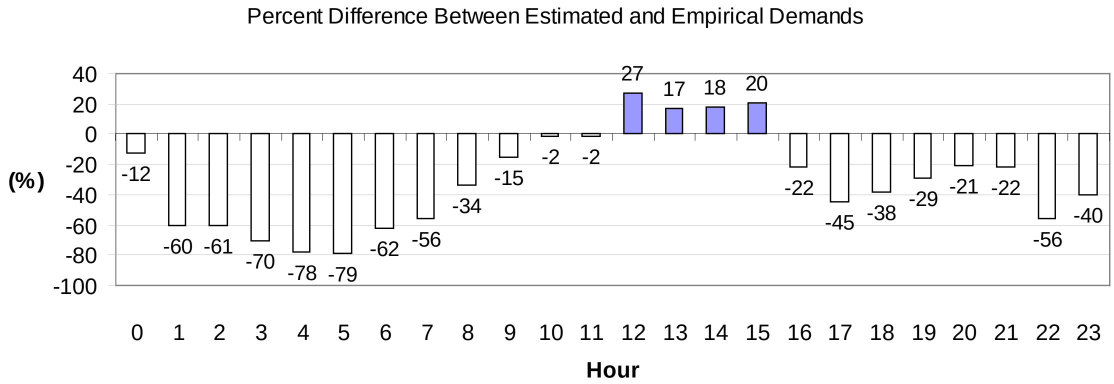

Figure G.8. The percent difference between the estimated Case 1A-PZ2 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

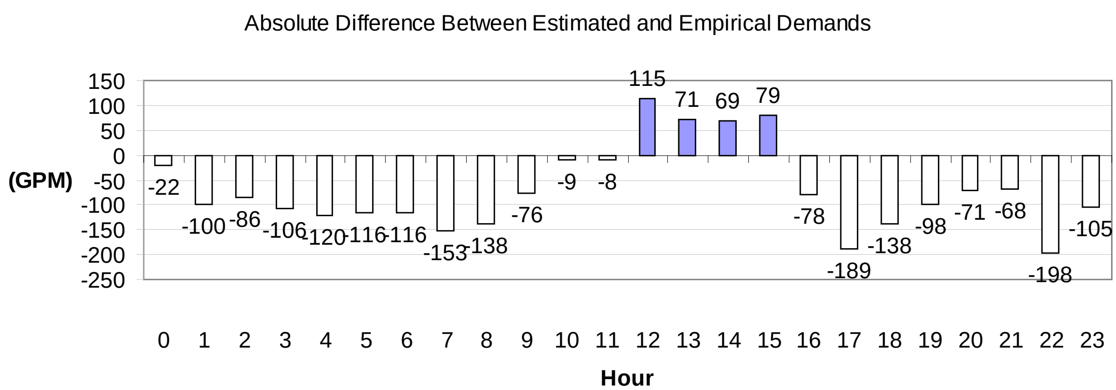

Figure G.9. The absolute difference in GPM between the estimated Case 1A-PZ2 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1J-PZ6

Description: The case examines the use of the calibration case (Case 1J) to estimate the water demand for pressure zone 6. The input parameters and assumptions are found in the details for calibration Case1J.

Results and Error Analysis

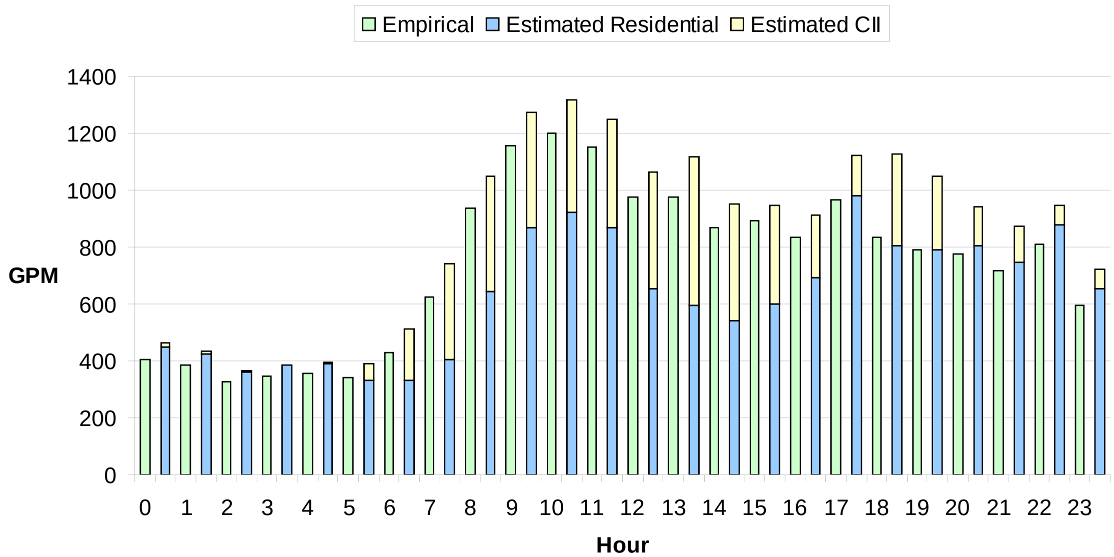

Figure G.10. The total empiric and estimated Case 1J-PZ6 hourly demands for pressure zone 6 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 6 at each one-hour time step.

Table G.4. Results and error measures for Validation Case 1J-PZ6. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1J-PZ6 Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	846	
Total Empiric Demand	737	
Total % Difference	15%	
Total Estimated Residential Demand	630	74%
Total Estimated CII Demand	216	26%
Relative Error	15%	

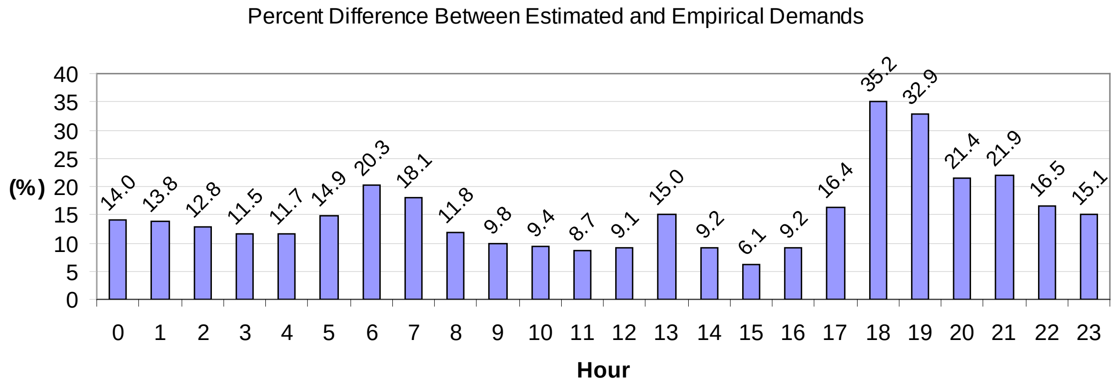

Figure G.11. The percent difference between the estimated Case 1J-PZ6 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

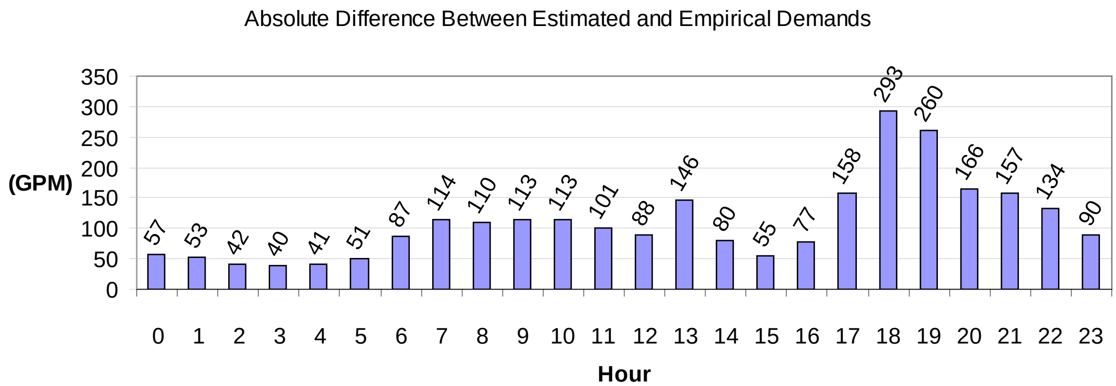

Figure G.12. The absolute difference in GPM between the estimated Case 1J-PZ6 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1J-PZ8

Description: The case examines the use of the calibration case (Case 1J) to estimate the water demand for pressure zone 8. The input parameters and assumptions are found in the details for calibration Case1J.

Pressure zone 8 was selected for validation because it has different land use characteristics than pressure zone 5 or pressure zone 6. There is less residential land use area and more industrial land use area. Applying the calibrated method to this pressure zone could be a more significant test of how well the approach will work because the land use characterization is less similar between the pressure zones 5 and 8.

Results and Error Analysis

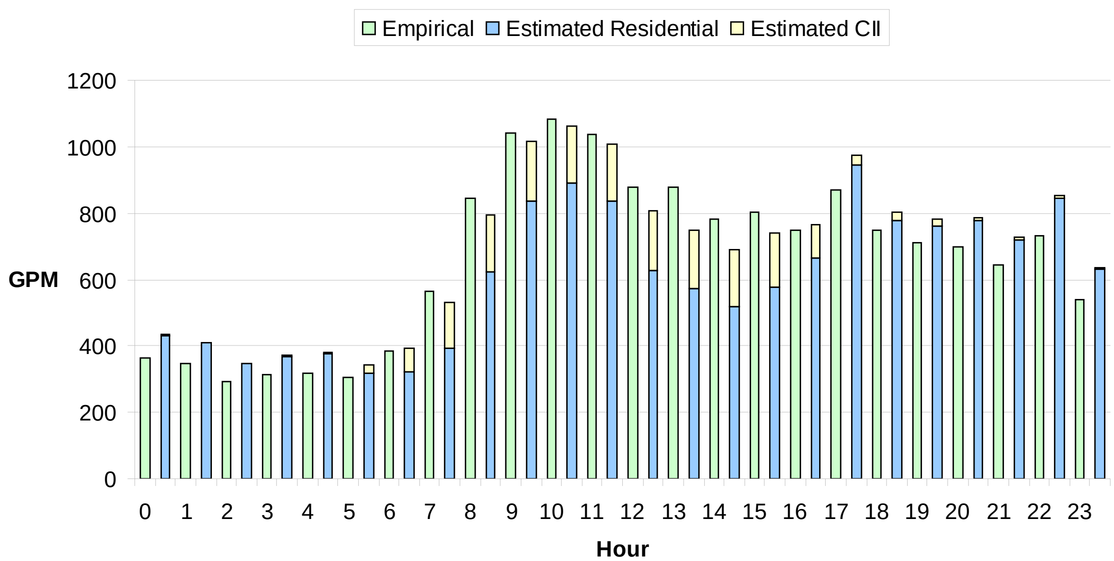

Figure G.13. The total empiric and estimated Case 1J-PZ8 hourly demands for pressure zone 8 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 8 at each one-hour time step.

Table G.5. Results and error measures for Validation Case 1J-PZ8. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1J-PZ8 Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	677	
Total Empiric Demand	663	
Total % Difference	2%	
Total Estimated Residential Demand	600	89%
Total Estimated CII Demand	77	11%
Relative Error	9%	

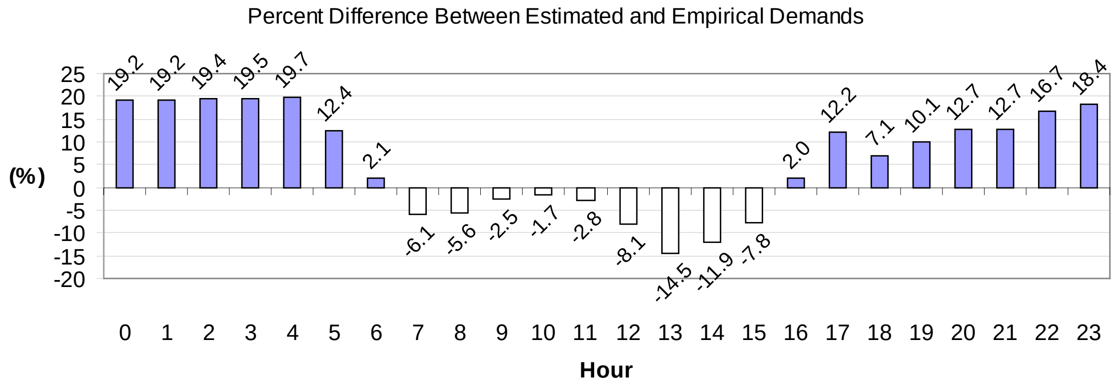

Figure G.14. The percent difference between the estimated Case 1J-PZ8 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

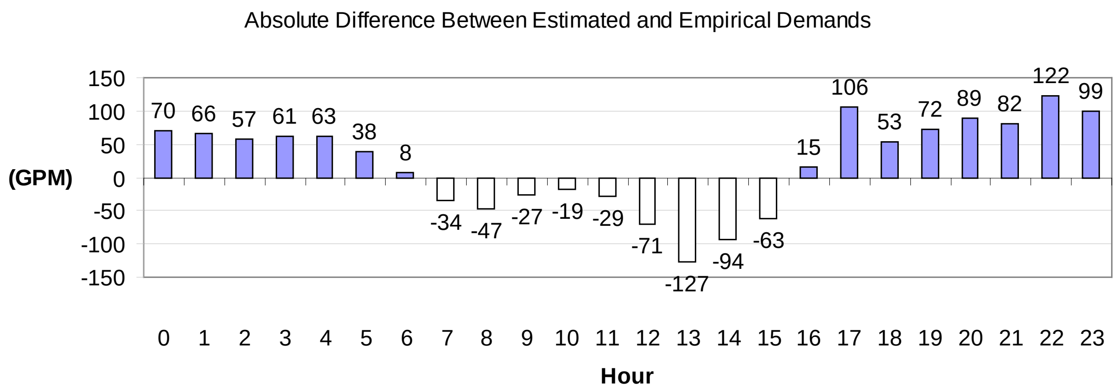

Figure G.15. The absolute difference in GPM between the estimated Case 1J-PZ8 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Case 1J-PZ2

Description: The case examines the use of the calibration case (Case 1J) to estimate the water demand for pressure zone 2. The input parameters and assumptions are found in the details for calibration Case1J.

Pressure zone 2 was selected for validation because it has different land use characteristics than pressure zones 5, 6 or 8. Compare to the calibration pressure zone 5, pressure zone 2 has more residential land use area, more industrial land use area, and much less commercial land use area.

Results and Error Analysis

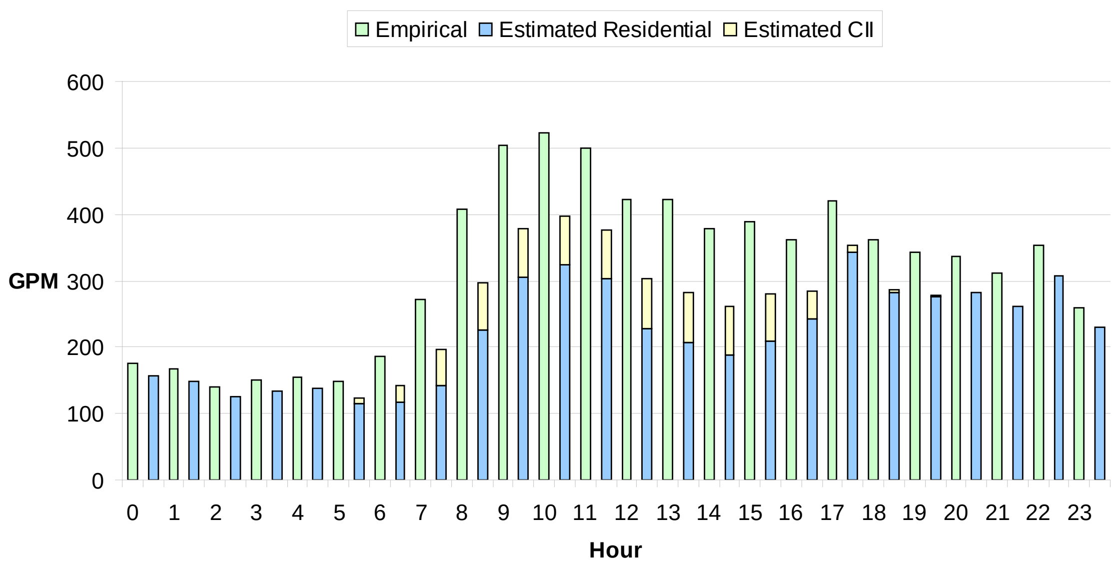

Figure G.16. The total empiric and estimated Case 1J-PZ2 hourly demands for pressure zone 2 are shown, with a breakdown of estimated residential and CII components indicated. The demand is aggregated across pressure zone 2 at each one-hour time step.

Table G.6. Results and error measures for Validation Case 1J-PZ2. The demand units are GPD. The percentage contributions of the residential and CII components to the total estimated demand are shown in the right column.

Case 1J-PZ2 Error Metrics		
(Demand units are GPM)		
Total Estimated Demand	251	
Total Empiric Demand	320	
Total % Difference	22%	
Total Estimated Residential Demand	221	88%
Total Estimated CII Demand	31	12%
Relative Error	22%	

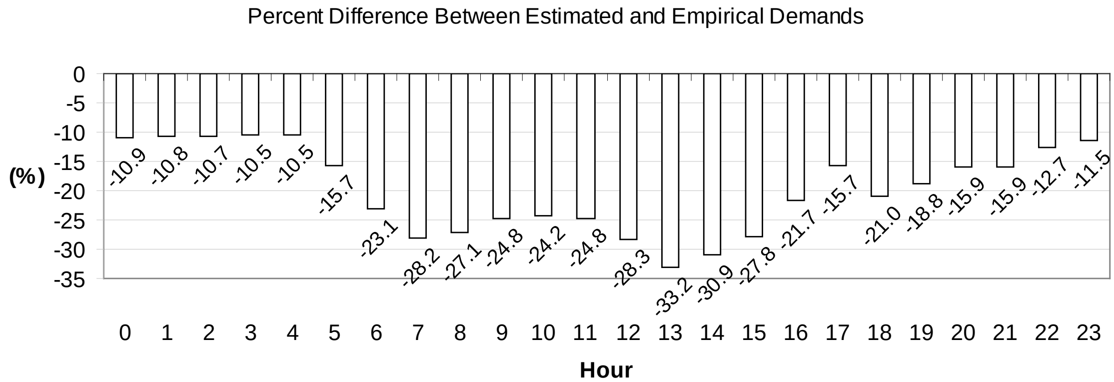

Figure G.17. The percent difference between the estimated Case 1J-PZ2 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

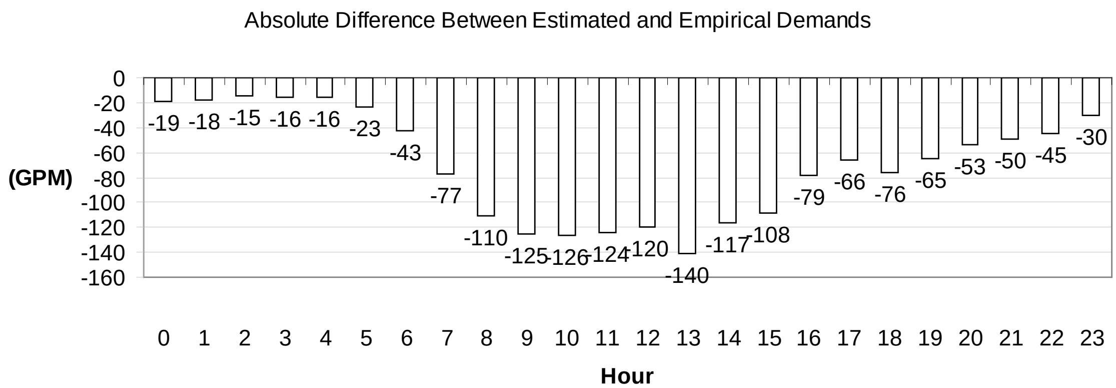

Figure G.18. The absolute difference in GPM between the estimated Case 1J-PZ2 and the empiric hourly demands is shown. The bars above the X-axis (positive values) indicate the demand was overestimated; the bars under the X-axis (negative values) indicate the demand was underestimated.

Appendix H: Empiric and methodology data issues

Considerations with the Empiric Data

Weekday versus Weekend Water Use Pattern

There are fundamental differences between weekday and weekend water use patterns (Homwongs *et al.* 1994; Buchberger and Wells 1996; Haestad 2003). Though the desire was to obtain empiric water demand data representative of a weekday, the actual water use pattern provided by the empiric data is for a Saturday. The SCADA data used to derive the empiric system-wide water use pattern were collected on Saturday, February 9, 2008.

Discrepancy between Local Time and SCADA System Clock Time

The empiric water demand data for the City water distribution system was developed by a consulting firm as part of a contract to create the 2009 Master Plan (Brown and Caldwell 2009). Appendix E summarizes the approach used by the consultant to estimate the empiric demand. One issue, identified within the Master Plan, was that the consultant suggested that the SCADA clock may have been offset (i.e., set forward) by several hours. This judgment was based on a shift in time between the expected peak times and the peaks of the diurnal water use pattern derived from the SCADA data. These SCADA data were collected for the day of February 9, 2008.

As part of this research, new SCADA data were collected for the City system and water use patterns were derived for Wednesday, April 29, 2009, (i.e., representative of a weekday) and for Saturday, April 25, 2009. (See Appendix I for details on the derivation of these daily diurnal water use patterns.) In addition, the water use pattern was derived using the same data collected on February 9, 2008, that had been utilized by the consultant. The process of deriving the original use pattern and the two new use patterns revealed that the water use pattern derived by the consultant was correct. However, there were two contributing factors related to the consultants' opinion that the SCADA clock was offset from local time. First, the clock on the SCADA system is not adjusted for Daylight Saving Time. The original data were collected during Daylight Saving Time and, therefore, there was a one-hour difference between SCADA time and local time. The second and more influential factor was that the SCADA data used by the consultants were collected on a Saturday. By deriving the new patterns for a Wednesday and a Saturday, it was revealed that these water demand patterns are fundamentally different. The morning peak water demand for a Wednesday (i.e., representative of a weekday) occurs 2-3 hours earlier than the morning peak of the Saturday.

In order to compare the water use pattern used for the 2009 Master Plan with the water use pattern derived for this research, the SCADA data had to be based on the same time stamp and at the same resolution (i.e., collection period). However, the two datasets

were based on different SCADA times and on different collection periods. To adjust the more recently collected SCADA data to conform with the 2009 Master Plan data, Visual Basic for Applications (VBA) scripts were developed. The VBA scripts to temporally aggregate the SCADA measurements and perform a linear interpolation of values are shown in Appendix J.

Water Use Pattern Multiplication Factors

The empiric system water use pattern introduces a small error into the methods for calibration and validation. The empiric pattern represents 24 one-hour dimensionless multiplication factors. The factors are used to scale the base demand at each demand junction to the representative levels for each one-hour period. To provide a dimensionless set of factors for the 24-hour period, the average of the 24 hourly factors must be 1. Stated another way, the sum of the factors must be 24. The issue with the empiric pattern is that the factors sum to 23.98. This results in a difference of .083% between the total base demand for any junction and the sum of its 24 hourly demand components.

Empiric Hydraulic Model from 2009 Master Plan was Unusable within EPANET

The original intent of the research was to use the EPANET hydraulic analysis software with the empiric hydraulic model provided by the 2009 Master Plan. This would have allowed a detailed analysis of the effects of using estimated demands on the hydraulic behavior for the Santa Fe system. However, Brown and Caldwell used a different hydraulic analysis software package. When the model was exported to the EPANET format, there were errors. Attempts at calculating hydraulic solutions using the exported model resulted in discrepancies between the calibrated model and the field measurements used to create the model. Therefore, it was not possible to run hydraulic cases using the estimated demand for comparison with the empiric model. If a hydraulically solvable pipeline network with demands had been provided, further and more detailed analysis could have been performed

Considerations with the Methodology Data

Commercial, Industrial, and Institutional Facilities Data

The CII facilities are obtained from the Dun and Bradstreet facilities database. Each facility is classified with a facility type. In some cases, the facility type is not defined. In these cases, no assumptions are made about water use rates per employee, so that no water use is assigned to these facilities. In addition, the geolocation (i.e., latitude and longitude of the facility) of some facilities is suspect. The geolocation was likely obtained through address matching which can vary widely in positional accuracy. Errors are also introduced when an address represents a location other than the actual facility location, such as a mailing address.

Selected Service Areas within Pressure Zones for Analysis

In some cases, the service area for a particular junction overlapped two or more pressure zones. For these cases, judgment was used to associate the service area with one pressure zone or another for calibration and validation analyses. For example, in some cases, the majority of a service area was within one pressure zone while its associated demand junction could be located in an adjacent pressure zone.

Appendix I: How to derive the system-wide 24-hour use pattern

The daily water use patterns for a Wednesday (i.e., a weekday) and a Saturday were derived using SCADA data acquired from the City of Santa Fe Water Division. In addition, the water use pattern for February 9, 2008, was derived. The SCADA data from this day were used to derive the empiric system water use pattern. This was done not only to validate the procedure and the resulting pattern but also to better understand the details of what the process entails.

The data required to develop a system use pattern are production data and tank data. The production data are inputs into the water system, and include wells and treatment plants. The tank data include water levels. All the SCADA data are dynamic and represent measurements at some time interval.

These include wells and reservoirs.

- Derivation of system water demand pattern/curve
  - Tank data
  - Production data
  - Formula for mass balance (Haestad 2003)
  - Formula for tank related demand contributions
  - Graphs of derived pattern for Wed in April, Sat in April, calibrated model pattern

Below is the mass balance equation for examining dynamic water demand behavior (Haestad 2003). It equates demand with water production (i.e., water injected into the system) minus outflows, plus adjustments due to changing water tank levels (i.e., a tank that is storing water represents water that is not being consumed by customers and a tank that is draining represents water that is being consumed). The equation is based on units of flow (i.e., volume per time) and can therefore be used for any number of time resolutions.

Mass Balance Equation

$$Q_{demand} = Q_{inflow} - Q_{outflow} + \Delta V_{storage} / \Delta t$$

where Q_{inflow} = average rate of production (cfs, m^3/s)

Q_{demand} = average rate of demand (cfs, m^3/s)

$Q_{outflow}$ = average outflow rate (cfs, m^3/s)

$\Delta V_{storage}$ = change in storage within the system (ft^3, m^3)

Δt = time between volume measurements (s)

(Haestad 2003)

Appendix J: VBA scripts for synchronizing SCADA measurements

The following Visual Basic for Applications (VBA) scripts were developed to adjust the SCADA measurements collected for the research so that they match the time stamp and temporal resolution of the SCADA measurements for the 2009 Master Plan (i.e., the empiric data). These scripts were important in helping to understand issues related to the SCADA measurements used for the 2009 Master Plan.

Listing of VBA basic module (basAverageValuesOverPeriod) to temporally aggregate and time-shift SCADA measurements to match a target start time and interval. The method uses a linear approach.

```
Option Explicit

'Use this to calculate average values over some period where the
' temporal resolution of the data is different (eg., finer) and
' possibly time-offset.

'Nomenclature: with variable names and comments, REFERENCE refers to the input times and
' corresponding measurements; TARGET refers the desired times at which the average will
' be calculated.
'
' The FIRST reference time is lower or equal in time value to TARGET START time
' The LAST reference time is last time value within TARGET END TIME

'For example, for the following REFERENCE times/values, what is the 1-hour average for
' the period centered at 1:00:00?
'0:03:06 4990.551087
'0:14:35 5194.160061
'0:26:04 5720.545721
'0:37:32 5328.735813
'0:49:01 5283.248816
'1:00:30 4999.632644
'1:11:59 5239.120525
'1:23:28 5484.760533
'1:34:57 5522.820891
'1:46:25 5213.188058
'1:57:54 5335.192012
'2:09:23 5280.160591
'2:20:52 5182.985833
'2:32:21 4657.107191
'2:43:50 4761.861344
'2:55:18 4806.924208
'3:06:47 5446.886792

'For the desired TARGET average at 1:00:00, the TARGET period for the example data above is
' 12:30:00 to 1:30:00

'Times are in format: hour:minute:second, e.g., 22:31:01, as string and converted to
' and used as minutes within this code;

Dim sPath As String
Dim sReferenceFilename As String        'input file of original times and measured values
Dim sTargetFilename As String           'input file of times at which average will be calculated
Dim sOutputAveragesFilename As String   'output filename for target times and calculated values

'REFERENCE times/values are the original times/measurements
Dim colReferenceTimes As Collection     'collection of times at which average for given period
                                        ' will be calculated -- converted to minutes (double)
Dim colReferenceValues As Collection    'collection of double y values

'TARGET times are the times at which the average will be calculated; the TARGET values
```

```
' are the interpolated values that are the output of this module
Dim colTargetTimesHHMMSS As Collection  'collection of target times in HH:MM:SS format
Dim colTargetTimes As Collection        'collection of target times as minutes (double)
Dim colTargetValues As Collection       'collection of double y values (to be derived)
Dim colTargetSumOfValues As Collection    'sum of y values used to derive above
Dim colTargetDivisorFactor As Collection  'divisor factor for y values to derive above

'TARGET period is the time period over which the values will be averaged
Dim dTargetPeriodMin As Double          'period of time window in minutes


Private Sub initVars()

   sPath = "C:\THESIS (primary) reconcile with other\Workspace City of SF SCADA Data - apr 1 week\9feb08_onthehalfhour"
   sReferenceFilename = sPath + "/" + "REFERENCE-TIMES-VALUES.txt"
   sTargetFilename = sPath + "/" + "TARGET-TIMES.txt"
   sOutputAveragesFilename = sPath + "/" + "CalculatedAverages-TargetTimesVals.txt"
   dTargetPeriodMin = 60#

End Sub

Public Sub performCalculation()

   initVars

   Dim sStatus As String
   sStatus = readReferenceValuesFromFile(sReferenceFilename)
   If sStatus <> "" Then
      MsgBox "Unable to read file: " + sStatus
      Exit Sub
   End If

   sStatus = readTargetTimesFromFile(sTargetFilename)
   If sStatus <> "" Then
      MsgBox "Unable to read file: " + sStatus
      Exit Sub
   End If

   sStatus = calculateAverageValues()
   If sStatus <> "" Then
      MsgBox "Unable to calculate average values: " + sStatus
      Exit Sub
   End If

   sStatus = writeTimesAndValuesFile(sOutputAveragesFilename)
   If sStatus <> "" Then
      MsgBox "Unable to write values to file: " + sStatus
      Exit Sub
   End If

   MsgBox "done"
End Sub

'this reads x-ref and y-ref that are space delimited - times are in 00:00:00 format
Private Function readReferenceValuesFromFile(sfilename As String) As String
  On Error GoTo errHand

   Set colReferenceTimes = New Collection
   Set colReferenceValues = New Collection

   Dim fs, a
   Dim sLine As String
   Dim sTemp As String
   Dim iLoc As Integer
   Dim dReferenceTimeInMinutes As Double

   Set fs = CreateObject("Scripting.FileSystemObject")
   Set a = fs.openTextFile(sfilename)

   'read from line: x-ref, y-ref, target x val but space-delimited
```

```
    Do Until a.atendofstream
        sLine = a.readline
        sLine = Trim(sLine)

        iLoc = InStr(sLine, " ")
        sTemp = Trim(Left(sLine, iLoc))
        dReferenceTimeInMinutes = convertHMStoMin(Trim(sTemp))
        colReferenceTimes.Add dReferenceTimeInMinutes

        sTemp = Mid(sLine, iLoc + 1)
        colReferenceValues.Add Val(sTemp)
    Loop

  a.Close

  readReferenceValuesFromFile = ""
  GoTo cleanup
errHand:
  readReferenceValuesFromFile = "could not read values from file"
cleanup:
  Set fs = Nothing
  Set a = Nothing
End Function

'this reads target times for averages, one per line, in format 00:00:00
Private Function readTargetTimesFromFile(sfilename As String) As String
  On Error GoTo errHand

    Set colTargetTimes = New Collection
    Set colTargetTimesHHMMSS = New Collection

    Dim fs, a
    Dim sLine As String
    Dim dTimeInMinutes As Double

    Set fs = CreateObject("Scripting.FileSystemObject")
    Set a = fs.openTextFile(sfilename)

    'read from line: x-ref, y-ref, target x val but space-delimited
    Do While Not a.atendofstream
        sLine = a.readline
        colTargetTimesHHMMSS.Add (Trim(sLine))
        dTimeInMinutes = convertHMStoMin(Trim(sLine))

        colTargetTimes.Add Trim(dTimeInMinutes)
    Loop

    a.Close

    readTargetTimesFromFile = ""
    GoTo cleanup
errHand:
    readTargetTimesFromFile = "could not read values from file"
cleanup:
    Set fs = Nothing
    Set a = Nothing
End Function

'string format is HH:MM:SS, where HH can be 1 or 2 digits and the minutes and seconds are always 2 digits
Private Function convertHMStoMin(sHMS As String) As Double
    Dim iLen As Integer
    Dim iLoc As Integer

    Dim iHour As Integer
    Dim iMinute As Integer
    Dim iSecond As Integer

    Dim sTemp As String

    iLoc = InStr(sHMS, ":")
```

```
    iHour = Val(Left(sHMS, iLoc + 1))
    iLen = Len(sHMS)

    sTemp = Right(sHMS, iLen - iLoc)
    iMinute = Val(Left(sTemp, 2))
    iSecond = Val(Right(sTemp, 2))

    Dim dMinutes As Double
    dMinutes = (iHour * 60) + iMinute + (iSecond / 60)

    convertHMStoMin = dMinutes
End Function

Private Function writeTimesAndValuesFile(sfilename) As String
    On Error GoTo errHand

    Dim fs, a
    Dim sLine As String
    Dim sTime As String
    Dim dValue As Double
    Dim lIdx As Long

    Set fs = CreateObject("Scripting.FileSystemObject")
    Set a = fs.createTextFile(sOutputAveragesFilename)

    'write times and average values to file
    a.writeline ("TIME" + " " + "AVGVAL")
    For lIdx = 1 To colTargetValues.Count
        sTime = colTargetTimesHHMMSS.Item(lIdx)
        dValue = colTargetValues.Item(lIdx)

        a.writeline (Trim(sTime) + " " + Trim(Str(dValue)))
    Next

    a.Close

    writeTimesAndValuesFile = ""
    GoTo cleanup
errHand:
    writeTimesAndValuesFile = "could not write values to file"
cleanup:
    Set fs = Nothing
    Set a = Nothing
End Function

Private Function calculateAverageValues() As String

    Set colTargetValues = New Collection
    Set colTargetSumOfValues = New Collection
    Set colTargetDivisorFactor = New Collection

    Dim dCurrentTargetTime As Double
    Dim dStartTime As Double
    Dim dEndTime As Double
    Dim dRefStartTime As Double
    Dim lRefStartTimeIndex As Long
    Dim dRefTime1 As Double
    Dim dRefEndTime As Double
    Dim lRefEndTimeIndex As Long
    Dim dRefTime2 As Double
    Dim lIdx As Long
    Dim lIdx2 As Long
    Dim lIdx3 As Long
    Dim bFoundStart As Boolean
    Dim bFoundEnd As Boolean

    'variables to calculate average using start-end times
    Dim lIdx4 As Long
    Dim dFirstReferenceTime As Double
    Dim dNextReferenceTime As Double
```

```
Dim dLastReferenceTime As Double
Dim dSumOfValues As Double
Dim dDivisor As Double

'for all target times - this assumes that the are sorted in increasing-order
For lIdx = 1 To colTargetTimes.Count

    'set start and end times for period of average
    dCurrentTargetTime = colTargetTimes.Item(lIdx)
    dStartTime = dCurrentTargetTime - (dTargetPeriodMin / 2#)
    dEndTime = dCurrentTargetTime + (dTargetPeriodMin / 2#)

    'find reference times that are before and after the current target time
    'this assumes that reference times are sorted in increasing-order

    'get reference time <= to start time
    bFoundStart = False
    For lIdx2 = 1 To colReferenceTimes.Count

        dRefTime1 = colReferenceTimes.Item(lIdx2)

        'look for first reference time that's greater than average-window start
        ' time, then get previous value
        If dRefTime1 > dStartTime Then
            If lIdx2 = 1 Then  'issue: first value has no prior value
                bFoundStart = False
            Else
                bFoundStart = True
            End If
            Exit For
        End If

    Next

    If bFoundStart Then
        lRefStartTimeIndex = lIdx2 - 1
        dRefStartTime = colReferenceTimes.Item(lIdx2 - 1)
    Else
        lRefStartTimeIndex = -9999
        dRefStartTime = -9999
    End If

    'get reference time >= to end time
    bFoundEnd = False
    For lIdx3 = 1 To colReferenceTimes.Count

        dRefTime2 = colReferenceTimes.Item(lIdx3)

        'get first reference time that is > the average-window end time
        If dRefTime2 > dEndTime Then
            bFoundEnd = True
            Exit For
        End If

    Next

    If bFoundEnd Then
        lRefEndTimeIndex = lIdx3 - 1 'is actually the time value prior to lIdx3
        dRefEndTime = colReferenceTimes.Item(lRefEndTimeIndex)
    Else
        lRefEndTimeIndex = -9999
        dRefEndTime = -9999
    End If

    dSumOfValues = 0
    dDivisor = 0
    If bFoundStart And bFoundEnd Then

        'consider first value
        dFirstReferenceTime = colReferenceTimes.Item(lRefStartTimeIndex)
```

```
        If dFirstReferenceTime < dStartTime Then
            'subtract end time of 1st reference time (this is the 2nd reference time)
            ' from start time to get percentage of reference time within target time range
            dNextReferenceTime = colReferenceTimes.Item(lRefStartTimeIndex + 1)
            dDivisor = dDivisor + _
                ((dNextReferenceTime - dStartTime) / (dNextReferenceTime - dFirstReferenceTime))
            dSumOfValues = dSumOfValues + _
                (((dNextReferenceTime - dStartTime) / (dNextReferenceTime - dFirstReferenceTime)) _
                * colReferenceValues.Item(lRefStartTimeIndex))
        Else
            'else entire range is within target start-end time
            dDivisor = dDivisor + 1
            dSumOfValues = dSumOfValues + colReferenceValues.Item(lRefStartTimeIndex)
        End If

        'calculate average of values within start and end times
        For lIdx4 = lRefStartTimeIndex + 1 To lRefEndTimeIndex - 1

            dSumOfValues = dSumOfValues + colReferenceValues.Item(lIdx4)
            dDivisor = dDivisor + 1

        Next

        'consider last value
        dLastReferenceTime = colReferenceTimes.Item(lRefEndTimeIndex)
        dNextReferenceTime = colReferenceTimes.Item(lRefEndTimeIndex + 1)
        If dNextReferenceTime > dEndTime Then
            'subtract end time of 1st reference time (this is the 2nd reference time)
            ' from start time to get percentage of reference time within target time range
            dDivisor = dDivisor + _
                ((dEndTime - dLastReferenceTime) / (dNextReferenceTime - dLastReferenceTime))
            dSumOfValues = dSumOfValues + _
                (((dEndTime - dLastReferenceTime) / (dNextReferenceTime - dLastReferenceTime)) _
                * colReferenceValues.Item(lRefEndTimeIndex))
        Else
            'else entire range is within target start-end time
            dDivisor = dDivisor + 1
            dSumOfValues = dSumOfValues + colReferenceValues.Item(lRefEndTimeIndex)
        End If

        colTargetSumOfValues.Add dSumOfValues
        colTargetDivisorFactor.Add dDivisor

        colTargetValues.Add dSumOfValues / dDivisor

    Else 'cannot calculate average -- missing info -- plug in placeholder of -9999
        colTargetSumOfValues.Add -9999
        colTargetDivisorFactor.Add -9999

        colTargetValues.Add -9999
    End If

  Next

  calculateAverageValues = ""

End Function
```

Listing of VBA basic module (basInterpolateWaterDemandValues) to read in water demand values at one time resolution and time stamp interval, and interpolate values for a different time resolution and time stamp interval.

```
Option Explicit

'Use this to read in water demand values at one time resolution and time stamp interval,
' and interpolate values for a different time resolution and time stamp interval.

'For example, have the following measurements:
'      > time  0:06:29     measurement 3452.33
'      >       0:12:28                 3942.91
'
'and want the interpolated value at time 0:10:00. In this case, the REFERENCE times (see
'variable names and comments) are the two times/measurements above; the TARGET time is
'0:10:00 and the TARGET VALUE is the interpolated value at time 0:10:00.

'The value is interpolated between the two values that are above and below the value.

'Nomenclature:
'           > reference - refers to recorded times/measurements
'           > target    - refers the times/values at which values will be interpolated

'Times are in format: hour:minute:second, e.g., 22:31:01, as string and converted to
' and used as minutes within this code;

'See PSEUDO CODE at end of this module

Dim sPath As String
Dim sReferenceFilename As String
Dim sTargetFilename As String
Dim sinterpolatedvalsfilename As String
Dim colReferenceTimes As Collection     'collection of reference times as minutes (double)
Dim colReferenceValues As Collection    'collection of double y values
Dim colTargetTimes As Collection        'collection of target times as minutes (double)
Dim colTargetValues As Collection       'collection of double y values (to be interpolated)


Private Sub initVars()

   sPath = "C:\THESIS (primary) reconcile with other\Workspace City of SF SCADA Data - apr 1 week"
   sReferenceFilename = sPath + "/" + "REFERENCE.txt"
   sTargetFilename = sPath + "/" + "TARGET.txt"
   sinterpolatedvalsfilename = sPath + "/" + "output-interpolatedTargetVals.txt"

End Sub

Public Sub performCalculation()

   initVars

   Dim sStatus As String
   sStatus = readReferenceValuesFromFile(sReferenceFilename)
   If sStatus <> "" Then
      MsgBox "Unable to read file: " + sStatus
      Exit Sub
   End If

   sStatus = readTargetTimesFromFile(sTargetFilename)
   If sStatus <> "" Then
      MsgBox "Unable to read file: " + sStatus
      Exit Sub
   End If

   sStatus = interpolateValues()
   If sStatus <> "" Then
      MsgBox "Unable to interpolate values: " + sStatus
      Exit Sub
```

```
    End If

    sStatus = writeValuesFile(sinterpolatedvalsfilename)
    If sStatus <> "" Then
        MsgBox "Unable to write values to file: " + sStatus
        Exit Sub
    End If

    MsgBox "done"
End Sub

'this reads x-ref and y-ref that are space delimited
Private Function readReferenceValuesFromFile(sfilename As String) As String
  On Error GoTo errHand

    Set colReferenceTimes = New Collection
    Set colReferenceValues = New Collection
    Set colTargetTimes = New Collection

    Dim fs, a
    Dim sLine As String
    Dim sTemp As String
    Dim iLoc As Integer
    Dim dReferenceTimeInMinutes As Double

    Set fs = CreateObject("Scripting.FileSystemObject")
    Set a = fs.openTextFile(sfilename)

    'read from line: x-ref, y-ref, target x val but space-delimited
    Do Until a.atendofstream
        sLine = a.readline
        sLine = Trim(sLine)

        iLoc = InStr(sLine, " ")
        sTemp = Trim(Left(sLine, iLoc))
        dReferenceTimeInMinutes = convertHMStoMin(Trim(sTemp))
        colReferenceTimes.Add dReferenceTimeInMinutes

        sTemp = Mid(sLine, iLoc + 1)
        colReferenceValues.Add Val(sTemp)
    Loop

  a.Close

  readReferenceValuesFromFile = ""
  GoTo cleanup
errHand:
  readReferenceValuesFromFile = "could not read values from file"
cleanup:
  Set fs = Nothing
  Set a = Nothing
End Function

'this reads target x vals one per line
Private Function readTargetTimesFromFile(sfilename As String) As String
  On Error GoTo errHand

    Set colTargetTimes = New Collection

    Dim fs, a
    Dim sLine As String
    Dim dTimeInMinutes As Double

    Set fs = CreateObject("Scripting.FileSystemObject")
    Set a = fs.openTextFile(sfilename)

    'read from line: x-ref, y-ref, target x val but space-delimited
    Do While Not a.atendofstream
        sLine = a.readline
        dTimeInMinutes = convertHMStoMin(Trim(sLine))
```

```
        colTargetTimes.Add Trim(dTimeInMinutes)
    Loop

    a.Close

    readTargetTimesFromFile = ""
    GoTo cleanup
errHand:
    readTargetTimesFromFile = "could not read values from file"
cleanup:
    Set fs = Nothing
    Set a = Nothing
End Function

Private Function interpolateValues() As String

    Set colTargetValues = New Collection

    Dim dCurrentTime As Double
    Dim lIdx As Long
    Dim lIdx2 As Long
    Dim dRefTime1 As Double
    Dim dRefTime2 As Double
    Dim dRefVal1 As Double
    Dim dRefVal2 As Double
    Dim bFound As Boolean
    Dim dTargetVal As Double

    'for all target times
    For lIdx = 1 To colTargetTimes.Count

        dCurrentTime = colTargetTimes.Item(lIdx)

        bFound = False
        'find reference times that are before and after the current target time
        For lIdx2 = 1 To colReferenceTimes.Count - 1

            dRefTime1 = colReferenceTimes.Item(lIdx2)
            dRefTime2 = colReferenceTimes.Item(lIdx2 + 1)

            If dCurrentTime > dRefTime1 And dCurrentTime < dRefTime2 Then
                bFound = True
                Exit For
            End If

        Next

        If bFound Then
            dRefVal1 = colReferenceValues(lIdx2)
            dRefVal2 = colReferenceValues(lIdx2 + 1)
            dTargetVal = linearlyInterpolate( _
                        dRefTime1, dRefVal1, _
                        dRefTime2, dRefVal2, _
                        dCurrentTime)

            colTargetValues.Add (dTargetVal)
        Else
            colTargetValues.Add (-9999)
        End If

    Next

    interpolateValues = ""
End Function

Private Function linearlyInterpolate(dX1 As Double, dY1 As Double, _
                                dX2 As Double, dY2 As Double, _
                                dTargetX As Double) As Double
```

```
    'equation of line y = mx + b

    Dim m As Double
    m = (dY2 - dY1) / (dX2 - dX1)

    Dim b As Double
    b = dY1 - (m * dX1)

    Dim targetY As Double
    targetY = (m * dTargetX) + b

    linearlyInterpolate = targetY

End Function

'string format is HH:MM:SS, where HH can be 1 or 2 digits and the minutes and seconds are always 2 digits
Private Function convertHMStoMin(sHMS As String) As Double
    Dim iLen As Integer
    Dim iLoc As Integer

    Dim iHour As Integer
    Dim iMinute As Integer
    Dim iSecond As Integer

    Dim sTemp As String

    iLoc = InStr(sHMS, ":")
    iHour = Val(Left(sHMS, iLoc + 1))
    iLen = Len(sHMS)

    sTemp = Right(sHMS, iLen - iLoc)
    iMinute = Val(Left(sTemp, 2))
    iSecond = Val(Right(sTemp, 2))

    Dim dMinutes As Double
    dMinutes = (iHour * 60) + iMinute + (iSecond / 60)

    convertHMStoMin = dMinutes
End Function

Private Function writeValuesFile(sfilename) As String
    On Error GoTo errHand

    Dim fs, a
    Dim sLine As String
    Dim dValue As Double
    Dim lIdx As Long

    Set fs = CreateObject("Scripting.FileSystemObject")
    Set a = fs.createTextFile(sinterpolatedvalsfilename)

    'write values to file
    For lIdx = 1 To colTargetValues.Count
        dValue = colTargetValues.Item(lIdx)

        a.writeline (Trim(Str(dValue)))
    Next

    a.Close

    writeValuesFile = ""
    GoTo cleanup
errHand:
    writeValuesFile = "could not write values to file"
cleanup:
    Set fs = Nothing
    Set a = Nothing
End Function

'--------------------pseudo code and examples-----------------
```

```
'
'read in array of sorted "new time" steps
'read in array of sorted "reference time" steps and reference values (use same index)
'
'for each 'new time value'
'
'    find the two 'reference time'/'reference values' entries that contain the current 'new time
'
'Value '
'
'        interpolate value for "new time" using linear approach and containing "reference"
' times/values
'
'end for
'
'
'Pseudo Code with More Detail and Examples
'
'nt = new time array
'nv = new value array
'rt = reference time array
'rv = reference value array
'
'for all new times
'
'    get nt (initial = 0:03:06)
'
'    Do Until nt > rt1 And nt < rt2
'
'
'    end do
'
'    calc new time value
'
'end for
'
'Equation of a Line
'calc new time value (x1, y1 (val1), x2, y2 (val2), nx, ny) val
'
'Y = mx + b
'
'm = (y2 - y1) / (x2 - x1)
'
'b: let x = 0 then b = y
'
'
'Example
'
'(1,0) to (2,2)
'
'm = 2 - 0 / 2 - 1 = 2
'
'y = 2x + b
'
'b = y - 2x = 0 - 2 = -2 (at x=1, y=0)
'
'so, y = 2x - 2
'
'at x=1.5, y = 2 (1.5) – 2 = 3 – 2 = 1
'
'x = 1.5, y = 1
'
'--------------------end of pseudo code and examples-----------------
```