# IMPROVEMENTS AND ASSESSMENTS OF WATER AUDITING TECHNIQUES

A Thesis

by

SARAH RUTH MEYER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2006

Major Subject:  Civil Engineering

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# ABSTRACT

Improvements and Assessments of Water Auditing Techniques.

(December 2006)

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Chair of Advisory Committee: Dr. J. Kelly Brumbelow

Water auditing is an emerging method of increasing accountability for water utility systems. A water loss audit according to the methodology of the International Water Association (IWA) is applied to a major North American water utility, San Antonio Water System (SAWS), which is already a leader in conservation policies. However, some modifications to the auditing process are needed for this model's application to a North American utility. These improvements to the IWA methodology include: calculating system input volume from multiple methods of measurements as well as numerous input points, incorporating deferred storage consumption (in this case aquifer storage and recovery) principles into the auditing process, calculating a volume of unavoidable annual real losses (allowable leakage) for a system with varied pressure zones, and defining procedures for assessing customer meter accuracy for a system. Application of the improved IWA audit method to SAWS discovered that its system input volume is being significantly undermeasured by current practices, current water loss control programs are very effective, customer accounting procedures result in large volumes of apparent loss, and current customer meter accuracy is adequate but could be marginally improved.  Application of the audit process to the utility is beneficial because it facilitates increased communication between utility departments, assesses shortcomings in current policies, pin-points areas needing increased resources, and validates programs that are performing well.

# DEDICATION

To my parents, Pat and Linde, with all my love.

Dad, thank you for your love, support, and constant motivation for me to continue learning and reach my educational goals. Mom, thank you for your love, continued nurturing, and all the laughs along the way.

This work is also dedicated to others who have helped me grow through the years; namely my grandmother, Lena Jakovich, and my Godparents, CA and Glenda Meyer.

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I would like to extend my sincerest gratitude to my advisor, Dr. Kelly Brumbelow, Assistant Professor in the Zachry Department of Civil Engineering at Texas A&M University.  Thank you for your dedication and enthusiasm as a mentor, a teacher, and a researcher.

I would also like to recognize and extend my thanks to Dana Nichols and the Conservation Department of San Antonio Water Systems who funded this research project.

Last, I appreciate the work and collaboration on this project from Dr. Kyle Murray, Assistant Professor in the Department of Earth and Environmental Science, and Dr. Cheryl Linthicum, Assistant Professor in the Department of Accounting, both at the University of Texas at San Antonio.

# TABLE OF CONTENTS

Page

Page

# LIST OF FIGURES

# LIST OF TABLES

# 1. INTRODUCTION

The focus of this thesis is testing, evaluating, and improving a particular method of water auditing. A water loss audit according to the standards and methodologies of the International Water Association (IWA) was applied to a major North American utility, the San Antonio Water System (SAWS), located in San Antonio, Texas. Methodologies and procedures for conducting this type of water audit on a unique utility were defined in areas where the guidelines are vague. The effectiveness of the audit model was evaluated in the context of SAWS. Also, policy and resource allocation recommendations were made for SAWS.

Water accountability describes a variety of activities affecting the water delivery efficiency of water utilities. Standards for water accountability are increasing for many water utilities as supplies are progressively strained (WSTB 2002). Growing populations coupled with periods of drought have increased the demand on current water supplies. Controlling losses in a water utility system is an efficient method of helping to ensure there will be enough water supply to meet future demand. Most of the regional water plans in Texas include conservation and loss reduction as a significant component of “new supply” for the next 50 years (TWDB 2002). One particular water accountability and conservation technique, which is presently gaining popularity, is water auditing. Completing a water audit on a utility system is essentially comparing the

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

volume of water input with the volume of water output. A water audit can tell how much water is lost from the system as well as pinpoint sources of revenue loss. Water losses can arise from various reasons including theft, poor accounting, operational error, and leaking pipes to name a few. Currently, the United States does not have any national agenda to minimize water lost by suppliers (Thornton and Kunkel 2002). Instead, the focus of water accountability has been primarily on the demand-side, for example, consumer based conservation. However, focusing on the supply-side of water accountability has many advantages including the reduction of adverse environmental impacts. According to Thornton and Kunkel (2002), "high losses directly require oversized infrastructure, excess energy usage, and unneeded withdrawals or abstractions from source water supplies, all of which have potentially unnecessary – and sometimes damaging – effects on the environment."

## 1.1. THESIS STATEMENT

Although it is a beneficial tool for water resources management, the IWA water auditing process needs refinement to be applicable to many North American water utilities. To test this hypothesis, the IWA water auditing methodologies, as outlined in the manual entitled *Performance Indicators for Water Supply Services* (Alegre et al. 2002) were applied to SAWS for the year 2004, and new techniques were proposed and evaluated. The following questions were addressed after completion of the water audit.

1. What are the apparent improvements of the IWA water auditing techniques when qualitatively compared to the most commonly used auditing method in North

America (the American Water Works Association M36 Manual entitled *Water Audits and Leak Detection* [AWWA 1999])?

2. What are the limitations of the IWA water auditing process when applied to North American utilities and how can it be improved? The IWA water audit is a standard and detailed set of procedures set forth to accurately capture all aspects and inefficiencies in a water system. Inevitably, the model outlined came up short in some instances of the application to SAWS. The model lacked flexibility to completely and accurately portray the uniqueness of the specific water system being analyzed. Improvements upon the IWA methodologies have been formulated to better capture all characteristics and processes taking place within SAWS. These suggested improvements may enable SAWS and other utilities to perform better audits in future years.
3. What are the most critical inefficiencies for the particular case of SAWS? Furthermore, what policies may help to reduce these inefficiencies? The IWA water audit uses a water (mass) balance model to quantify all volumes of water in the system over the one year study period. This model is the essence of the IWA water audit, and upon audit completion the water balance volumes can be compared side by side to understand where the system losses are occurring, where utility management resources should be focused, and where improvements should be made. This research identified the most critical inefficiencies in the SAWS, as well as made suggestions for operational procedures to address the issues identified.

## 1.2. PROCEDURE

The following is the procedure followed in completion of this thesis project.

### 1.2.1. Research of Available Audit Methods

The International Water Association method for water auditing was investigated in detail along with case study examples. This method was also compared and contrasted with the AWWA's Manual M36 suggested method for water auditing. Current regulations for water accountability in Texas were also examined. Section 2 of this thesis contains all of the information from this portion of the study.

### 1.2.2. Audit of San Antonio Water System According to IWA Methodology

A water loss audit was completed on SAWS for the year 2004 (also identified as FY2004). This audit was sponsored by SAWS Conservation Department and was carried out by an interdisciplinary team of researchers, engineers, hydro-geologists, and accountants from Texas A&M University and the University of Texas at San Antonio. Input was included from SAWS staff of various departments. This thesis project focuses only upon the portion of the water loss audit completed by civil engineers at Texas A&M University. Other components of the audit were completed by alternate team members, so conclusions are not drawn concerning their work. The audit components focused upon in this thesis study are:

- **System Input Analysis –** Inputs were derived from over 100 wells located in three aquifers, the majority of the wells being located in the Edwards Aquifer.

- **Unavoidable Annual Real Losses (UARL) Analysis –** This calculation estimated a volume of leaks from the system that are undetectable or would be uneconomical to repair. UARL represents a level of allowable physical losses from the system.
- **Deferred Accounting System –** A new method was formulated that incorporates operation of an aquifer storage and recovery project into the standard water balance notation.
- **Customer Metering Inaccuracies –** The standard water balance includes a category determining the amount of water lost or gained due to incorrect meter measurements. However, there are no guidelines for how this analysis should be carried out. A procedure was created to determine metering inaccuracies in the system.

### 1.2.3. Audit Limitations Identified and Resolved

This portion of the procedure was completed concurrently with performing the water loss audit (section 1.2.2). During the application of the IWA audit to the SAWS, several limitations of the audit were discovered. As each limitation was identified, a solution was formulated. New methodologies were developed to incorporate the aquifer storage and recovery project into the water balance accounting system and to calculate UARL for a system with multiple pressure zones. Other difficulties encountered and addressed were calculation of system input from multiple methods of volume measurement and defining a procedure to estimate the accuracy of the system flow meters.

### 1.2.4. Analyze Audit Results for SAWS

Lastly, the audit results specific to SAWS were evaluated. The following questions were asked in order to understand the reliability and accuracy of the audit results as well as to understand the final water balance and what it suggests about SAWS efficiency and performance. While these questions are asked in the context of SAWS, it is important that these types of questions be asked after applying the IWA audit to any utility. Interpreting the audit results correctly is just as important as completing the audit properly.

- Does the completed water balance make sense? Do system inputs equal the system outputs? What kind of conclusions can be drawn from the resulting water balance?
- Were there any categories in the audit that lacked significantly in the reliability or accuracy ratings? If so, how can confidence in the data be increase for future audits?
- Does SAWS experience enough real losses from their system to indicate that further resources should be spent upon recovering these real losses? When considering the expanding water needs of the City of San Antonio in the upcoming years, would recovering these real losses be of substantial magnitude to satisfy a significant portion of the city’s water needs?

- What decisions and innovations were carried out by the research team during the auditing process that would be beneficial for utilities to understand when carrying out the audit themselves in future years?
- What are the benefits to the utility for completing this audit?

## 1.3. THESIS STRUCTURE

This thesis consists of five additional sections. Section 2 presents a literature review, which compares and contrasts the International Water Association auditing method with North America's most common audit method, AWWA's Manual M36. In addition, section 2 discusses water loss audit requirements and trends in the State of Texas. Section 3 presents useful background information which acquaints the reader with unique characteristics of the City of San Antonio, such as climate, geography, and population as well as water demand trends. Also presented is pertinent information on the infrastructure components of SAWS, such as pumping and booster station configuration, system pressure zone layout, available water sources for the utility, and creation of the aquifer storage and recovery project. Section 4 clearly defines the methodologies developed during this thesis research for various aspects of the water audit including:

- Estimating the volume of water input into the distribution system.
- Calculating an economically allowable and unavoidable volume of leaks in the distribution system. (UARL)

- Creating an accounting system for both yearly and continuous operations of the aquifer storage and recovery project within SAWS.
- Determining losses due to under-registering water meters throughout the system.

Section 5 explains all results from the completed application of the IWA audit to SAWS. A water balance is presented, which compares resulting volumes of water at various points in the delivery cycle of the water system. This water balance diagram allows various forms of non-revenue water in the system to be pin-pointed, so that plans can be formulated to reduce these system losses in the future. Section 6 closes this thesis by giving suggestions for conducting improved water audits in the future. This section also advises the utility (SAWS) on what this audit concludes their current inefficiencies are, and gives recommendations for addressing these issues.

# 2. REVIEW OF WATER AUDITING METHODS

Two of the most prevalent water auditing techniques currently used are discussed in this section. In section 2.1, an overview of the currently endorsed method by the American Water Works Association (AWWA) is discussed. This method is currently under review and will soon be changed to reflect the methods used by the IWA. The IWA water auditing method is discussed in great detail in section 2.2, since this method is the focus of this research project. Sections 2.2.7.1 through 2.2.7.3 present case studies of application of the IWA audit throughout the world. Next, section 2.3 discusses present water accountability requirements by law in the State of Texas. This information is also pertinent due to the fact that the IWA methods are being tested on a Texas utility. Each of the three audit methods (AWWA, IWA, and State of Texas) will be analyzed according to the following categories: Tasks/Method, Vocabulary, Input Data, Output Results, Provisions for Error and Uncertainty, and Limitations. This will allow for easy comparison between the three auditing methods.

## 2.1. AMERICAN WATER WORKS ASSOCIATION AUDIT METHOD: MANUAL M36

The AWWA has announced that it will publish in 2007 a manual describing the IWA water auditing process for use in the United States. It is the new AWWA Manual M36 and is entitled *Accountability and Loss Control Programs for Drinking Water Utilities* (Brumbelow et al. 2005). There are no federal regulations in the U.S. requiring use of this forthcoming manual; however its creation – and endorsement by AWWA - is a step closer to uniform water accountability practices in the United States.

The current AWWA Manual M36 was published in 1999 and is entitled *Water Audits and Leak Detection*. Use of this manual is also not currently required in most North American utilities; however it is the recommended method of water auditing during the past decade. The following sections briefly outline the water auditing method as explained by the 1999 Manual M36 as well as point out some of the shortcomings of this water auditing method.

### 2.1.1. Tasks/Method

The AWWA Manual M36 audit is divided into the following tasks as described in Chapter 2 of the manual (AWWA 1999).

1. **Measure the Supply –** Identify water sources. Measure water from each source. Assess measurement accuracy from each source and adjust input volume accordingly.
2. **Measure Authorized Metered Use –** Identify metered water uses. Measure metered water uses. Assess meter accuracy and adjust amount of water used accordingly.
3. **Measure Authorized Unmetered Use –** Identify and estimate amount of water used by unmetered customers. These uses could include water used for firefighting and training, flushing mains, storm sewers, and sanitary sewers,

street cleaning, schools or other public buildings, or water landscaping of public parks.

4. **Measure Water Losses –** All volumes of water that do not fit the previous three tasks by default are considered "unaccounted-for-water". The object of task four is to identify potential water losses and estimate the volumes of each type of loss. These losses can include accounting errors, unauthorized connections, evaporation of water stored, reservoir overflows, discovered leaks, reservoir seepage and leakage, and any water lost due to malfunctioning equipment or system controls.
5. **Analyze Audit Results –** Audit results define the calculation of two quantities. The first is *potential water system leakage* which is total water loss minus all measured water losses (from task 4). Total water loss is equivalent to system input (corrected for meter errors) minus all authorized water uses. The second result quantity this audit defines is *recoverable leakage*. This quantity is simply the *potential water system leakage* multiplied by 50%, suggesting that half of all potential leaks can be discovered and repaired.

### 2.1.2. Vocabulary

The following terms are useful to understand when conducting an audit according to the AWWA Manual M36. Some of these terms are similarly defined in section 2.1.1. Definitions are paraphrased from the Manual M36 (AWWA 1999).

- **Supply** is defined as water supplied to the system that has been adjusted for metering inaccuracies and changes in storage (reservoir or tanks) for the audit period.
- **Authorized Metered Use** is defined as water used by registered customers who have metered connections. Adjustments are made for metering inaccuracies.
- **Authorized Unmetered Use** is defined as water used for allowable uses, but not through a metered connection.
- **Water Losses** are defined as water that is consumed that does not generate revenue for the utility, or water that is physically lost from the system (leaks).

There are two additional phrases associated with the Manual M36 audit.

- **Accounted-for-water** is defined as "water that is either metered or used for an authorized, unmetered use" (AWWA 1999).
- **Unaccounted-for-water** is defined as "water that is neither metered nor authorized. This water is considered lost from the system. The water does not produce revenue and is not available for beneficial uses." (AWWA 1999) The previously discussed concept *potential system leakage* is included in unaccounted-for-water.

### 2.1.3. Input Data

The AWWA M36 audit is considered to be a “bottom-up” audit approach. This type of audit requires sorting through the most basic information that a utility gathers (SCADA data, billing records, leak reports, field visits etc.) and working one’s way up the chain to build an overall picture of the utility. This type of audit is costly and requires extensive labor hours to perform. However, the advantage of a “bottom-up” audit approach is that it will identify all internal issues that prevent the utility from obtaining maximum efficiency (TWDB 2005).

Data required according to the Manual M36 is a map of the distribution system with all water sources identified, total water recorded from each input source, information on meters in the system, meter testing and calibration records, data on reservoir storage levels, system billing records, and consumption records. In addition, the M36 Manual needs data in order to estimate authorized unmetered water use. Samples of this type of information include records of fire fighting, line flushing, street cleaning, and other miscellaneous maintenance tasks, as well as water used for city landscaping (AWWA 1999).

### 2.1.4. Output Results

The primary output result from the Manual M36 audit is quantification of the volume of unaccounted-for-water in the system and the corresponding revenue loss for these water losses. In addition, a benefit-to-cost ratio is calculated to advise if leak detection projects implemented to recover the lost water is economical. Other basic results of the Manual M36 audit are the final volume of water supplied to the system after adjustments have been made, final volume of authorized metered water use, final estimated volume of authorized unmetered water use, and final estimates of measured water losses in the system.

### 2.1.5. Provisions for Error and Uncertainty

AWWA's Manual M36 has no provisions for determining error and uncertainty in data or audit results.

### 2.1.6. Limitations

The following are weaknesses that have been cited regarding AWWA's Manual M36 water auditing methods. (These shortcomings have been corrected by the IWA auditing method.) First, the current M36 method lacks performance indicators which give an overall assessment of all aspects of the utility system performance and allow a standard of comparison between utility systems. The Manual M36 uses the term "unaccounted-for-water" to represent any volume of water that cannot be measured or attributed a revenue value. This definition is much less specific than the IWA method for defining non-revenue water, where every drop is counted and its point of loss in the system is identified. Lastly, the IWA method is used much more widely than AWWA's auditing method. IWA is used in 20 different countries for at least 27 water systems (Kunkel 2002a), whereas the AWWA auditing method is used only in North America on a limited and voluntary basis. In general, North America is in need of a consistent and well defined water loss accounting procedure.

There are a couple of problematic issues associated with many other North American water loss auditing formats. Although these problems are not specifically found in the Manual M36, the following methods are commonly used and information is misrepresented. First, since there is no standard definition for a minimum allowable level of leakage from the system (IWA calls this unavoidable annual real losses – UARL) each utility defines this acceptable level for themselves. In many instances they include discovered leaks and storage overflows as part of authorized consumption instead of including these in the loss category (Kunkel 2002a). Another inconsistency in North American audits is reporting the system’s water loss estimate as a percentage of their system input instead of as a yearly volume. Per capita water usage is high in North America, especially in comparison with the rest of the world. Reporting loss as a percentage of input undervalues the magnitude of the water losses because the corresponding water system inputs are also large (Kunkel 2002a). Reporting water losses in units of volume makes the issue of waste more specific than reporting losses as a system wide percentage. Making this information publicly available will inform customers of water accountability issues, so that they too can be involved in conservation on the demand side as well as encouraging their utility to conserve (and remedy losses) on the supply side.

## 2.2. INTERNATIONAL WATER ASSOCIATION AUDIT METHOD

It is important to clearly explain this water auditing technique because it is becoming the standard for audits in the United States. It is already deemed the gold standard in water accountability practices and is used in numerous locations internationally, such as Great Britain, South Africa, Italy, Australia, and New Zealand (Kunkel 2002a). In the year 2000, the International Water Association (IWA) published their auditing manual entitled, *Performance Indicators for Water Supply Services*. This method was developed in Great Britain and was motivated by a drought they suffered in the mid 1990's. It has proved to be an effective water accountability method for their country. The following sections will explain the IWA auditing method according to the six specified categories.

### 2.2.1. Tasks/Method

The essence of the IWA Audit Methodology is the International Standard Water Balance shown in the following Fig. 2.1 (Lambert et al. 2000).

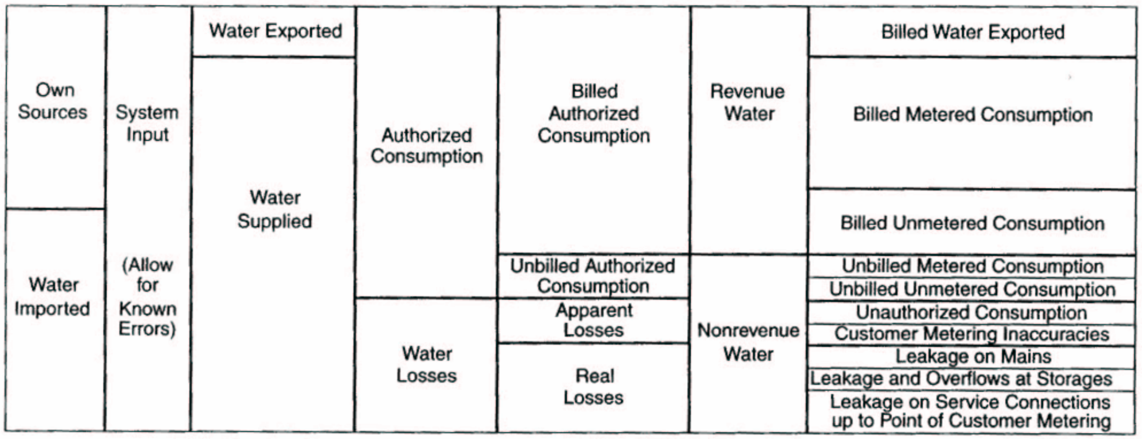


**Fig. 2.1**. International Standard Water Balance (Lambert et al. 2000).

In the IWA water balance diagram, each column is a different notation for describing the same volume of water at some point in the delivery cycle of the utility system. Likewise, each aligned row totals the same volume of water. Performing an IWA audit involves quantifying each entry (volume per year) in Fig. 2.1. Depending upon the size of the utility system, quantifying each of these entries can become an arduous process of sifting through SCADA (supervisory control and data acquisition system) information, billing records, and leakage reports, meter testing records, and so on. By quantifying all entries in the water balance, the utility company can build a complete picture of their system efficiency and determine where to focus their resources to produce the greatest amount of improvement.

The IWA audit is considered to be a “bottom-up” audit approach. This type of audit requires sorting through the most basic information that a utility gathers (SCADA data, billing records, leak reports, field visits etc.) and working one’s way up the chain to build an overall picture of the utility. This type of audit is costly and requires extensive labor hours to perform. However, the advantage of a “bottom-up” audit approach is that it will identify all internal issues that prevent the utility from obtaining maximum efficiency (TWDB 2005).

### 2.2.2. Vocabulary

It is important to comprehend some of the common terminology used in the water balance diagram (Fig. 2.1), which is also used in the IWA audit manual. This vocabulary is important because its use is becoming common place among those who study water accountability and formulate water policy for countries, states, and planning regions throughout the world. As will be made clear in section 2.3 of this paper (focusing on Texas), the common use of the audit terminology is the first sign that the IWA auditing method is spreading in the water accountability world. This terminology is also important because it is replacing a sub-par method of water accountability that used the general term “unaccounted-for-water” to describe all water in the utility system that for any number of reasons did not earn revenue for its use by consumers. All of the following definitions paraphrased from a book entitled *Water Loss Control Manual* (Kunkel 2002a) are specific forms of “unaccounted-for” or non-revenue water.

- **Real Losses** are physical losses from the distribution system. Examples are pipe main leaks, service connection leaks, bursts, system blow-offs, and storage tank overflows. These losses are charged at the wholesale cost of water because they occur before the water reaches the customer.

- **Apparent Losses** is water that reaches a customer or other end user, but is not properly measured or tabulated. Examples are inaccurate customer billing records, inaccurate customer metering (a larger amount of water reaches the user then the meter registers), and unauthorized consumption (theft) of water. These types of losses are charged at the customer retail cost of water.
- **Unbilled Authorized Consumption** is metered or unmetered water used by registered customers, the water supplier itself, or others who are implicitly or explicitly authorized to do so by the water supplier. Examples are water used for fire-fighting, public buildings such as schools, the courthouse, police department, etc. which may be granted free use of water.

It is also important to understand the definitions of the water balance components shown in the last column of the water balance, Fig. 2.1. This last column symbolizes the various ways that the utility system output can be described and quantified.

- **Billed Exported Water** is water sold to other utility companies.
- **Billed Metered Consumption** is the amount of water used by metered paying customers.
- **Billed Unmetered Consumption** is use of water by customers who do not have meters, but do pay for use of water. These customers' water use is likely estimated by a utility approved procedure, or they are simply charged at a flat rate per month.

- **Unbilled Metered Consumption** is water used by public facilities (city parks, court houses, schools, etc). Authorized users meter the water they consume, but they don’t have to pay for it.
- **Unbilled Unmetered Consumption** is for authorized city uses like fire-fighting, street cleaning, line flushing etc, which are typically unmetered.
- **Unauthorized Consumption** is an apparent loss where water is lost due to theft through illicit connections or tampering of meters so they will under-register.
- **Customer Metering Inaccuracies** is an apparent loss where water is lost due to under-registering meters. Meters more commonly under-register than over-register; however a meter accuracy analysis will determine the behavior present in the particular system.
- **Leakage on Mains** is a real loss where water physically leaks from the pipes.
- **Leakage and Overflows at Storages** is a real loss where water physically overflows from storage tank reservoirs.
- **Leakage on Service Connections up to Point of Customer Metering** is a real loss between the service connection and the water main.
- **Unavoidable Annual Real Losses (UARL) –** UARL is not shown specifically on Fig. 2.1, however it is a subsidiary category of the three types of leakage listed. UARL is an allowable volume of leaks, which occur at these three locations (mains, service connections, and storage tanks).

### 2.2.3. Input Data

Section 4.1 of this thesis expands upon the type of data used in the audit analysis. The IWA audit is also considered to be a “bottom-up” audit approach. Therefore, the data used is similar to that used in the M36 Manual audit. The most important input data is SCADA data for metered flows, measured pressures, and pump run times. Also used was billing records, consumption records, leak detection reports, field visits, meter accuracy testing records, and day to day operational information from utility employees.

### 2.2.4. Output Results

The major product of an IWA audit is the water balance with values assigned to all system output quantities for easy comparison of non-revenue water categories. Another significant result of an IWA audit is a list of performance indicators. Section 2.2.5.1 describes performance indicators in detail. In addition, each piece of data used in calculation of the performance indicators and in determining final volumes for the water balance is assigned both an accuracy and reliability value. This is termed confidence grading of data and is expanded upon in section 2.2.5.1 of this thesis.

#### *2.2.4.1. Performance Indicators*

The IWA auditing manual outlines the necessary audit calculations in a very detailed step-by-step process. It divides all aspects of a water utility system into six categories of performance indicators (PI). The IWA audit manual (Alegre et al. 2002) defines performance indicators as “a quantitative measurement of a particular aspect of the utilities’ performance or standard of service. They assist in the monitoring and evaluation of the efficiency and effectiveness of the utility.” These indicators are as follows:

- Water Resources Indicators
- Personnel Indicators
- Physical Indicators
- Operational Indicators
- Quality of Service Indicators
- Financial Indicators

Within each of the six performance indicators listed above are sub-categories that further quantify smaller pieces of the water system performance. These sub-categories are the pieces of the audit that contain specific formulas for data to be input and calculated. For example, the Operational Indicator section of the audit contains sub-categories that allow the auditor to quantify leakage control, pump refurbishment, calibration of water level meters, apparent losses and real losses just to name a few of the needed calculations.

PIs are of beneficial use to all stakeholders of a utility. For the utility themselves, the PIs identify the strengths and weaknesses of different divisions of the utility and provide a benchmark each auditing period to measure self-improvement or comparison with other utilities. Regulatory agencies are another important stakeholder group in the system. For regulatory agencies, PIs allow the utilities to be easily monitored and ensure compliance with any laws or policies of the governing body. The governing policy-makers are important stakeholders and have interest in the audit and PIs so that they can compare utilities' performances, identify problems, and formulate policies to guide and correct issues of public concern (Alegre et al. 2002).

One of the most useful PIs in the IWA audit is named the infrastructure leakage index (ILI). It is new to the IWA auditing methodology and not normally quantified in other North American audits. The ILI is a unitless ratio comparing the volume of annual real losses (all physical losses from the system) to the volume of unavoidable annual real losses (physical losses that are undetectable or uneconomical to repair).

$$\text{ILI}=\frac{\text{Annual Real Losses}}{\text{UARL}} \tag{2.1}$$

Since the ILI is a ratio and not a percentage of annual consumption, the ILI value can be compared between any utility (using these IWA calculation methods) anywhere in the world. According to Kunkel (2002) "The ILI ratio is a great way to demonstrate loss management performance, as each system effectively compares the ratio of its individual best possible performance against how it is actually performing." An ILI of 1.0 is ideal but not economically feasible to achieve until water becomes a much more expensive commodity or becomes a scarce resource. ILI values between 1.5 and 2.5 are considered satisfactory for most utility systems (Kunkel 2002a). For comparison purposes, a sample of seven North American utilities, an average ILI of 7.37 was determined (Lambert et al. 2000).

### 2.2.5. Provisions for Error and Uncertainty

The IWA auditing method evaluates the error and uncertainty of all data used in the audit, and then assigns reliability and accuracy values for all final results. IWA has termed this uncertainty analysis *confidence grading* of data and it is described in detail in section 2.2.5.1.

#### *2.2.5.1. Confidence Grading of Data*

Confidence grading of data is an important attribute of performing an IWA water audit because it quantifies the reliability and accuracy of each piece of information. The confidence grading scheme that is outlined in the IWA auditing manual was developed so that when using the performance indicators, the reliability of the data is known and taken into consideration when performing calculations. Possible errors in the data collected must be evaluated and assessed. Each performance indicator calculation is given a confidence rating which describes both how accurate and reliable the information is believed to be. These confidence ratings can also be used to dictate how to improve the system efficiency in the future. If the audit finds that there is little confidence in the accuracy of the meters on the well pumps, then possibly these meters should be replaced or calibrated more often on a routine schedule.

Table 2.1 summarizes the reliability and accuracy ratings that each performance indicator calculation can be given according to the IWA auditing manual.

**TABLE 2.1.** IWA Audit Confidence Grading System Notation (Alegre et al. 2000)

| Reliability Rating | | Accuracy Rating | |
|---|---|---|---|
| A = | highly reliable | 1 = | (+/-) 1% |
| B = | reliable | 2 = | (+/-) 5% |
| C = | unreliable | 3 = | (+/-) 10% |
| D = | highly unreliable | 4 = | (+/-) 25% |
| | | 5 = | (+/-) 50% |
| | | 6 = | (+/-) 100% |
| | | X = | Values Outside the Valid Range |

As an example, according to Table 2.1, a data value given the confidence grading of "B3" is described as a reliable data value with a likely accuracy of plus or minus ten percent of the given value.

### 2.2.6. Limitations

The IWA audit, like any model, has its limitations. When applying the IWA methods to SAWS, a few weaknesses were discovered. First, the IWA audit method was not defined to accommodate the operation of SAWS aquifer storage and recovery system. This weakness arises when the utility has a facility which accommodates over-year storage and the distribution system acts as a transmission system to move water between production and storage facilities. To remedy this problem, a deferred accounting system was developed to work in conjunction with the traditional IWA water balance after slight modifications were made. The second limitation recognized was the absence of guiding procedures to calculate the system's UARL. SAWS, similar to many utilities, has a varied topography and consequently multiple pressure zones, booster stations, and pressure reducing valves throughout the distribution system. This complexity leads to difficulty in calculating an average system pressure, which is one of the inputs into the empirically derived UARL equation. A spatial analytical method was developed to address this variability in system pressure and to provide guiding procedures for calculation UARL in future audits (Brumbelow et al. 2006).

### 2.2.7. IWA Audit Case Studies

Three case studies are presented where the IWA audit has been applied very successfully. Lessons can be learned from these case studies, as well as from the most current case study; application of IWA audit methodologies to SAWS.

#### ***2.2.7.1. Great Britain*** (Thornton and Kunkel 2002a)

Great Britain privatized their water utility companies in 1989. Later, in 1992, the government began requiring that all water companies produce annual reports, which followed a standard format quantifying water losses. Published nationally for all to read, these reports made clear that the utilities were losing large amounts of water. Great Britain experienced a severe drought in 1995 and 1996. This drought spurred further government regulation (a National Leakage Initiative was began) and mandatory minimum leakage targets were set. After five years of employing various leak detection techniques, water auditing, and other water accountability methods, leakage from the water supply systems was reduced by 40 percent, or approximately 480 million gallons of water per day. This is a fantastic accomplishment, and Great Britain is known internationally for their leak detection methods, auditing methods (the IWA water audit), and their success with privatization. These accomplishments in reducing water losses by such a great percentage may not have been possible if the following had not been required of them:

- Completing annual water loss calculations for every water utility system in the nation.
- Requiring a standard format (IWA method) for carrying out calculations, using performance indicators, and confidence grading of data.
- Publishing water loss results, creating public accountability for the efforts.

### ***2.2.7.2. Philadelphia, Pennsylvania, USA*** (Kunkel 2002b)

Philadelphia is one of the oldest cities in the United States, and therefore has one of the oldest water systems (over 200 years old), which has historically also been one of the most progressive water systems. The Philadelphia Water Department (PWD) reached its climax of water service in the mid 1950's, supplying on average 377 MGD of water to customers. By 2001, this rate had decreased to 270 MGD due to loss of industry and urban sprawl. In the 1970's and 1980's, the PWD conducted a variety of studies to determine their amounts of unaccounted-for-water. They soon realized their water losses were quite high; therefore they began employing accountability measures such as master meter calibration, meter replacement, and leak detection technology.

Even after these efforts, unaccounted-for-water levels remained near 100 MGD. A hike in water tariff rates in 1993 created much public attention to water accountability issues and soon a Water Accountability Committee was formed to pursue solutions to the PWD losses.

The Philadelphia Water Accountability Committee worked closely with the AWWA's Leak Detection and Water Accountability. This group formulated a water auditing process, which the PWD executed for the first time in 1996. This format for water auditing soon was published by the AWWA as their Manual M36. Philadelphia continued this type of audit for the next couple of years. George Kunkel, of the PWD, became chair of the AWWA Leak Detection and Water Accountability Committee in 1998. During this time period, other internationally recognized experts joined the committee, including Alan Lambert who chaired the IWA Task Force on Water Loss and is a known leader and promoter in leakage management techniques. Kunkel directed the group in exploring international water auditing methods and tested the applicability of these methods to North American water utilities. Under Kunkel's research and direction, the PWD transitioned to use of the IWA audit methodology in 2000. The PWD hired international experts to assess the utilities losses. In addition to completing the IWA audit, a sub-contractor was hired to perform night flow analysis and other field measurements to supplement the audit.

PWD audit results according to IWA methodology determined that the utility experience 94.7 MGD of non-revenue water. This quantity was further broken down to be equivalent to 18.6 MGD of apparent losses, 70.2 MGD of real losses, and 5.9 MGD of authorized unbilled usage.  These losses were equated to a financial loss of $16.7 million.

The application of the IWA water audit to Philadelphia is important because it is the first time this audit was used in North America.  The IWA audit methodology was tested and refined during this application.  George Kunkel of the PWD continues to be a leader in the field of water accountability and an ambassador for integrating and sharing this international method of water loss control with North America's recognized authority on water, the AWWA.  The PWD makes their IWA audit available for all to see.  It is in the format of a series of Microsoft Excel spreadsheets and was reviewed extensively by the research team before completion of the SAWS IWA audit.

#### ***2.2.7.3. São Paulo, Brazil*** (de Freitas and Paracampos 2002)

The São Paulo Water and Sewer Company (SABESP) provides water and sewer services to the metropolitan region of São Paulo, inhabited by 17 million people.  Since 1995, SABESP has been undergoing a large reorganization and has put forth significant efforts to increase their system efficiency and reach both their financial and operational goals.  To help reach these goals, SABESP has conducted water audits according to the IWA methodology, which have produced great benefits to their utility.  Their first IWA water audit (in 1997) indicated that 13 percent of the apparent losses the utility was experiencing were due to fraud (illicit connections).  In response to this startling statistic, they put resources into training staff to reduce fraud.  This involved increasing the number of inspections to 4,500 monthly.  Of the inspections conducted, roughly five percent lead to the discovery of fraudulent actions which has led to the recovery of about 800 cubic meters of water per case. In addition to increased inspections, SABESP began paying contractors based upon the quality of their work in order to motivate excellence in the field for system repairs. This case study is a wonderful illustration of how an IWA audit can pinpoint the areas within a utility which need attention, more resources, and investigation in order to increase overall system efficiency.

## 2.3. TEXAS WATER DEVELOPMENT BOARD REQUIREMENTS

In 2003, the 78th Texas Legislature created House Bill 3338, which amended Section 16.0121 of the Texas Water Code to require every public utility which supplies potable water to conduct a water loss audit once every five years. A standard auditing format was created by the Texas Water Development Board (TWDB) and is available on their website (http://www.twdb.state.tx.us). The audit results were reported to the TWDB who in turn compiled the information submitted. The Legislature and Regional Water Planning Groups will review the information in order to identify appropriate and efficient water management strategies for the future. The first required water loss audit used data collected from the 2005 calendar or fiscal year. Utilities filled out a simple standard three page form, which were due by March 31, 2006.

### 2.3.1. Tasks/Method

#### *2.3.1.1. Current Requirements in the State of Texas*

The TWDB publishes a manual entitled *Water Loss Manual*, which describes Texas's auditing requirements, terminology, water balance, how to carry out the calculations on the audit worksheet and much more. After examining this manual and the Texas water audit reporting form, it is clear that both are based upon the ideas and methodologies of the IWA audit. The introduction to the TWDB *Water Loss Manual* states:

> "The new methodologies being used enable water utilities to operate very efficiently. Based on the International Water Association's methodology which has been used all over the world and recently in the United States, these methods are proven to work. They eliminate unaccounted for water, and the end results direct focus to problem areas."

The Texas audit is only three pages in length and lacks the detail and data confidence grading system of the IWA audit, but the water balance that it is based upon is identical, the terminology is the same, and it introduces the idea of performance indicators only when calculating real water losses. The Texas water audit addresses four main points of water loss: loss from distribution lines, meter inaccuracies, deficiencies in accounting methods, and water theft (TWDB 2005).

### *2.3.1.2. Looking to Future Requirements in Texas*

After reading the TWDB's *Water Loss Manual*, it is obvious that the State of Texas agrees with the methodology of the IWA audit. Information was obtained from Mr. Mark Mathis with the Municipal Water Section of the TWDB. Mr. Mathis, who is responsible for assimilating the water audit policy, was asked what he thought the future held for Texas water auditing policies and if he thought the State of Texas would progress to requiring complete annual audits according the IWA methodology. Mr. Mathis replied that ideally they would, but of course all is dependent upon the legislature and what they decide to do in 2007. He agreed that a bottom-up approach would be best, but that most of the utility systems in Texas serve less than 50,000 customers and would thus not have the financial means or employee resources to conduct this type of in-depth audit. Mr. Mathis said that the original HB 3338 was written to require audits annually, but this constraint was changed to every five years in order to help the bill pass. In conclusion, he stated that for now, the State of Texas is content with knowing how well water is tracked by each utility. They are satisfied with introducing a consistent methodology that has categories for each type of water use while also associating a cost to that use.

### 2.3.2. Vocabulary

The vocabulary used in Texas *Water Loss Control Manual* is identical to the IWA audit vocabulary with the following exception.

- **Balancing Error** is defined as the difference between system input and system output in the water balance diagram.  Theoretically, the two quantities should be identical.  The TWDB has created this term, balancing error, to make it appear acceptable in instances when system input does not equal system output.  When systems have balancing errors, it indicates that the information input into the audit should be reviewed and the validity of the estimates made in the audit should be considered (TWDB 2006).

### 2.3.3. Input Data

This Texas water loss audit is considered a top-down audit, meaning it "utilizes data the utility should already have without additional fieldwork.  Data is transferred from other reports to the water audit form, enabling the utility to see which areas warrant more fieldwork" (TWDB 2005).  Examples of input data required is system input volume, meter accuracy, records for authorized water consumption, billing adjustments/waivers records, unauthorized consumption estimates, storage tank overflow estimates, water lost due to main breaks/leaks, water lost due to customer service connection breaks/leaks, and financial records for the utility.

### 2.3.4. Output Results

The major result of this audit is quantifying both apparent and real losses.  Similar to the IWA audit, apparent losses include customer metering inaccuracies, billing adjustments and waivers, and unauthorized consumption.  Also similar to the

IWA audit, real losses include storage tank overflows, water main breaks and leaks, and customer service line breaks and leaks.  The Texas audit also has a few technical performance indicators for real losses and financial performance to use in comparing one utility to another.  The indicators specified are (TWDB 2005):

- Total daily real losses divided by miles of main in system.
- Total daily real losses divided by number of service connections in system.
- Total cost of apparent losses.
- Total cost of real losses.

### 2.3.5. Provisions for Error and Uncertainty

The State of Texas *Water Loss Control Manual* has no provisions for determining error and uncertainty in data or audit results.  It only suggests that if a balancing error is present in the system, then the validity of the data used should be reviewed (TWDB 2006).

### 2.3.6. Limitations

This auditing method does not account for UARL, undocumented real losses, or deferred accounting principles. Also, since this audit is a "top-down" audit, it does not incorporate the detail or completeness that a "bottom-up" audit approach would capture. This audit does not assess the reliability or accuracy of the data used in the calculations, which is an important aspect of assessing the efficiency of the system and improving it with each year. Another shortcoming of the TWDB audit method is the extremely lenient requirements in its application rate of recurrence. Conducting the audit once every five years is not frequent enough to capture patterns in water system behavior or frequent enough to see if any policy changes enacted after the first audit are effective. It is strongly recommended that the State of Texas require utilities to perform the audit yearly. Last, the audit methodology according to the TWDB has provisions for a balancing error in systems where system inputs do not equal system output. This is essentially unaccounted-for-water and its addition to the audit neglects the whole point of using IWA audit methodology in the first place.

# 3. OVERVIEW OF THE CITY OF SAN ANTONIO, TEXAS, AND THE SAN ANTONIO WATER SYSTEM (SAWS)

The purpose of this section is to briefly describe the physical, geographical, meteorological, and demographical characteristics of the region served by San Antonio Water System as well as the extent of the infrastructure that is currently in use by the utility. This background knowledge will put the unique qualities of this large utility into context and allow for better understanding of general discussion on the system in subsequent sections of this research report.

## 3.1. DEMOGRAPHICS, GEOGRAPHY, AND CLIMATE

According to the 2005 US Census population estimates, San Antonio, Texas is the seventh largest city in the United States and is growing faster than most other large American cities (Pearson Education 2006). The city's population exceeded 1.2 million in 2005, approximately a 9.8 percent increase since the year 2000 census. It is expected that by the year 2050, the population in the SAWS service area will grow to nearly 1.8 million (SAWS 2005), an increase of about 50 percent. In the audit year, 2004, the per-capita water consumption for the SAWS service area was 129 gallons per capita per day (GPCPD). Through increased conservation efforts, SAWS expects the per capita water consumption to decrease and stabilize around 116 GPCPD in a year with normal rainfall amounts or 122 GPCPD during a dry year (SAWS 2005). Taking into consideration these predictions for population increases and consumption patterns, SAWS expects its water demand to increase by approximately 60,000 acre-feet per year or about 37 percent of current system input volumes by the year 2050 (SAWS 2005). SAWS is always exploring opportunities for obtaining new sources of water supply to meet future demands, whether it is by minimizing system losses, furthering conservation efforts, or adding new water supply sources to its repertoire.

San Antonio is the county seat of Bexar County. There are two major water supply utilities in Bexar County, serving residents of the City of San Antonio as well as surrounding areas. These utilities are San Antonio Water System (SAWS) and Bexar Metropolitan Water District (BexarMet). Each utility company has its own sources of water. SAWS is the larger of the two systems, serving approximately 315,000 customer connections at the end of the year 2004 (SAWS 2004). In 2006, BexarMet serves approximately 80,000 customers connections (Bexar Met Water District 2006). SAWS is owned by the City of San Antonio. On the other hand, BexarMet was created by the Texas Legislature in 1945 as a stand alone agency to serve a residential housing boom in San Antonio and has since then grown by taking over ownership of many small independently owned utilities, spread disjointedly throughout the area (Bexar Met Water District 2006).

The City of San Antonio is geographically located in south-central Texas, approximately 140 miles from the Gulf of Mexico. According to the 2005 United States Census, the city covers 412.07 square miles. The city sits along a geologic feature named the Balcones Escarpment, which is an inactive normal fault line running from southwest to north-central Texas forming the boundary between the hill country (to the north) and the coastal plains (to the southeast) (Collins et al. 1997 and SAWS 2006d). Fig. 3.1 shows the location of the city with in the State of Texas. This geographic location is unique, contributing to the dynamics of the Edwards Aquifer and is the reason behind the fresh water springs in the area such as the Comal Springs, the San Marcos Springs, San Pedro Springs and many more in the region.

In San Antonio, monthly/average/annual precipitation amounts have been recorded for the last 135 years, since 1871. Records show that the average annual precipitation has been 29.05 inches (73.79 cm), with a maximum of 52.28 inches (132.79 cm) and a minimum of 10.11 inches (25.68 cm) in one calendar year. The year 2004 (the year analyzed in this research project) has a record of 45.33 inches (115.14 cm) of precipitation occurring over the course of the year (National Weather Service 2005a). This amount of precipitation exceeds the annual average by 16.28 inches (41.35 cm) indicating that 2004 was a very wet year for the area. This information is important when considering the scope of the water loss audit because excess rainfall over the Edwards Aquifer Recharge Zone causes increased recharge and subsequently increased water supply. In San Antonio, monthly/average/annual temperatures have been recorded for the last 121 years, since 1885. Records show that the average annual temperature is 69.1 degrees Fahrenheit. July and August are the hottest months of the year and consistently reach an average monthly temperature in the mid-eighties (National Weather Service 2005b). During summer months, daily maximum temperatures are normally in the nineties and sometimes reach 100 degrees Fahrenheit.

## 3.2. WATER SUPPLY SOURCES IN 2004

SAWS is effectively working towards diversifying its water sources, to counter current over dependence upon the Edwards Aquifer. During the auditing year, 2004, SAWS had three primary water sources which will be discussed in the following sections. These sources and their corresponding percent of water supplied in 2004 are the Edwards Aquifer (97.75%), the Trinity Aquifer (2.25%), and the Carrizo-Wilcox Aquifer (0%). SAWS also considers its water reuse program to be a significant source of water, however this program will not be discussed in this research project. Fig. 3.1 geographically shows the SAWS service area (outlined in black), the location of the three pertinent aquifers, the location of SAWS well fields, and the location of SAWS aquifer storage and recovery project.

### 3.2.1. Edwards Aquifer

The Edwards Aquifer is located along the Balcones Fault Zone in south-central Texas. It is well known as one of the most productive and permeable aquifers in the United States, serving more than 1.7 million people in the San Antonio area as well as water for agricultural and industrial uses (Schindel et al. 2005). Geologically, the Edwards Aquifer is comprised of Cretaceous-aged Edwards Group limestone, which has formed a karst aquifer system. This means that the aquifer is a very well integrated underground drainage system, like an underground river and has a high rate of

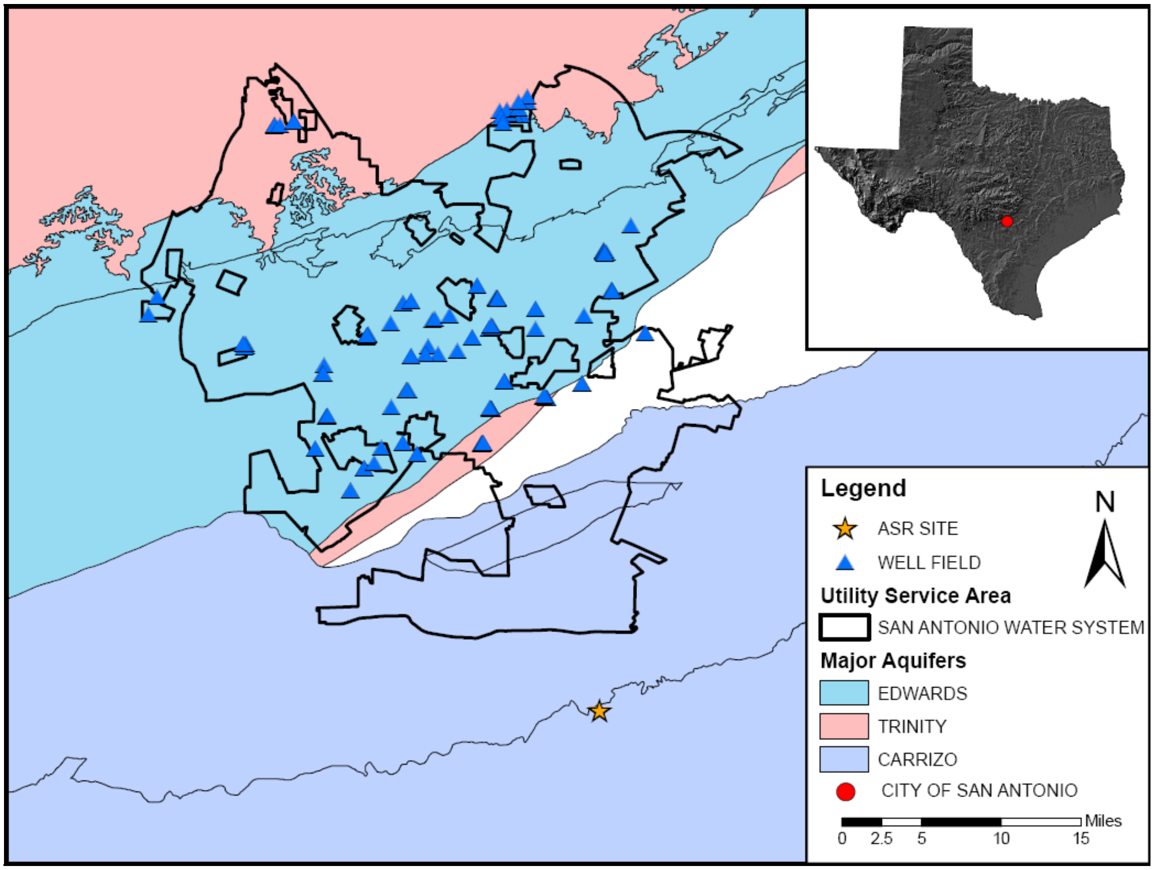


**Fig. 3.1** Exhibit showing geographic location of San Antonio and area aquifers.

permeability (Schindel et al. 2005).  The Edwards Aquifer has three major components; the Contributing (drainage) Zone, the Recharge Zone, and the Artesian Zone, which are shown in Fig. 3.2.

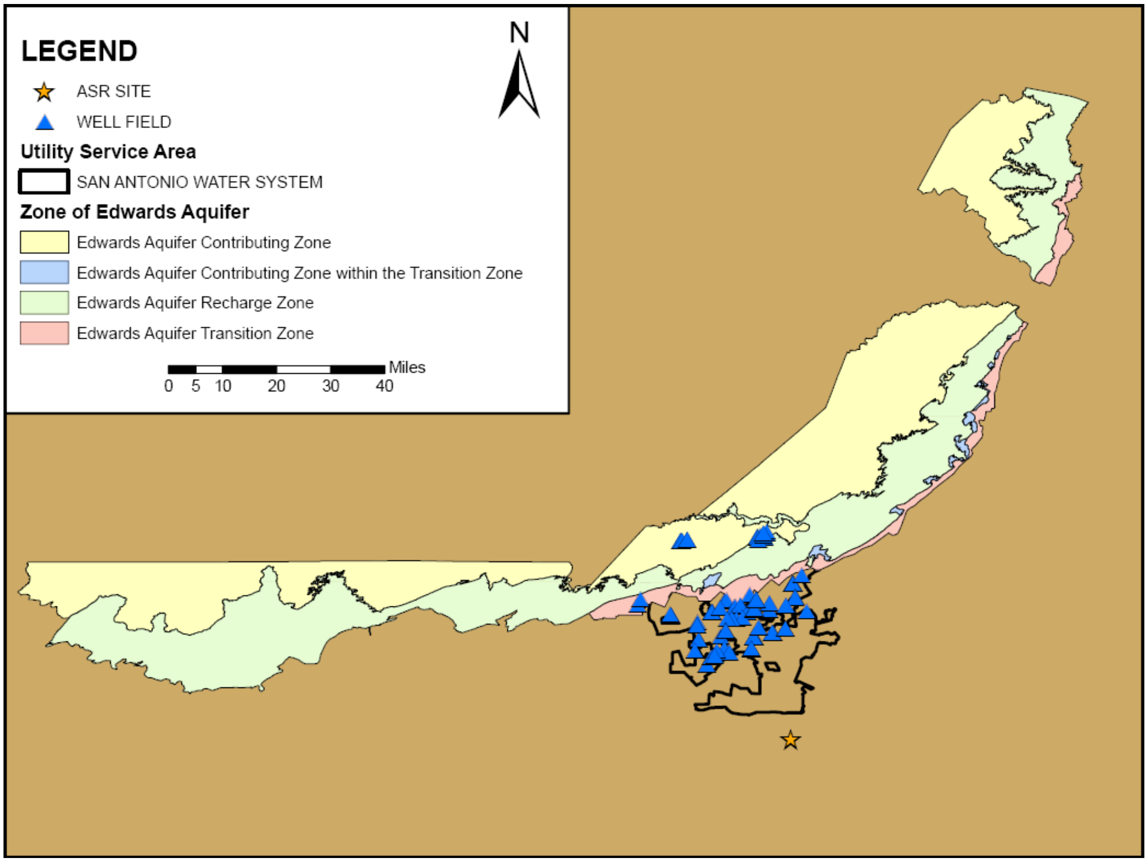


**Fig. 3.2** Exhibit showing Edwards Aquifer contributing, recharge, and transition zones.

The Contributing Zone is located over the Edwards Plateau. In this area, rainfall permeates the ground and forms a large water table where water forms spring fed streams and runs downstream into the Recharge Zone. Fractures, faults, caves, and sinkholes in the Edwards Limestone are exposed in the Recharge Zone. It is here that the water quickly permeates into the aquifer, traveling through the karst system, and flowing downstream to the Artesian Zone of the aquifer. The Artesian Zone ("transition" in Fig. 3.2) is where most wells are located. This zone crosses through the center of the City of San Antonio. In many places there is even enough pressure in this zone that water erupts from the surface forming springs and artesian wells (Edwards Aquifer Authority 2006a).

The Edwards Aquifer, until recently, was the sole water source for the City of San Antonio. In 1993, the Texas Legislature passed an act forming the Edwards Aquifer Authority (EAA) whose mission is to “manage, enhance, and protect the Edwards Aquifer System” (Edwards Aquifer Authority 2006b). Due to this special legislative action, the EAA has authority to regulate the amount of water SAWS, as well as any and all other consumers can pump from the aquifer each year. In 2004, SAWS had the right to pump up to 228,000 acre-feet of Edwards Aquifer water, where 38,000 acre-feet of these rights were leased for short term usage (SAWS 2004).

### 3.2.2. Trinity Aquifer

The Trinity Aquifer is extensive and forms a belt through the center of Texas, stretching from the Red River to the eastern boundary of Medina and Bandera counties. It serves the metropolitan area of Dallas/Ft. Worth and is the primary water source for much of the Texas hill country. Its permeability is much lower than the Edwards Aquifer and it is not yet regulated by a single government entity. The Trinity Aquifer is currently the topic of much political debate and its regulated status could very well change in the next couple of years (Eckhardt 2006a).

On February 25, 2002 SAWS delivered the first water from wells located in the Trinity Aquifer. This event pioneered the first non-Edwards Aquifer water to be introduced to the SAWS water distribution system (SAWS 2006b). In 2004, there were

11 wells in the Trinity Aquifer, located at the Oliver Ranch and BSR property sites. In February of 2000, SAWS signed a ten year contract to pump up to 4,500 acre-feet into their distribution system, supplied from up to eight wells at Oliver Ranch (Needham 2000a). In September of 2000, SAWS signed a contract to purchase up to 1,500 acre-feet of water per year from the BSR wells (Needham 2000b).

### 3.2.3. Carrizo-Wilcox Aquifer

The Carrizo-Wilcox Aquifer spans from the Rio Grande River in southwest Texas to northeast Texas and into the state of Louisiana and Arkansas. This aquifer crosses southern Bexar County and the SAWS service area as well as neighboring counties Wilson and Atascosa. The Carrizo-Wilcox Aquifer is primarily sand with some gravel, clay, silt, and lignite layers. Carrizo-Wilcox water can be treated by conventional methods or used as is. Due to the relatively lower permeability of this sand aquifer it is considered an ideal site for aquifer storage and recovery (ASR) (Eckhardt 2006b).

ASR is simply using an alternate aquifer to store surplus water for use at a later date. It is an ideal method of storage for several reasons. First, water is stored underground, so it is not subject to losses caused by evaporation like a surface reservoir. Second, storing water at an ASR site allows the people who pay for the site's development to benefit from the water withdrawal in times of shortage. Third, a primarily sand aquifer has a low permeability, meaning that when water is injected into an unconfined sand aquifer it forms a stationary dome, or in a confined sand aquifer it forms a horizontal layer around the well-pump. The water does not travel far, so it is there; ready to be withdrawn at a later date (Eckhardt 2006b). This system is an ideal solution to water shortages in the San Antonio area. The Edwards Aquifer is highly permeable and in times of intense rainfall the aquifer level rises quickly, and causes the connected streams to flood. In these times of surplus flow, water can be pumped from the Edwards Aquifer, treated (this requirement by law), transported to an ASR site, and injected into a sand aquifer for storage. In times of drought, this same water can be pumped from the ASR site, back into the utilities distribution system.

In 1999 and 2000, SAWS purchased 3,200 acres of agricultural land in southern Bexar County, over the Carrizo-Wilcox Aquifer (Needham 1999 and Needham 2000a). Over the next few years, SAWS designed and constructed its first ASR facility named the Twin Oaks Treatment Plant and Recovery Site. SAWS constructed several injection wells, a water treatment plant, and connected this site to its water distribution system with transmission lines. In February of 2002, to appease local interest groups, SAWS stated that it would only pump water if a stage III drought occurred and it would not pump more than 28,000 acre-feet over a period of two years from the ASR site (Needham 2002). The ASR facility came online during the audit year 2004. SAWS conducted routine tests, such as line flushing and injected approximately 1,809.5 MG of water into the Carrizo-Wilcox Aquifer (Haby, J., personal communication, July 26, 2005).

## 3.3. PROJECTED WATER SUPPLY REQUIREMENTS

In 2005, SAWS published a study entitled *Water Resource Plan Update*. It is a comprehensive review of a previous study completed in 1998 entitled *Securing Our Water Future Together, 1998 Water Resource Plan,* which was approved by San Antonio city council in 2000. This latest study has published projections for future water supply needs through the year 2050. The task force who completed these comprehensive studies formulated two scenarios: Planning Scenario 1 (PS1) and Planning Scenario 2 (PS2). PS1 encompasses the current SAWS service area as well as eight other small cities adjacent to SAWS service area. PS2 includes a much larger area, and plans for SAWS to serve as a regional wholesale water provider for all areas included in PS1 as well as the remainder of Bexar County (including BexarMet Water Utility), and portions of Comal, Kendall, and Medina Counties (SAWS 2005). Only the final results with regard to future water supply requirements will be discussed in this research paper. If the reader would like further information, including methodology behind these studies, please see these named SAWS studies which can be downloaded from <http://www.saws.org/our_water/waterresources/waterresourceplan>.

Fig. 3.3 shows the predicted amounts of water required (in acre-feet) through the year 2050 for PS1 and PS2 using a future per capita consumption of 122 GPCPD (cited as the consumption for a dry, critical year planning period) and predicted population growth estimates. In PS1, by the year 2050, an estimated 232,604 acre-feet of water will be needed. In PS2, by the year 2050, an estimated 312,028 acre-feet of water will be needed, keeping in mind that PS2 involves absorbing other existing utilities including the sources of water for each additional utility.

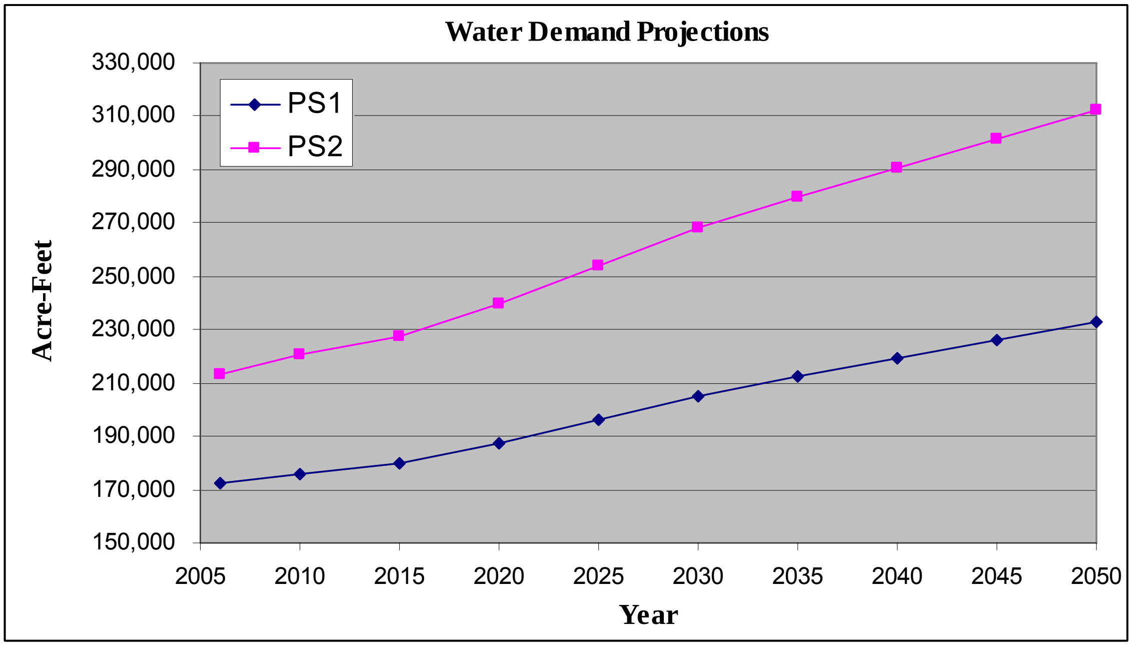


**Fig. 3.3** Water demand projections (after SAWS 2005).

## 3.4. SAWS INFRASTRUCTURE

SAWS infrastructure and distribution system is extensive, making it one of the largest water utilities in the United States. During the year 2004, SAWS increased their customer base as well as their number of metered connections by 2.8% (SAWS 2004a). It serviced a total of 315,116 potable water customers (SAWS 2004a) and maintained 4,324 miles of water main in their system (SAWS 2004). It can produce a maximum of 894.6 MGD and can store up to 159.6 MG of water (SAWS 2004a). SAWS has an extensive Supervisory Control and Data Acquisition (SCADA) system in place. This system constantly measures pipeline pressure at select points in the system, storage tank levels, flow at the well meters, flow at the high service pumps, runtime at the high service pumps, and many types of alerts, alarms, and water quality tests. The following sections detail some of the most important infrastructure components in SAWS within the context of a water loss audit.

### 3.4.1. Pumping Stations: Primary and Secondary

There are over 100 wells operated by the SAWS, currently located at 31 different pumping stations. There are two types of pumping stations in the SAWS; primary and secondary. Figs. 3.4 and 3.5 show each type of pumping station. In these two figures, the clock pictured represents the "run-time constant" method of measurement and the circle with the x inside represents the location of a flow meter. The squares with a "P" inside represent high service pumps and the circles with a "W" inside represents a well with a small well pump.

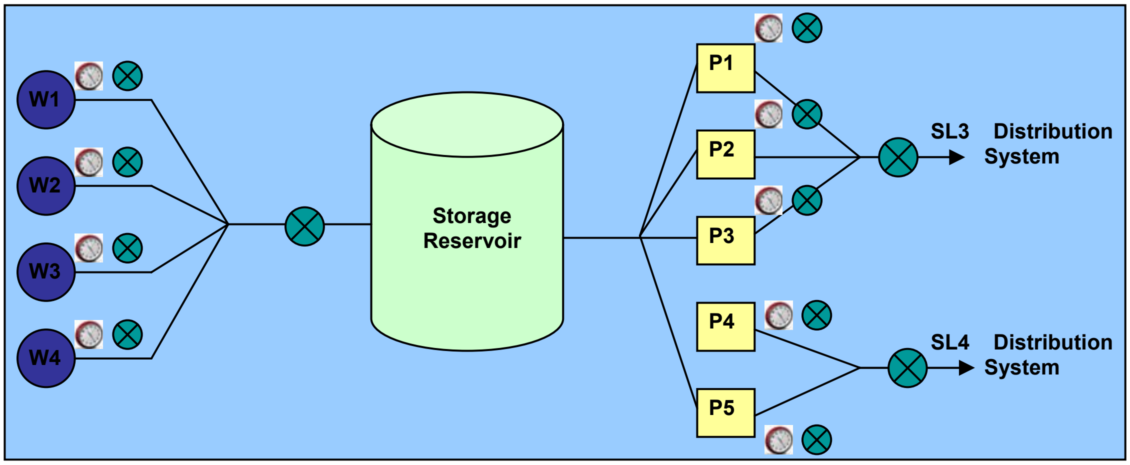


**Fig. 3.4.** Schematic diagram of a typical SAWS primary pumping station.

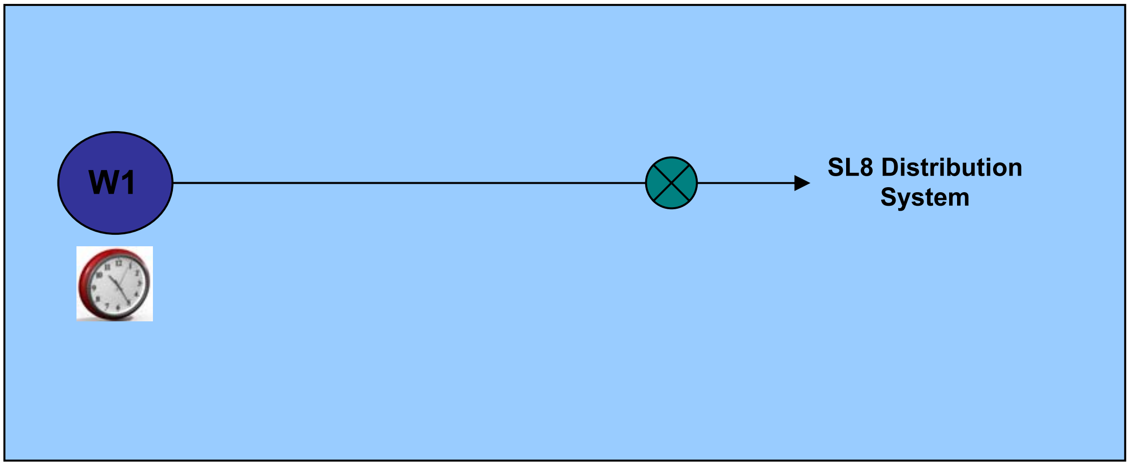


**Fig. 3.5.** Schematic diagram of a typical SAWS secondary pumping station.

Primary pumping stations have multiple wells drilled at each site. Each well is metered. Next, primary pumping stations sometimes have a branch meter placed prior to the storage reservoir. Primary pumping stations always have at least one storage reservoir tank at the site in varying sizes. After the storage tank, there are multiple high service pumps (HSPs). These HSPs pump water from the storage tank and into the distribution system. Each HSP has two forms of measurement. First, each HSP is metered. Second, the time each HSP is run per day is monitored. These runtime values (in hours) can be multiplied by a flow rate constant which then represents the total volume pumped from that specific HSP into the distribution system over the measured time period. More on this run-time constant method of measurement will be learned in section 4.1, *Determining System Water Input*. Last, water pumped from the HSP to the distribution system can, and typically is, sent to more than one pressure zone of the system. For example, in Fig. 3.4, the water is being transmitted into two different pressure zones (also called service levels – SL), three and four of the SAWS distribution system.

Secondary pumping stations are normally much simpler than the primary pumping stations. They are comprised of a single well which is connected to a single well pump. This well pump transmits water to a single pressure zone in the SAWS distribution system. The well pumps at secondary pumping stations are metered and each pump's run-time is monitored. Usually, secondary pumping stations do not have storage tank reservoirs, do not service more than one pressure zone, and although run time is recorded in the SCADA system, run-time constants are not always derived for the well pumps.

### 3.4.2. Booster Stations

San Antonio is known as being the gateway to the Texas hill country, and subsequently the elevation of the SAWS service area varies between a minimum of 420 feet and a maximum of 1900 feet. In order to provide adequate pressure in all water lines and service connections throughout the system in such a varied topography, SAWS has divided its system into approximately 12 major pressure zones. At the border between each pressure zones, there are booster stations to increase the water line pressure as it moves from one zone to another of increased elevation. The SCADA system monitors line pressure at both the suction and discharge points of the booster stations. This data was utilized in the unavoidable annual real loss analysis, as will be explained in section 4.2.

## 3.5. SAWS CONSERVATION EFFORTS

SAWS is well known for being a progressive utility company with regard to wise water use policies and conservation standards.  Notable conservation efforts already employed by SAWS include enforcing landscape watering restrictions when the Edwards Aquifer dips to a certain level (currently 650 feet), providing free low flow toilets to its customers, providing plumbing services to low income customers, extensive educational and advertising programs to make the population aware of the importance of water conservation and accountability, a tiered billing rate structure to emphasize wise water use, and a variety of rebates are available to customers willing to employ water saving measures in their homes (SAWS 2006a).  Also of interest is SAWS construction and future expansions of infrastructure which delivers re-cycled water to appropriate users such as golf courses or cooling plants (SAWS 2005).  Fig. 3.6 demonstrates the recent success of this utility in encouraging its' customers to minimize their daily water consumption.  It is appropriate to commend the SAWS Conservation Department's accomplishments.  It set a goal to reduce per capita consumption to 132 GPCPD by the year 2025.  SAWS saw this goal met much earlier, by 2004 (SAWS 2005).

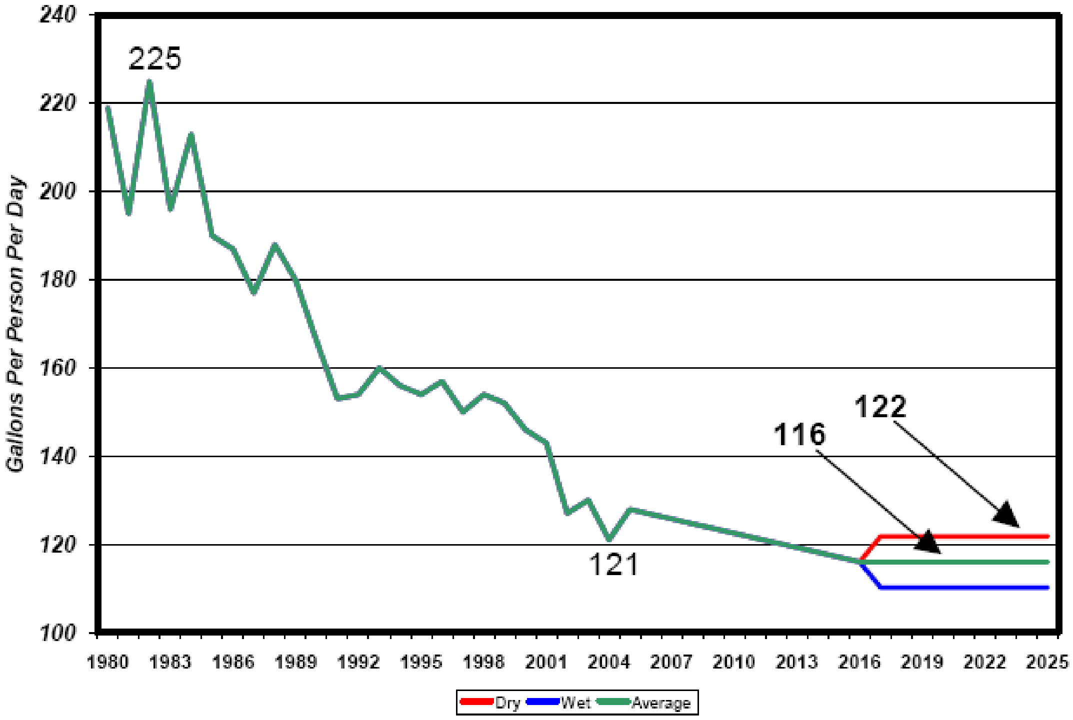


**Fig. 3.6.** Past and projected per capita consumption for SAWS (SAWS 2005).

Completing a detailed water loss audit according to the methodology of the IWA is another tool in SAWS already extensive portfolio of conservation policies and actions. SAWS Conservation Department sees the IWA water loss audit as a tool to direct their improvement efforts to areas in their system where it can achieve the greatest overall benefit.

# 4. ADAPTATIONS AND IMPROVEMENTS TO AUDIT METHODOLOGY

The purpose of this section is to discuss useful modifications to the original International Water Association (IWA) water audit methodology defined by *Performance Indicators for Water Supply Services* (Alegre et al. 2002). This water audit model has been adapted, refined, and in some instances expanded to incorporate the unique characteristics and management practices of the San Antonio Water System. These improvements will be of interest to anyone applying the original model, because many of the same questions will likely be encountered during the auditing process. This section will first describe the SAWS data used in the auditing process (Section 4.1), then discuss model improvements for calculating the system input volume (Section 4.2), next define methodology for analyzing unavoidable annual real losses (Section 4.3), then formulate methods for incorporating deferred consumption (aquifer storage and recovery system) into the audit (Section 4.4), and last define a process for assessing the accuracy of meter measurements throughout the system (Section 4.5).

## 4.1. DATA PROVIDED

SAWS has provided the following types of data which was used in completion of the water loss audit. It is important to note that the first two types of data listed can be linked by a common identifier – “point name”. These two combined data sets provided an extensive amount of information and was the basis for the majority of calculations in the audit. Only data sets pertinent to the water balance components discussed in this thesis are named.

- **Supervisory Control and Data Acquisition (SCADA) –** SAWS has an extensive SCADA system which measures pipeline pressure at select points in the system, storage tank levels, flow at the well meters, flow at the high service pumps, runtime at the high service pumps, and many types of alerts, alarms, and water quality tests. SCADA measurements were obtained in hourly time steps for the year 2004.
- **Geographic Information Systems (GIS) Data –** The given GIS database provides a wealth of information. The following named shapefiles directly apply to audit calculations. Shapefiles of all water mains in the service area included useful attributes such as length, installation date, material type, and main size. The topography of the City of San Antonio is hilly, therefore causing the SAWS service area to be divided into multiple pressure zones. Shapefiles of these pressure zones are provided. Also provided is a shapefile detailing the locations of all SAWS facilities. Facilities pertinent to this study are the locations of the primary and secondary pumping stations, booster stations, well fields, potable water storage tanks, fire hydrants, and maintenance centers. A shapefile detailing the measurement of all system pressure points has also been provided to the research team.
- **Leakage Detection Records –** SAWS has an aggressive and well documented leak detection/ location program in place aimed at reducing unaccounted-for-

water in their distribution system. Records provided include leak volumes found due to assignment gallons (leaks called in and reported by area residents) and survey gallons (leaks found by crews surveying the water lines).

- **Meter Calibration and Testing Records –** The SAWS meter testing shop regularly tests all large diameter meters (3” through 12” diameter) in the system every 18 months. They also test small diameter (mostly residential) meters (5/8” through 2” diameter) if the customer makes a request, if water bills have been abnormally high or low, or if it is time for a replacement meter to be installed. All meter tests are recorded and available for review in the meter testing shop.
- **ASR System Records –** The SCADA system measures the flow to and from the injection wells at the Twin Oaks Reservoir and Storage Facility separately from the SCADA system which monitors the water distribution system. Information from SAWS staff was obtained regarding testing of the ASR system as it came online as well as line flushing tests.
- **Personal contact with SAWS Employees -** A water audit is truly a multidisciplinary effort and obtaining first hand knowledge from SAWS staff will be of vital importance in completing the water loss audit.

## 4.2. DETERMINING SYSTEM WATER INPUT

### 4.2.1. Introduction

The process of determining total water input to the SAWS distribution system is made complex by several factors. First, water enters the system at individual wells, and the number of system input points (i.e., wells) is very high with over 100 points. These wells withdraw water from three different aquifers, one of which – the Edwards Aquifer – is highly regulated and requires careful data collection. Second, water enters the system at two types of pump stations. The majority of water entering the system is stored at primary pump station sites before being pressurized by high service pumps (HSPs) and entering the main body of the distribution system. However, secondary pump station sites input water directly to the system with high pressure well pumps rather than HSPs and do not have intermediate storage facilities. Third, the division of the SAWS distribution system into "service levels" (or pressure zones) also means that some HSP stations input water to multiple service levels requiring multiple data measurements. Fourth, SAWS has installed and developed two different technologies for measuring system input volumes – flow meters and runtime constant measurement. While data from both technologies is archived, they can produce very different values. Both types of measurements are not available at all system input points; thus, the best calculation possible for total system input requires mixing of values from the two technologies. Lastly, the existence of the Twin Oaks Aquifer Storage and Recovery (ASR) project means that some of the system input points are actually bi-directional input/output points.  Thus, care must be taken to ensure that flow volumes recorded there have appropriate directional information.

This section presents methodology for calculating total system water input for the SAWS distribution system for FY2004.  Varying methods of measurement are explained with pros and cons identified.  A final value for system input volume for FY2004 is determined.  Issues related to data accuracy and reliability are acknowledged.

### 4.2.2. Calculating System Input

Total system input is calculated by simple addition of selected values stored in the SAWS SCADA database combined with an adjustment for meter inaccuracy where applicable.  The specific SCADA points used are listed in Table 4.1 with a brief description of each.  In the FY2004 audit, all SCADA data was supplied by SAWS personnel at a time interval of 1 hour; that is, measurements were aggregated to values applicable for an hour’s operation each.  This time-step allowed high resolution inspection of the data while keeping data sets at a manageable size.  A total of 3,173,563 individual data values (metered and runtime hourly measurements) were analyzed to produce the total system input value.

**TABLE 4.1.** SCADA Points Used To Calculate System Input Volume

| SCADA Point Name | Description | Measurement Type | FY2004 Volume (MG) |
|---|---|---|---|
| *Primary Pump Stations* | | | |
| 34SSL3FL | 34th Street HSPs pumping to service level (s.l.) 3 | Runtime | 166.2 |
| 34SSL4FL | 34th Street HSPs pumping to s.l. 4 | " | 1,899.8 |
| AN1SLFL | Anderson Street HSP total | " | 6,677.2 |
| ARTSLFL | Artesia Street HSP total | " | 2,158.3 |
| BSNSLFL | Basin Street HSP total | " | 5,877.5 |
| MALSLFL | Maltsberger HSP total | " | 5,068.7 |
| MARSLFL | Marbach HSP total | " | 724.0 |
| MICSL5FL | Micron Drive HSPs pumping to s.l. 5 | " | 153.6 |
| MICSL7FL | Micron Drive HSPs pumping to s.l. 7 | " | 13.5 |
| MKTSLFL | Market Street HSP total | " | 3,736.4 |
| MSNSLFL | Mission Street HSP total | " | 3,125.5 |
| NC1SL5AFL | Nacogdoches #1 HSPs pumping to s.l. 5 | " | 1,641.4 |
| NC1SL6FL | Nacogdoches #1 HSPs pumping to s.l. 6 | " | 2,516.2 |
| NC2SL9FL | Nacogdoches #2 HSP total | " | 1,320.6 |
| PMSSLFL | Piper’s Meadow HSP total | " | 181.8 |
| RANSL4FL | Randolph HSPs pumping to s.l. 4 | " | 1,919.8 |
| RANSL6FL | Randolph HSPs pumping to s.l. 6 | " | 252.6 |
| SELSLFL | Seale Road HSP total | " | 590.0 |
| TC2SLFL | Turtle Creek #2 HSP total | " | 45.0 |
| WURSL5FL | Wurzbach HSPs pumping to s.l. 5 | " | 2,535.2 |
| WURSL7FL | Wurzbach HSPs pumping to s.l. 7 | " | 5,145.7 |
| SGASLFL | San Geronimo HSP total | " | 4.4 |
| SSHSLFL | S&S Hills HSP total | " | 6.9 |
| CTISLFL | Concept Therapy HSP total | " | 2.1 |
| CULSLFL | Culebra HSP total | " | 34.2 |
| *Secondary Pump Stations* | | | |
| BBCFI001 | Babcock Road well | Metered | 0.01 |
| BB1FI001 | Barbet #1 well | Metered | 0.3 |
| BB2SLFL | Barbet #2 well | Runtime | 447.6 |
| BSEFI001 | Basse Road well | Metered | 0.9 |
| BKGSLFL | Brackenridge wells total | Runtime | 565.1 |
| DRMSLFL | Dreamhill well | Runtime | 737.8 |
| GATSLFL | Gateway wells total | Runtime | 112.3 |
| KLSSLFL | Klaus Road well | Runtime | 752.1 |
| KWSLFL | Kelly wells total | Runtime | 395.4 |
| LC3FI001 | Lackland City #3 well | Metered | 119.8 |
| LC6FI010 | Lackland City #6 well | Metered | 379.7 |
| LC6FI020 | Lackland City #6A well | Metered | 515.4 |
| LLSSLFL | Loma Linda well | Runtime | 526.7 |
| NRSSLFL | Northwood Station well | Runtime | 792.2 |
| RAMFI001 | Ramsey Road well | Metered | 2.6 |
| STSFI001 | Stahl Road well | Metered | 0.7 |
| SUNSLFL | Sunshine well | Runtime | 149.5 |
| SUTSLFL | Sutton well | Runtime | 121.4 |
| TC3SLFL | Turtle Creek #3 well | Runtime | 152.4 |
| WLZSLFL | Walzem well | Runtime | 80.6 |
| WSTFI001 | West Avenue well | Metered | 5.4 |
| WLKSLFL | Woodlake well | Runtime | 76.7 |

**TABLE 4.1.** (continued)

| SCADA Point Name | Description | Measurement Type | FY2004 Volume (MG) |
|---|---|---|---|
| *Trinity Aquifer (Secondary) Pump Stations* | | | |
| BSRSLFL | BSR wells total | Runtime | 191.1 |
| ORRSLFL | Oliver Ranch wells total | Runtime | 1,002.10 |
| | TOTAL OF ALL STATIONS | | 52,924.35 |

Water enters the SAWS distribution network at two types of input stations. Primary pumping stations include one or more wells with low pressure well pumps, one or more on-site intermediate storage tanks, and multiple high service (i.e., high pressure) pumps (HSPs), as shown in Fig. 3.4. Most of the water entering the distribution does so at one of the 19 primary pump stations (about 87% in FY2004).

Flows are sometimes measured at the well pump discharges and are always measured at the HSP discharges. Since no withdrawals of water are made from the intermediate storage tanks other than to feed into the HSPs, the HSP discharges can be considered to be the points of system input with corrections for any spillage from the intermediate storage tanks.

Secondary pumping stations are generally characterized by a well with a high pressure pump that feeds directly into the distribution system with no intermediate storage, as in Fig. 3.5. These stations are used mostly to supplement system input during high demand periods and accounted for only about 13% of total input in FY2004.

At both primary and secondary stations two different methods were used to calculate water input. At almost all stations, meters have been installed on individual pumps' discharge lines. Several different meter types (including ultrasonic, turbine, totalizing, etc.) are used. However, SAWS staff's confidence in metered values is low for a variety of reasons. Many of the meters are not installed according to generally accepted practices that require meters to be located on long sections of straight pipe without bends. Other meters are installed too close to pump discharges. These installation issues severely affect meter accuracy due to improper flow conditions through the meters. Other meters must be read manually and are checked only at infrequent intervals. Thus, reported values may not correspond to the times when water actually passed through the meters.

The system input method given more credence by SAWS staff is the "runtime constant flow" method. In this method, volume of flow through a pump is determined by multiplying the length of time that the pump operates by the average volumetric flowrate through the pump. The average pump flowrate is termed the pump's "runtime constant." As an example, on January 6, 2004, Mission Street station HSP #1 operated for 17.16 hours, and the runtime constant for this pump is 8.5 million gallons per day (MGD). Thus, the volume of water input to the distribution system by this pump is:

$$\frac{17.16\ hours}{24\ {}^{hrs}\!/_{day}} \times 8.5 \frac{million\ gals}{day} = 6.08\ million\ gals \tag{4.1}$$

Volumetric flowrate through a given pump is determined by the pressure difference between the inflow and outflow sides of the pump. Analysis of system pressures performed as part of the UARL analysis (Section 4.2) found that pressure at a fixed point in the distribution system does not change significantly over time. Thus, the runtime constant method is a reasonable one. Additionally, a pump's flowrate may change with physical changes to the pump's components – e.g., corrosion or cavitation damage to an impellor. For this reason, it is advisable to regularly inspect pumps for damages and re-derive runtime constants. This activity was regularly performed by SAWS in past years in the "Pump Evaluation Program" (PEP) in the mid to late 1990s. At one time, each system pump was inspected and calibrated annually, but this evaluation is now done only on an "as needed" basis, according to SAWS staff. Past PEP evaluations have shown the runtime constant method to have accuracy "of about ± 3 - 5%" (Bilderback, personal communication, 2005).

The following tables demonstrate the variety of data that is collected and recorded at the pump stations. Data for the 34th Street primary pump station is presented in Table 4.2. This table organizes all variations of data measured by the SCADA system. It shows that water input can be quantified by metered flow at each of the individual five wells (columns two and three), runtime constant flow measurements at each of the individual five HSPs corresponding to the wells (columns four and five), and then by runtime constant flow measurements at separate inputs to both service levels three and four (columns six and seven). Notice that the total input flow (shown in the bottom row of the table) varies between the measurement methods. The two runtime constant flows are very similar as expected, whereas the metered flow is significantly less.

**TABLE 4.2.** Example Of Available System Input Data For The Primary Pump Station At 34$^{TH}$ Street

| Point Name | Metered Flow (MG/year) | Point Name | Runtime Flow (MG/year) | Point Name | Runtime Total Flow (MG/year) |
|---|---|---|---|---|---|
| 34SFI010 | 455.83 | 34SMN001 | 536.64 | 34SSL3FL | 166.20 |
| 34SFI020 | 999.06 | 34SMN002 | 1225.95 | 34SSL4FL | 1899.83 |
| 34SFI030 | 139.58 | 34SMN003 | 119.54 | | |
| 34SFI040 | 47.88 | 34SMN004 | 71.72 | | |
| 34SFI050 | 118.61 | 34SMN005 | 93.05 | | |
| **Total** | **1760.96** | **Total** | **2046.89** | **Total** | **2066.02** |

Table 4.3 is an excerpt of the summarized measurement volumes for a few of the secondary pump stations. There is a significant variation between metered flow values (columns one and two) and the runtime flow values (columns three and four) in this table. The runtime total flow values (columns five and six) are simply the previous runtime flows aggregated according to service level. Rounding errors are present in this addition of values. In the complete data set, there is no consistent pattern in the differences between metered and run-time flows. The complete data set for the system input analysis is included in Appendix B.

**TABLE 4.3.** System Input Flow Measurements For A Sampling Of The Secondary Pump Stations

| Station | Point_Name | Metered Flow (MG/year) | Point_Name | Runtime Total Flow (MG/year) |
|---|---|---|---|---|
| Turtle Creek 3 | TC3FI001 | 617.56 | TC3SLFL | 152.42 |
| Babcock Rd. | BBCFI001 | 0.013 | BBCSLFL | 0 |
| Barbet #1 | BB1FI001 | 0.29 | BB1SLFL | 0 |
| Barbet #2 | BB2FI001 | 541.61 | BB2SLFL | 447.61 |

As previously stated, SAWS staff has greater confidence in the runtime constant method for determining system input, although metered data are archived in the system's

SCADA database. Differences between metered and runtime data are very large in many cases; for FY2004, a few examples include differences of 15% at the 34th Street Primary Station, 56% at the Artesia Primary Station, and over 300% at the Turtle Creek #3 Secondary Station. Therefore, when estimating the total water volume input into the system preference was given to runtime constant measurements. All primary stations' flow volumes were estimated by runtime values, and 15 of the 24 secondary station totals were estimated by the runtime method. For nine of the secondary station totals runtime constant flows were either not in the SCADA database or were zero but the year's metered flow was some value greater than zero. For these cases, a conservative assumption was made that a data error existed in the runtime value, and the metered value represented a truer picture of water entering the system at that point; thus, the metered flow value was used at these points. These nine points' annual flow volume for FY2004 totals to 1,024.84 million gallons (MG), which is 1.9% of the system total.

Section 4.4 of this thesis describes the assessment of meter accuracy for all meters in SAWS. The analysis concludes that non-residential meters are evaluated to be 96.5% accurate. To determine a final system input volume, a meter accuracy adjustment is applied to the nine points in the system where metered flow values were used instead of the run-time constant method of measuring flow. The meters at the primary and secondary pumping stations are large diameter meters; therefore the non-residential meter accuracy value is applied to the 1,024.84 MG of measured system input. This equated to an apparent loss of 35.9 MG, which was added to the final measured system input volume.

Also, during maintenance phase testing of the ASR project, approximately 5 MG of water was pumped from the Carrizo-Wilcox Aquifer into the SAWS distribution system (Haby, personal communication 2005). This volume of water was also accounted for in the total system input volume.

### 4.2.3. Final Determination of System Input Volume

The total system input volume for FY2004 is about 52,965 million gallons. A confidence grade of "A2" has been assigned to this value. The reliability score is "A" (highly reliable) because records for all system input points were available for analysis. The accuracy score "2" (accuracy better than or equal ± 5%) corresponds to SAWS staff's expected reliability for the runtime constant flow method "of about ± 3 - 5%".

## 4.3. UNAVOIDABLE ANNUAL REAL LOSS ANALYSIS IMPROVEMENTS

The IWA water audit manual, *Performance Indicators for Water Supply Services*, (Alegre et al. 2000) provides an empirical formula for calculating unavoidable annual real losses (UARL), but does not provide detailed direction on how to apply this formula. The following sections describe the analysis procedures developed in this thesis to apply the UARL formula to SAWS.

### 4.3.1. Introduction to UARL Concept

Estimating Unavoidable Annual Real Losses (UARL) is an integral part of the water auditing process. The volume of UARL calculated for a specific water system represents the volume of losses that are “acceptable” in the auditing period. These losses are usually leaks that are small enough to be undetectable or leaks that are uneconomical to repair (Kunkel 2002). UARL provides a baseline for allowable losses in a water system and is compared to the value for real losses. The IWA audit manual, *Performance Indicators for Water Supply Services* (Alegre et al. 2000), utilizes the UARL value in the calculation of the Infrastructure Leakage Index (ILI) performance indicator (Operational Indicator 25). This indicator is a very succinct measure of the relative magnitude of losses in the water distribution system. The ILI is computed as the system real losses divided by the UARL. Therefore, an ILI value of 1.0 would mean that a system has eliminated all real losses economically feasible, and ILI values greater than 1.0 indicate that real losses exceed the lowest feasible levels for the system. The importance placed on this indicator transfers to the importance of calculating UARL values correctly.

The UARL calculation has several inputs; length of water mains, number of service connections in the system, average operating pressure throughout the system, and average length of service connections.

Extensive international research efforts have produced the following empirical equation for calculating UARL (Alegre et al. 2000, Kunkel 2002, Philadelphia Water Department 2004):

$$UARL = P \times N_C \times 365 \times \left[ \left( \frac{5.4 L_M}{N_C} \right) + 0.13 + 7.5 L_P \right] \tag{4.2}$$

where $UARL$ is calculated in units of gallons per year, $P$ is the average operating pressure of the system in units of pounds per square inch (psig), $N_C$ is the number of service connections in the system, $L_M$ is the total length of water mains in miles, and $L_P$ is the average length per service connection in miles. (The presentation of UARL calculations by Kunkel [2002] includes some typographical errors. The equation presented above includes corrections of these errors and is in agreement with Alegre et al. [2000] and Philadelphia Water Department [2004], the latter source being written by a group chaired by George Kunkel).

Three separate methods are described here for computation of UARL. These methods differ in their levels of complexity, required resources, and potential accuracy, but they allow SAWS staff and other auditors some flexibility in performing future audits. Method A is the most complex and potentially most accurate method; it relies upon analysis using both database (e.g., Microsoft Access) and geographic information system (GIS, e.g., ESRI ArcView) software. Method B reduces complexity by not requiring use of GIS software but still separates the database analysis by SAWS pressure zones. Method C is the simplest method available and relies on simple arithmetic means of system pressures without regard for pressure zone differences.

Each calculation method is described in detail below. Accuracy of the methods is compared in the conclusion of this section.

### 4.3.2. UARL Method A: Full GIS and Database Analysis

Method A is the most complex set of procedures determined in this project to calculate UARL. This method includes database querying to determine time-averaged pressure at 66 pressure points in the distribution system and spatial interpolation in GIS from these pressure points to estimate pressure along the 4,380 miles of mains while respecting pressure zone boundaries. Then, further spatial analysis is used to determine the weighted product of system pressure and main length needed in equation 4.2. In the remainder of section 4.2.2, Method A concepts and mathematical calculations will be presented. Also, a step-by-step procedure for using Method A is included in Appendix A of this thesis.

Method A begins by rewriting the UARL equation above (equation 4.2) as:

$$UARL/365 = \left(5.4 \times L_M \times P\right) + \left(0.13 \times N_C \times P\right) + \left(7.5 \times L_P \times N_C \times P\right) \qquad (4.3)$$

where both sides now produce daily UARL values, and the three terms on the right-hand side represent, respectively, losses along mains, losses at service connection taps on mains, and losses along service connection lines. The coefficients 5.4 and 7.5 both have units of gallons/day/psig/mile of pipe; a fundamental assumption in this calculation is that unavoidable losses are driven by length of pipe and pressure in the pipe. Pressure in a water distribution system is not the same at all locations due to two factors: (1) friction losses as water flows through pipes, and (2) design of the system to include pressure zones with boundaries created by booster pumps and pressure reducing valves. Thus, careful consideration must be given to determining the pressure *P* used in the UARL calculation.

The procedure adopted in Method A is to separate the pressure zones from each other and then in each zone spatially interpolate pressure in the mains based on a selection of pressures measured in that zone. This required further modification of equation 4.3:

$$UARL/365 = \left[ 5.4 \times \sum_{pz} \left( \sum_{i} L_{M,i} \times P_i \right)_{pz} \right] + \left( 0.13 \times N_C \times P_{swm} \right) + \left( 7.5 \times L_P \times N_C \times P_{swm} \right) \qquad (4.4)$$

where *pz* is an index on pressure zone, *i* is an index on pipe-pressure elements (small segments of pipe where pressure is within a specified range), and $P_{swm}$ is the spatially weighted mean pressure in the entire system, calculated as:

$$P_{swm} = \frac{\sum_{pz} \left( \sum_{i} L_{M,i} \times P \right)_{pz}}{L_M} \qquad (4.5)$$

This approach seeks to increase accuracy by mapping the interpolated system pressure surface onto the pipe locations to find the spatially weighted mean pressure. While detailed maps of mains were used in the audit, no data was collected on the location of service connections, and no mapping or interpolation was performed on service connection lines. Thus, it is assumed that spatial density of service connections in the system is proportional to density of mains, and the spatially weighted mean pressure is applicable to mains and service connections alike.

The pressure points used in the analysis are listed in Table 4.4 by SCADA name with pressure zone in which each is located and the location type of the pressure point (midpipe, pump discharge, or pump suction). Pump discharge and suction points were included in the analysis to increase the available number of pressure points, and these were carefully selected so that discharge and suction points balanced each other out in a specific pressure zone to avoid biasing the mean pressure value too high or low. Assessment of variation in hourly pressure at individual points found very little change over the course of the year, and time-averaged annual values were used for all calculations.

**TABLE 4.4.** Pressure Points Used In UARL Analysis

| Pressure Zone | Pressure Point | 2004 Average Pressure (psig) | Point Type |
|---|---|---|---|
| **2** | P18PI140 | 66.3 | Midpipe |
| | SEWPI140 | 66.4 | Midpipe |
| | VALPI140 | 97.2 | Midpipe |
| **3** | BKHPI140 | 82.0 | Midpipe |
| | DELPI140 | 74.5 | Midpipe |
| | FARPI140 | 76.1 | Midpipe |
| | H90PI140 | 63.0 | Midpipe |
| | LOCPI140 | 54.8 | Midpipe |
| | PHSPI140 | 72.6 | Midpipe |
| | PYRPI140 | 91.4 | Midpipe |
| | RIVPI140 | 70.4 | Midpipe |
| **4** | ACMPI140 | 85.7 | Midpipe |
| | BRPPI140 | 63.4 | Midpipe |
| | BURPI140 | 58.1 | Midpipe |
| | CARPI140 | 49.1 | Midpipe |
| | FSTPI140 | 86.8 | Midpipe |
| | LTCPI140 | 85.1 | Midpipe |
| | MERPI140 | 41.6 | Midpipe |
| | TRHPI140 | 49.8 | Midpipe |
| | WILPI140 | 96.3 | Midpipe |
| | WLZPI140 | 75.7 | Midpipe |
| **5** | BUCPI140 | 75.6 | Midpipe |
| | CROPI140 | 51.5 | Midpipe |
| | EDNPI140 | 84.4 | Midpipe |
| | PMSPI140 | 76.7 | Midpipe |
| | SHRPI140 | 69.5 | Midpipe |
| | WESPI140 | 52.5 | Midpipe |
| **6 & 9** | ENPPI140 | 60.9 | Midpipe |
| | ENSPI150 | 65.2 | Pump Discharge |
| | JDBPI140 | 42.8 | Pump Suction |
| | JUDPI140 | 111.8 | Midpipe |
| | JUNPI140 | 91.8 | Midpipe |
| | PKNPI140 | 93.7 | Midpipe |
| | SSEPI140 | 44.7 | Pump Discharge |
| | STSPI001 | 74.0 | Midpipe |
| **7** | BSQPI140 | 80.1 | Midpipe |
| | BTRPI140 | 105.5 | Pump Discharge |
| | CALPI140 | 83.5 | Midpipe |
| | CLNPI140 | 73.8 | Midpipe |
| | DRHPI140 | 75.0 | Midpipe |
| | GRNPI140 | 76.8 | Midpipe |
| | GULPI140 | 62.8 | Midpipe |
| | HARPI140 | 77.6 | Midpipe |
| | HUNPI140 | 88.6 | Midpipe |
| | INGPI140 | 40.0 | Midpipe |
| | OAKPI140 | 103.1 | Midpipe |
| | OCKPI140 | 73.4 | Midpipe |
| | OKWPI140 | 85.1 | Midpipe |
| | TZLPI140 | 103.1 | Midpipe |

**TABLE 4.4.** (continued)

| Pressure Zone | Pressure Point | 2004 Average Pressure (psig) | Point Type |
|---|---|---|---|
| **8** | I10PI140 | 126.2 | Pump Discharge |
| | INWPI140 | 77.6 | Pump Discharge |
| | MDBPI140 | 58 | Pump Discharge |
| | SSBPI140 | 58 | Pump Discharge |
| | UNIPI160 | 70.5 | Pump Suction |
| | WC1PI140 | 75.6 | Pump Suction |
| **10 & 11A** | ENSPI140 | 109.3 | Pump Discharge |
| | EVNPI140 | 24.9 | Pump Suction |
| | WINPI140 | 64.8 | Pump Discharge |
| **11 & 12** | ARBPI150 | 13.3 | Pump Suction |
| | CDRPI140 | 107.9 | Pump Discharge |
| | DOMPI140 | 90.9 | Pump Discharge |
| | HILPI140 | 155.7 | Pump Discharge |
| | RGRPI150 | 52.9 | Pump Suction |
| | RT2PI140 | 49.2 | Pump Discharge |
| | WC2PI140 | 123.7 | Pump Discharge |
| | WLBPI140 | 121.1 | Pump Discharge |

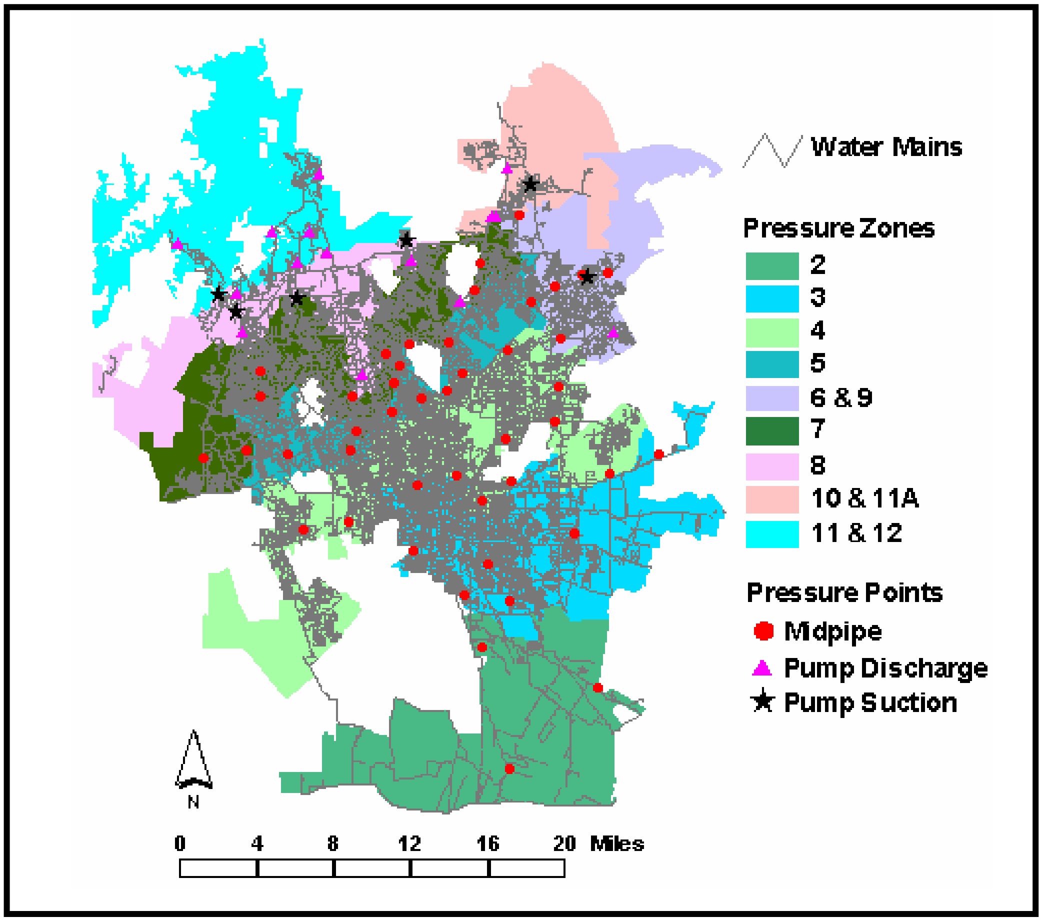
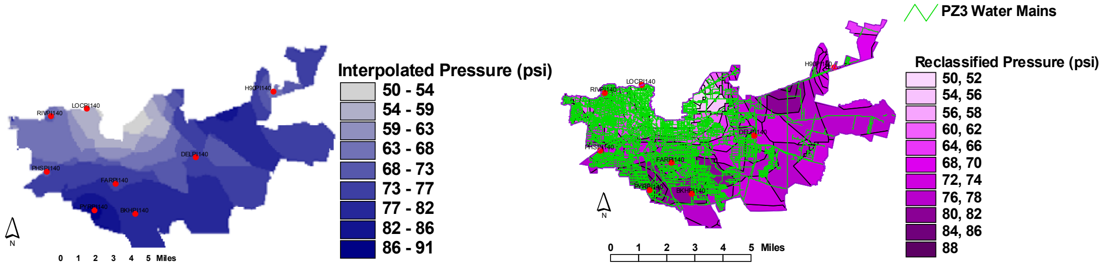


**Fig. 4.1.** Map of pressure zones, pressure points, and water mains used in UARL analysis.

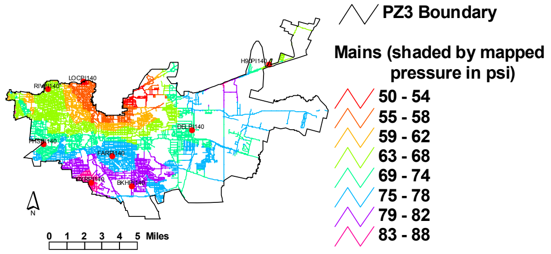
It was necessary to combine three pairs of pressure zones for various reasons. Pressure zone six had only one pump suction point available, so it was combined with zone nine. The location of points in zones 10, 11, and 12, combined with the geographical shape of these zones caused difficulties for the spatial interpolation routine in the GIS software. Thus, zones 10 and 11A were combined, and zones 11 and 12 were combined. Although these changes likely introduce some small error in the calculations, it is expected to be negligible as the length of mains in these zones is about ten percent of the total for the system. A map of the final set of pressure zones and pressure points is shown in Fig. 4.1.

In each pressure zone, average pressure was spatially interpolated on a small-cell grid using an inverse distance weighting (IDW) algorithm in GIS. Pressure within each zone was interpolated using only the listed pressure points within the zone. The grid of continuously valued pressures was then reclassified to values incremented by two psig. This step was necessary to accommodate later spatial analysis functions in the GIS. As an example of what this step did, a specific point in the distribution system might have an interpolated pressure of 55.7 psig based upon nearby pressure points. The grid cell over this point would have had its pressure value reclassified to 56 psig. A nearby point having interpolated pressure of 54.8 psig would have its pressure value reclassified to 54 psig. The reclassified pressures were then mapped onto water mains in the pressure zone. This step produced a large set of segments of water main in each zone, where each segment had finite length and a constant pressure along that length. Each zone's mapped main-pressure segments were then tabulated and totaled to produce the lengths of main in that zone at each possible value of pressure from 0 to 156 psig in increments of two psig. Then, the products of length and pressure were summed in each zone to produce the term $\left(\sum_i L_{M,i} \times P_i\right)_{pz}$ needed in equation 4.4 above. This process is illustrated schematically for pressure zone three in Fig. 4.2. The computed zonal values of total main length, pressure-main length product, and weighted pressure (i.e., pressure-length product divided by total main length) are given in Table 4.5 for all zones.



*(b) Pressure values reclassified to 2 psig increments with mains*

*(a) Static pressure IDW interpolated to continuous values*



*(c) Reclassified pressure values mapped on to main segments*

| | *Pressure Zone 3* | | |
|---|---|---|---|
| **Segment** | **LENGTH (ft)** | **PRESSURE (psi)** | **L x P (ft*psi)** |
| 1 | 444 | 76 | 33730.6 |
| 2 | 1046 | 76 | 79533.6 |
| 3 | 33 | 56 | 1861.9 |
| 4 | 184 | 66 | 12149.3 |
| ↓ | ↓ | ↓ | ↓ |
| 21846 | 127 | 74 | 9371.1 |
| 21847 | 13 | 74 | 955.0 |
| 21848 | 10 | 74 | 746.6 |
| 21849 | 7 | 74 | 492.2 |

**$\sum$ L =** 4,918,008 ft
**$\sum$ L =** 931.44 mi

**$\sum$ L x P =** 344,761,456 ft*psi
**$\sum$ L x P =** 65,296 mi*psi

*(d) Tabular calculation of main segment length-pressure products and zonal sum*

**Fig. 4.2.** Spatial analysis and calculation of the product of main length and system pressure for pressure zone 3.

The number of service connections in the SAWS distribution system $N_C$ was assumed to be equal to 315,000, the number of system customers stated in the FY2004 SAWS Annual Report. The length and exact location of individual service lines were not obtained. It was assumed that service line density was directly correlated with main density in the pressure zones.

**TABLE 4.5.** Zonal And Total Values Of Main Length, Main Length-Pressure Product, And Weighted Pressure

| **Pressure Zone** | **Length of Mains (mi)** | **Main Length** x **Pressure (mi·psig)** | **Weighted Mean Pressure (psig)** |
|---|---|---|---|
| 2 | 172 | 13,750 | 79.7 |
| 3 | 931 | 65,296 | 70.1 |
| 4 | 1,199 | 83,881 | 70.0 |
| 5 | 485 | 37,915 | 78.2 |
| 6 & 9 | 299 | 23,017 | 77.0 |
| 7 | 864 | 67,139 | 77.7 |
| 8 | 255 | 20,376 | 80.0 |
| 10 & 11A | 69 | 2,986 | 43.4 |
| 11 & 12 | 106 | 10,408 | 98.5 |
| Total System | 4,380 | 324,767 | 74.2 |

Average length of service lines was estimated at 50 feet and varied between 25 and 75 feet to understand the sensitivity of the final UARL value to this parameter. If average service line length is outside of this range, further calculations should be performed to revise the UARL calculation.

Filling in numerical values in equation 4.4, the final UARL calculation is thus:

$$UARL/365 = \left[5.4\times(324,767)\right] + \left[0.13\times(315,000)\times(74.2)\right] + \left[7.5\times\left(\frac{50}{5280}\right)\times(315,000)\times(74.2)\right] \tag{4.6}$$

This yields 6.452 million gallons per day or 2.355 billion gallons per year. This value represents 4.4% of the system input of 52.965 billion gallons per year determined in section 4.1.

As mentioned above, the average service line length was assumed to be 50 feet. To test sensitivity of the UARL value to this parameter, UARL was computed for average service line lengths of 25 and 75 feet. The corresponding UARL values were 2.051 and 2.657 billion gallons per year, respectively, representing ±12.9% of the baseline UARL value. Thus, while some sensitivity exists to the assumed average service line length, the baseline UARL value of **2.355 billion gallons per year** can be used with some confidence.

### 4.3.3. UARL Method B: Database Analysis Including Individual Pressure Zones

Method B is a somewhat simplified set of procedures compared to Method A in that it does not require further use of GIS software and relies upon past GIS analysis for main length totals in the individual pressure zones. It does preserve the separation of the pressure zones in intermediate calculations. However, the main length-pressure product is calculated using a simple arithmetic mean of the pressure points in the zone rather than the spatially weighted mean pressure used in Method A. In the remainder of section 4.2.3, Method B concepts and mathematical calculations will be presented. Also, a step-by-step procedure for using Method B is included in Appendix A of this thesis.

The Method A UARL equation above (equation 4.4) is now re-written as:

$$UARL/365 = \left[5.4 \times \sum_{pz}\left(L_{M,pz} \cdot \overline{P}_{pz}\right)\right] + \left(0.13 \times N_C \times \overline{P}_{sys}\right) + \left(7.5 \times L_P \times N_C \times \overline{P}_{sys}\right) \qquad (4.7)$$

where $L_{M,pz}$ is the length of mains in a single pressure zone, $\overline{P}_{pz}$ is the arithmetic mean of average annual pressure of the pressure points within a single pressure zone, *pz* is an index on pressure zone, and $\overline{P}_{sys}$ is the system average pressure computed as:

$$\overline{P}_{sys} = \frac{\sum_{pz}\left(L_{M,pz} \times \overline{P}_{pz}\right)}{L_M} \qquad (4.8)$$

where $L_M$ is total length of mains in the system. All definitions of pressure zones and pressure points remain as in Method A (see Table 4.4). Calculations for main length-pressure products and system average pressure are shown in Table 4.6.

**TABLE 4.6.** Zonal, Total Main Length, And Pressure Calculations

| **Pressure Zone** | **Main Length,** $L_{M,pz}$ **(mi)** | **Zonal Mean Pressure,** $\overline{P}_{pz}$ **(psig)** | $L_{M,pz}$ x $\overline{P}_{pz}$ **(psig·mi)** |
|---|---|---|---|
| 2 | 172 | 81.8 | 14,112 |
| 3 | 931 | 73.0 | 67,975 |
| 4 | 1,199 | 69.2 | 82,901 |
| 5 | 485 | 68.3 | 33,151 |
| 6 & 9 | 299 | 73.1 | 21,847 |
| 7 | 864 | 80.6 | 69,666 |
| 8 | 255 | 77.7 | 19,769 |
| 10 & 11A | 69 | 66.3 | 4,561 |
| 11 & 12 | 106 | 89.3 | 9441 |
| System Total | 4,380 | 73.9 | 323,423 |

Table 4.6 can be directly compared to Table 4.5 to see the differences in calculated values introduced by the simplifying assumptions of Method B. Several zones see very small changes in mean pressure. Generally these zones had very small differences in average pressure among the zone’s included pressure points or the spatial density of mains was highly correlated with the density of pressure points. A few zones have large differences in mean pressure, notably 5, 10 & 11A and 11 & 12. Zone 5 has a very uneven geographical distribution of pressure points compared to main locations. The latter two zones had no midpipe pressure points and uneven main locations. Fortunately, the respective changes appear to cancel each other out with a very small change in the system mean pressure (-0.3 psig).

Assumptions regarding service connections and service line lengths remain unchanged from Method A. The Method B UARL calculation is thus:

$$UARL/365 = \left[5.4 \times (323,423)\right] + \left(0.13 \times (315,000) \times (73.9)\right) + \left(7.5 \times \left(\frac{50}{5280}\right) \times (315,000) \times (73.9)\right) \tag{4.9}$$

Equation 4.9 yields 6.426 million gallons per day or **2.345 billion gallons per year**.

The Method B value is 0.4% less than that of Method A. This difference is extremely small and appears to justify the simplifying assumptions used in Method B. However, it should be remembered that several pressure zones had significant changes in mean pressure values. As the SAWS distribution system expands (especially in pressure zones 10, 11, and 12), careful consideration should be given to periodically revising the GIS analysis and comparing to the simplified values of Method B.

### 4.3.4. UARL Method C: Database Analysis without Pressure Zones

Method C is the most simplified set of procedures compared to the two previous methods. It does not require any use of GIS software, and it does not preserve the separation of the pressure zones in intermediate calculations. System mean pressure is a simple arithmetic mean of the 66 pressure points given in Table 4.4.

The Method A UARL equation above (equation 4.4) is now re-written as:

$$UARL/365 = \left[5.4 \times L_M \times \bar{P}\right] + \left(0.13 \times N_C \times \bar{P}\right) + \left(7.5 \times L_P \times N_C \times \bar{P}\right) \tag{4.10}$$

where $\bar{P}$ is the simple arithmetic mean of all 66 pressure points. This mean for 2004 is 76.0 psig. All other values are as previously discussed. The Method C UARL calculation is thus:

$$UARL/365 = \left[5.4 \times (4,380) \times (76.0)\right] + \left(0.13 \times (315,000) \times (76.0)\right) + \left(7.5 \times \left(\frac{50}{5280}\right) \times (315,000) \times (76.0)\right) \tag{4.11}$$

Equation 4.11 yields a UARL value of 6.612 million gallons per day or **2.414 billion gallons per year**. This represents a change of +2.5% over the Method A value. As higher UARL values will lead to lower values of the Infrastructure Leakage Index (ILI), this change is not a conservative one, although it is a small one.

### 4.3.5. Summary of UARL Calculations

Three methods of differing complexity have been presented for computing unavoidable annual real losses (UARL). Results from the three methods are summarized in Table 4.7.

**TABLE 4.7**. Summary Of UARL Calculations

| **Method** | **UARL (billion gal/yr)** | **Change from Method A** | **Percentage of System Input*** |
|---|---|---|---|
| A | 2.355 | - | 4.45% |
| B | 2.345 | -0.4% | 4.43% |
| C | 2.414 | +2.5% | 4.56% |

* Compared to the system input (52,965 MG) as calculated in Section 4.1.

While Method A is considered the most accurate method, the value produced by Method B is remarkably similar and requires much less effort. However, the SAWS system is expanding with miles of main growing by about two percent each year (based on 2002-2004 data). Future audits should every few years re-evaluate the need for revised spatial analysis, inclusion of more pressure points, separation of currently combined pressure zones, etc., to ensure accuracy of the UARL value. It is believed that Method B may be used for the next two years with reasonable accuracy. Method C may be used if very quick results are needed, but these results should be revised when possible by a Method A or B calculation.

## 4.4. DEFERRED CONSUMPTION ACCOUNTING

It is recommended that a “deferred consumption accounting” category be added to the traditional water balance diagram (shown in Fig. 2.1). When incorporating the SAWS aquifer storage and recovery (ASR) project into this standard water balance model, there was no obvious category for this type of water use and supply, therefore an updated and more adaptable water balance model was developed (shown in Fig. 4.3). The following sub-sections detail the limitations of the “International Standard Water

Balance" model in the context of SAWS and then describe the applications and operation of the improved water balance.

### 4.4.1. Introduction to ASR Operations

During the audit year, 2004, SAWS initiated operation of its ASR project. Throughout the course of the year, SAWS tested the Twin Oaks ASR facility, transmitting Edwards Aquifer water to the ASR site, injecting the water into the Carrizo-Wilcox Aquifer, and then subsequently withdrawing water from the ASR site, and transporting it back into the SAWS distribution system. In the operation of the ASR project, SAWS uses its distribution system infrastructure to transport water to and from the ASR site. In addition to withdrawing stored Edwards Aquifer water from the ASR site, SAWS also has rights to withdraw native Carrizo-Wilcox water. Currently there are not restrictions or capped withdrawals on the Carrizo-Wilcox Aquifer (like there is with the Edwards Aquifer), but to be prepared for any future regulatory changes SAWS should also properly account for the amounts of Carrizo-Wilcox water it withdraws. The year 2004 proved to be a wet year in the area; therefore use of this facility to supply water was not needed. In dryer years to come, it will be an important source of water supply for SAWS. A reliable accounting method for water withdrawn from both the Edwards and Carrizo-Wilcox aquifers at the ASR project is necessary.

### 4.4.2. ASR Departure from Standard Water Balance Accounting

Integrating the ASR project into standard water auditing procedures is a challenging task. The basic/original model does not allow for water to be input from regular production wells and then transmitted through the distribution system to be stored until a later unknown date. This process does not occur on a convenient one year time scale as the audit is intended. An improved model is needed to account for circumstances where produced water is stored somewhere (in a surface reservoir, an aquifer, above ground tanks, etc) until it is needed at a later date. This scenario applies only when the distribution system is also used as the transmission system (Brumbelow et al. 2006).

### 4.4.3. Improved Water Balance Accounting

Fig. 4.3 is a revised version of the International Standard Water Balance (Lambert et al. 2000) including deferred accounting principles. New entries in this figure are described as follows. Under conditions where water is being sent to the ASR site, the amount of water input into the distribution system contains a portion that will be stored at the ASR site and is best described as “deferred consumption”. Deferred consumption is an authorized activity which does not produce immediate revenue (Brumbelow et al. 2006). Under conditions where water is withdrawn from the ASR site and supplied to the SAWS distribution system, both stored Edwards and native Carrizo-Wilcox water is supplied to the system. This amount of water is best described as "previously deferred and now supplied". According to the modified water balance in Fig. 4.3, when water is withdrawn from the ASR project it is deemed Edwards water until the volume of cumulative input into the ASR site is reached. Then, any further volume of water pumped from the ASR site is deemed to be Carrizo-Wilcox water. This is a convenient and necessary accounting approach to model the behavior of the ASR project; however, SAWS makes no effort to distinguish between the two "types" of water being withdrawn. The volume of Carrizo-Wilcox water supplied to the distribution system is considered to be a part of the "water newly supplied" category in the modified water balance.

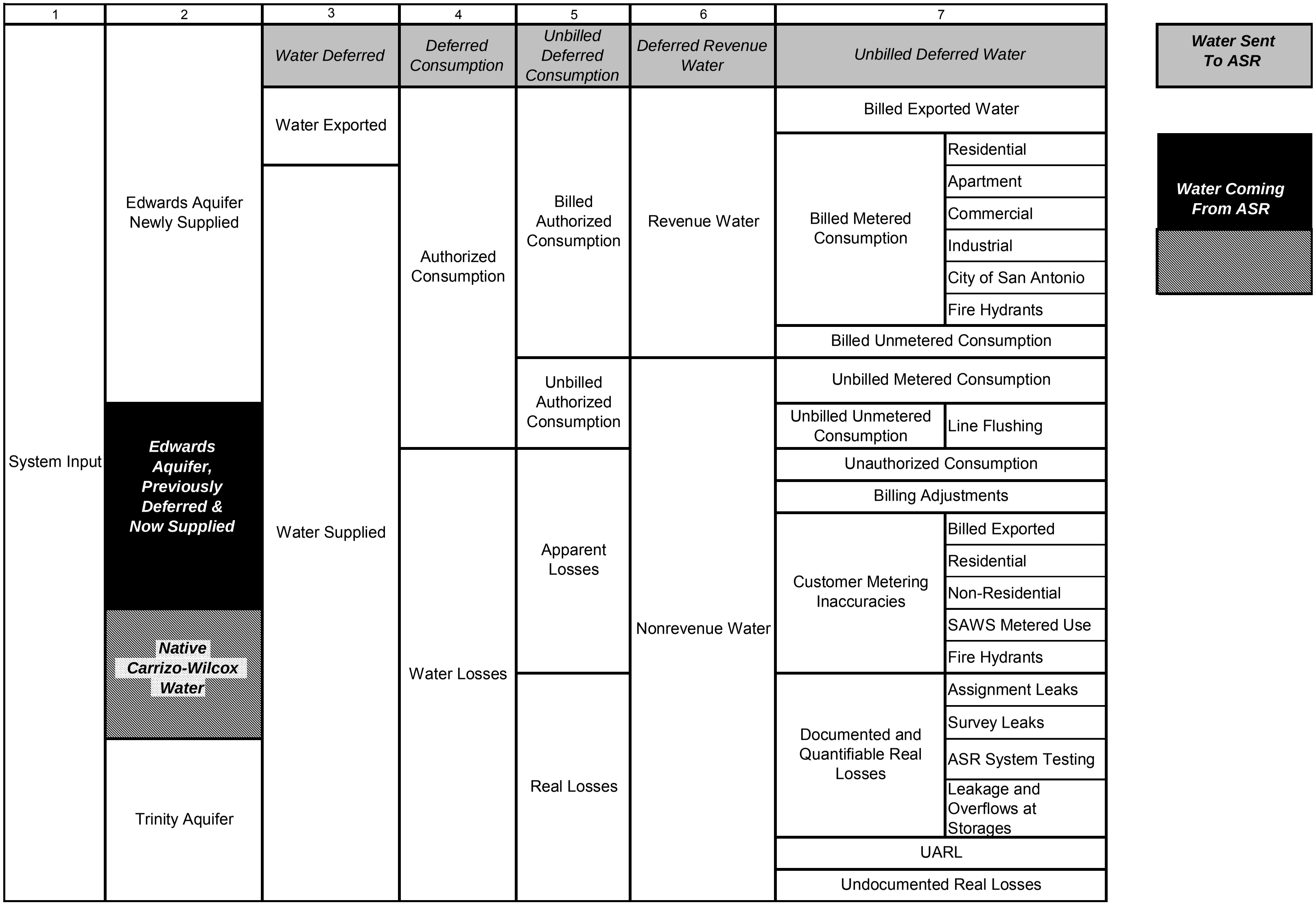


Fig. 4.3. Single year distribution system water balance (Brumbelow et al. 2006).

Fig. 4.4 is a representation of accounting principles behind the on-going operation of the ASR site, not limited to the one-year audit timetable due to the presence of “carryover” quantities being assessed. This schematic depicts the previous discussion in symbolic terms where both Edwards and Carrizo-Wilcox Aquifer water is present at the ASR facility. During periods of water withdrawal (recovery) from this site, first any positive accounting credits of Edwards Aquifer water are used. (The term accounting credit is used to identify and track the volume of Edwards Aquifer water stored at the ASR site over time.) When the positive accounting credits of Edwards Aquifer water are used up from storage, any additional volumes of water withdrawn from the ASR site are counted as native Carrizo-Wilcox Aquifer water. This figure also includes carry-over quantities from year to year to account for cumulative storage of Edwards Aquifer water. When the ASR project is in recovery mode and supplying water to the distribution system, any water introduced to the system is first subtracted from available stored Edwards Aquifer water according to quantities assessed in Fig. 4.4 and then introduced into that specific year’s water balance as *Edwards Aquifer, Previously Deferred and Now Supplied*. The ASR site is monitored by a SCADA system independent of the SAWS distribution system, so it is possible to accurately and comprehensively account for all water volumes represented in Figs. 4.3 and 4.4.

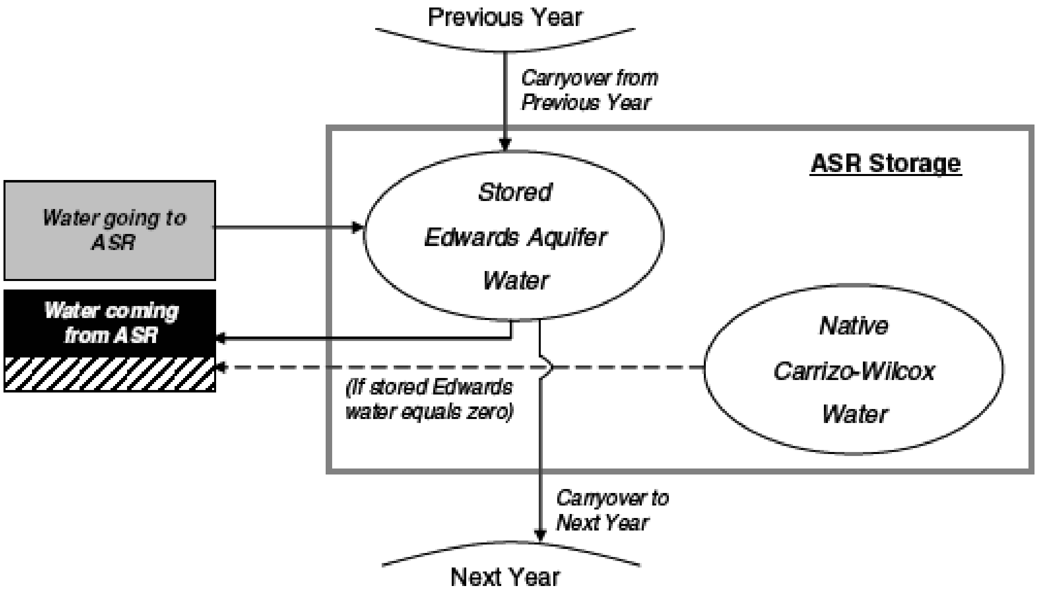


**Fig. 4.4.** Single year stored water balance with carryover quantities (Brumbelow et al. 2006).

## 4.5. ASSESSING METER ACCURACY

Metering water use at the customer end is an important method of enforcing water accountability. Therefore, one of the most critical tasks in an IWA water loss audit is quantifying the accuracy of meters in the utility system. This task is essential to successful utility operations because these customer meters are a significant source of income for the utility. If these customer meters are consistently under-registering, then a larger amount of water reaches the end user than the meter measures. This is a source of lost income for the utility and its cost per unit of water “lost” is valued at the consumer water fee. Conversely, meters can also over-register, creating dissatisfied customers with higher water bills than are appropriate. This section describes the methodology used in the meter accuracy analysis of SAWS for the IWA water loss audit. First, in section 4.4.1, guidelines for determining meter accuracy according to the IWA audit procedures are reviewed as well as shortcomings. Second, in section 4.4.2, details are given on SAWS meter testing procedures as well as statistics on meter sizes, age, and locations. Third, in section 4.4.3, the improved procedure developed for assessing meter accuracy for SAWS is described in detail.

### 4.5.1. How Does Meter Accuracy Fit into the Audit Methodology?

According to the International Standard Water Balance (shown in Fig. 2.1), *Customer Metering Inaccuracies* fall under the category of *Apparent Losses*. These apparent losses are an important sub-category of non-revenue water. Apparent losses are more expensive and charged at the customer retail cost of water, because they are lost at the customer delivery point in the water system.

Section A of the IWA audit manual describes how each component of the water balance is calculated. Calculation box A22 from the IWA manual is named “Metering Inaccuracies Water Losses”. Many of these calculation boxes contain formulas, definitions, or instructions for how the water balance component should be calculated. There are no such suggested procedures for determining this component of the water balance (Alegre et al. 2002); therefore new calculation procedures were developed, which are described in section 4.4.3. Once the metering inaccuracy water balance component is calculated (A22), it is needed for the following performance indicator calculations:

- Water resource indicator 1 – Inefficiency of use of water resources.

- Operational indicator 23 – Apparent losses.
- Operational indicator 24 – Real losses.
- Financial indicator 37 – Non-revenue water by cost.

Although, no direction is given in the IWA auditing format, AWWA has completed many studies on metering procedures and technology as well as formulated standards which SAWS meter testing shop follows carefully. Estimating meter accuracy is a very important task in the grand scheme of completing a water loss audit, and care should be taken to correctly develop a set of procedures and assumptions according to thorough tests and previous research studies.

### 4.5.2. Inventory of SAWS Meters

SAWS has an extensive meter testing program and shop. All of the following information, in section 4.5.2, was obtained from Louis Gutierrez, Jr., the Foreman for Meter Repair, who is in charge of operations in the SAWS meter testing shop. The information was obtained during a site visit on March 17, 2006.

As of March 2006, there were a total of 339,343 meters throughout the system. Meter sizes range from 5/8-inch through 12-inches in diameter. Residential meters are sizes 5/8-inch through 3/4-inches in diameter. Meters sizes 1-inch through 2-inches are typically used for apartments and small businesses. Commercial/industrial meters are 3-inches through 12-inches in diameter. The standard replacement age for all small diameter meters (5/8" through 2") is 15 years. This is the suggested meter replacement schedule according to AWWA Manual M6 entitled *Water Meters – Selection,* *Installation, Testing, and Maintenance* and is incorporated into SAWS operating procedures. Large diameter (3” through 12”) water meters are normally used longer than 15 years, until they can no longer be recalibrated or repaired to perform under acceptable accuracy ranges. The SAWS meter testing shop routinely tests all large diameter meters in the system every 18 months. Testing of small diameter meters does not occur over a similar routine time frame. Instead, small meters are tested for accuracy for one of the following reasons:

- A customer calls in complaining about an abnormally high water bill.
- SAWS staff notices abnormal behavior in records, such as unusually high or low bills or water consumption rate and believes there is a leak or the meter is at fault.
- If a customer fails to pay their water bill, SAWS will remove their water meter and test it in the meter shop before re-circulating it back into the field.
- Meters 15 years old are automatically removed and not tested for accuracy.

Meter tests are completed in accordance with AWWA Manual M6. High, medium, and low flow rates are tested for each meter and the percent accuracy is recorded. Table 4.8 shows acceptable accuracy ranges of meter flow tests for small diameter size meters, obtained from the SAWS Meter Testing Shop. Small diameter size meters are shop tested, therefore the flow rate and volume of water transmitted through each meter is standardized based upon meter size. Large diameter meters are tested in the field; therefore the flow rates and volumes used for testing are not standard and therefore not displayed in the table below. The SAWS Meter Testing Shop made all meter test records available for review and analysis.

**TABLE 4.8.** Parameters For Shop Testing Of Small Diameter Size Meters

| Meter Size | Test | Test Flow Rate (GPM) | Volume (ft^3) | Acceptable Accuracy (%) |
|---|---|---|---|---|
| 5/8" | High | 13 | 1 | 98.5 to 101.5 |
| | Medium | 2 | 1 | 98.5 to 101.5 |
| | Low | 1/4 | 1 | 90 to 101.5 |
| 3/4" | High | 13 | 1 | 98.5 to 101.5 |
| | Medium | 2 | 1 | 98.5 to 101.5 |
| | Low | 1/4 | 1 | 90 to 101.5 |
| 1" | High | 40 | 10 | 98.5 to 101.5 |
| | Medium | 4 | 10 | 98.5 to 101.5 |
| | Low | 3/4 | 1 | 95 to 101.5 |
| 1 1/2" | High | 80 | 10 | 98.5 to 101.5 |
| | Medium | 8 | 10 | 98.5 to 101.5 |
| | Low | 1 1/2 | 10 | 95 to 101.5 |
| 2" | High | 120 | 10 | 98.5 to 101.5 |
| | Medium | 25 | 10 | 98.5 to 101.5 |
| | Low | 4 | 10 | 95 to 101.5 |

The meters in SAWS are produced by a variety of manufacturers. Fig. 4.5 graphically shows the distribution of meters among the different manufactures.

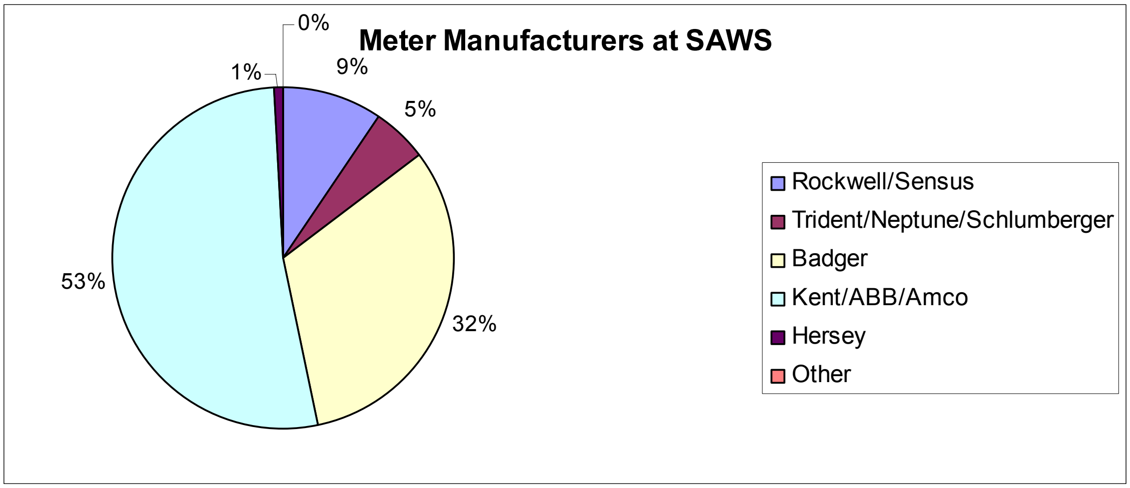


**Fig. 4.5.** Distribution of water meters according to brand manufacturer.

## 4.5.3. Procedure Developed for Meter Accuracy Assessment

### *4.5.3.1. Data Collection*

The author conducted a site visit to SAWS meter testing shop and sampled test records. It is important to note that when sampling test records, a significant effort was made to randomly sample records from a range of meter manufactures and to gather records only from tests completed in 2005 and 2006. This range of two years was selected for the following reasons.

- Recent data was more readily available.
- It encompassed the 18 month routine meter test time span for commercial/industrial meters, ensuring that the same meter would not have more than one test represented in the sample.

- By using two years of meter test data, a larger sample of records was available to represent the whole system. This is important for the larger size meters, because there are few of them in the system.

See Table 4.9 to view number of samples for each meter size in comparison with the total number of meters in the system.

**TABLE 4.9.** Samples Of Meter Test Records Categorized According To Meter Size

| **Meter Size** | **Meters in Service** | **Meter Records Sampled** |
|---|---|---|
| 5/8" | 295,906 | 165 |
| 3/4" | 20,631 | 18 |
| 1" | 10,341 | 21 |
| 1 1/2" | 6,040 | 9 |
| 2" | 4,238 | Records disregarded* |
| 3" | 894 | 35 |
| 4" | 711 | 26 |
| 6" | 414 | 19 |
| 8" | 122 | 16 |
| 10" | 44 | 10 |
| 12" | 2 | 0 |
| **Total** | **339,343** | **319** |

* Records were disregarded for 2-inch meters due to non-representative sample.

### *4.5.3.2. Data Analysis*

After meter testing records were gathered, the high, medium, and low flow accuracy information was assimilated into spreadsheet format and organized by size of meter for easy analysis. For each division of meter size, a simple average was calculated for each of the three flow categories. See Table 4.10 to view an example of the categorized and averaged data for the sample of ten-inch meters.

**TABLE 4.10.** Average Accuracy Calculations For Sample Of 10-Inch Water Meters

| | | *% Accuracy* | | | | |
|---|---|---|---|---|---|---|
| **Date Set** | **Year Tested** | **High Flow** | **Medium Flow** | **Low Flow** | **Make** | **Model** |
| 1995 | 2005 | 100 | 99 | 100 | Hersey | MFM-MVU |
| 1996 | 2005 | 98 | 98 | 98 | Hersey | MFM-MVU |
| 2000 | 2005 | 98 | 97 | 100 | Hersey | ? |
| ? | 2005 | 98 | 98 | 97 | Rockwell | Turbine |
| 1990 | 2005 | 100 | 100 | 100 | Rockwell | Turbine |
| 1987 | 2005 | 98 | 98 | 98 | Rockwell | Turbine |
| 1998 | 2005 | 98 | 97 | 98 | Neptune | Turbine |
| 2001 | 2005 | 99 | 99 | 100 | Neptune | Turbine |
| 2000 | 2005 | 100 | 99 | 100 | Hersey | FM-MVR |
| 2002 | 2005 | 99 | 100 | 100 | Hersey | FM-MVR |
| | Average = | 98.8 | 98.5 | 99.1 | | |
| | Weighted Average of Tested Meters = | 98.9 | | | | |
| | Estimated Average Accuracy for all 10” Meters in System = | 99.4 | | | | |

Once average accuracy of the meter was calculated for each of the three flow categories, weighting factors were applied to these three percentages to estimate the overall accuracy of each size of water meter. Bowen (1993) (cited by Yee 1999) recommends the following formula for calculating weighted average meter accuracy.

In equation 4.12, $W_{Ave}$ is the weighted average accuracy of tested meters, $A_{LF}$ is the average test result flow accuracy at low flow and in accordance $A_{MF}$ is at medium flow and $A_{HF}$ is at high flow.

$$W_{Ave} = 8.8\%(A_{LF}) + 18.5\%(A_{MF}) + 72.8\%(A_{HF}) \tag{4.12}$$

In Table 4.10, the weighted average accuracy for the test sample of 10-inch water meters was calculated as 98.9% using equation 4.12. The weighting factors described in the cited studies (Yee 1999, Bowen 1993) of residential water use were also applied to commercial/industrial sized meters (as shown in this example, Table 4.10). This application of the residential weighting factors to larger meters is obviously out of the scope of these particular studies. However, they were used because there were no other fitting alternatives at this time.

At this point in the meter accuracy analysis, another set of assumptions were applied to relate the accuracy tests to true field conditions for all meters in the system. First, small diameter meters are discussed. SAWS does not routinely test these smaller sized meters. Instead they are tested upon customer request, when SAWS staff notices irregularities in water bills, or before sending a meter that was removed from a non-paying customer back out to the field. This irregular testing scheme likely results in a sample of meters biased to underreporting of customer usage when compared to the total population of meters. As an attempt to minimize this bias, the sample of small diameter meters tested was assumed representative of meters nearing the end of standard service life, and the final estimate of meter accuracy was determined as the average of (1) the value aggregated from the meter test records and (2) a value of 100% accuracy. This is based on the following assumptions.

- Accuracy of new water meters decreases at a constant rate over time (Yee 1999).
- New meters placed into service are 100 percent accurate (AWWA 1999).

For the case of large diameter meters, routine testing procedures were carried out by SAWS, so confidence in the accuracy results for this part of the analysis are greater. As was done for small diameter meters, overall large diameter meter accuracy was determined as the mean of (1) the test results and (2) a value of 100%. In Table 4.10, the final estimated average accuracy for all 10-inch meters in the system is 99.4 percent. This, second step of averaging was completed for the large diameter meters based upon the following assumption.

- Each time the meters are routinely tested (every 18 months), if they are determined to be outside the specified range of accuracy, they are repaired to meet this standard or are replaced with a meter that does meet the standard. Therefore, after each routine test, the meters are assumed to be 100 percent accurate. This accuracy will deteriorate linearly over time until it reaches the accuracy which the next routine test defines. Thus, the halfway point between the test value and 100 percent is the best estimate of the representative accuracy for all meters in the system of that particular size.

With regard to customer metering inaccuracies, the water audit is ultimately interested in determining two things; (1) the volume of water (gallons/year) lost due to under-registering meters and (2) the monetary value associated with this amount of water lost.

Table 4.11, shows final calculations for determining the total amount of water lost due to metering inaccuracies in the SAWS. Column three in the table is simply the estimated average accuracy for all meters in the system according to size. (Column three is the final result of calculations completed in Table 4.10.) There are no numbers for both the two-inch and 12-inch meter sizes in this table. This is because the two-inch meter testing data was considered to be a non-representative sample of the system. Thirty-nine two-inch meter test records were gathered and analyzed. The estimated average accuracy for all two-inch meters in the system was calculated to be 39.7 percent from this sample. This of course seems abnormally low, considering none of the other meter sizes dipped anywhere near this value. Looking back at the sample of test records for the two-inch meter, many of these records registered zero accuracy for all flow levels indicating the meter is completely broken. It is likely in these instances that these problems were quickly identified from the SAWS billing record system, and that the broken meters were quickly replaced. The 12-inch meters had no data available during the 2005 to 2006 year time span that meter data records were gathered. There are only two 12-inch meters in service in the entire SAWS utility. It is not known why there are no records of recent meter tests for these two meters, possibly these two meters are newly installed.

The purpose of column four in Table 4.11 is to calculate a representative percentage of meter accuracy for residential (small diameter) versus non-residential (commercial/industrial large diameter) meters. This was completed by weighting each individual meter size average accuracy (column three) according to the overall proportion of each meter size in the system. Therefore, since there are 295,906 5/8-inch meters of a total of 337,156 residential meters in the system, obviously the 5/8-inch size meters weighting is much greater in proportion. Representative accuracies of 97.2% for residential meters, and 96.5% for non-residential meters were calculated according to equation 4.13.

$$A_R = \frac{X_{5/8}N_{5/8} + X_{3/4}N_{3/4} + X_1N_1 + X_{3/2}N_{3/2}}{N_{5/8} + N_{3/4} + N_1 + N_{3/2}} \tag{4.13}$$

Where $A_R$ = Weighted average accuracy for residential meters.

$X_i$ = Estimated average accuracy for each size of meter $i$.

$N_i$ = Number of meters in service for each size of meter $i$.

This same formula was utilized for non-residential meter sizes.

The volumes of water displayed in column five in Table 4.11 were determined by an alternate member of the research project team, Dr. Cheryl Linthicum of UTSA. She was able to determine the amount of water billed out to residential and to commercial/industrial customers by reviewing SAWS accounting records. This volume of water is used to determine the volume of water lost due to under-registering meters (column six) according to equation 4.14. An important assumption at this point in the discussion is that residential accounting records act in consistency with our assumption that all meters 5/8-inch through two-inches are residential. We are counting the billing account type “apartment” to be part of residential. In parallel, we must assume that all commercial/industrial accounting records are consistent with meters three-inches through 12-inches being non-residential. The City of San Antonio account type is being incorporated into the commercial/industrial category. In reality, it is very possible that two-inch meters could fall into either categories as well as other meters close in size.

$$M_{error} = V_R(1 - A_R) + V_{c/i}(1 - A_{c/i}) \tag{4.14}$$

Where $M_{error}$ = Apparent losses due to meter errors (gal/year).

$V_R$ = Average annual volume for residential meters (gal/year).

$V_{c/i}$ = Average annual volume for commercial/industrial meters (gal/year).

$A_R$ = Weighted average accuracy for residential meters.

$A_{c/i}$ = Weighted average accuracy for commercial/industrial meters (gal/year).

**TABLE 4.11.** Final Meter Analysis Showing Volume Of Losses Due To Meter Error In SAWS

| Classification | Meter Size | Average Accuracy for Meter Size | Weighted Average Accuracy for Classification | Average Annual Volume for Classification (MG/year) | Classification Apparent Loss (MG/year) |
|---|---|---|---|---|---|
| Residential | **5/8"** | 97.2% | 97.2% | 34,836 | 1,057 |
| | **3/4"** | 96.8% | | | |
| | **1"** | 99.9% | | | |
| | **1 1/2"** | 94.3% | | | |
| | **2"** | Sample thrown out. | | | |
| Non-Residential | **3"** | 94.9% | 96.5% | 14,431 | 407.7 |
| | **4"** | 96.3% | | | |
| | **6"** | 99.4% | | | |
| | **8"** | 99.3% | | | |
| | **10"** | 99.4% | | | |
| | **12"** | No data available. | | | |
| | | | | **Total (MG/year) =** | 1,465 |

Upon conclusion of the analysis of system wide meter accuracy in the SAWS utility, in 2004 approximately 1.465 billion gallons of water did not generate revenue due to consistently under-registering meters, where commercial/industrial meters are slightly less accurate than residential meters. This apparent loss of water accounts for approximately 2.79% of the system input for the year 2004 and translates to lost revenue of approximately $2.46 million.

# 5. SAWS WATER LOSS AUDIT RESULTS

This section presents all final results from the analysis and application of IWA audit methodology, including recommended improvements, on the SAWS for FY2004. First, the water balance is presented along with both quantitative and qualitative descriptions of each pertinent category in the figure.  Next, the most important performance indicators are defined and discussed as they were applied to SAWS. Together, these two items provide a comprehensive picture of SAWS, and gage the utilities operational efficiency and performance during 2004.  These are the end products of an IWA audit and should be calculated every year from 2004 and on, to compare the system's performance and progress over time.

## 5.1. FINAL WATER BALANCE

Fig. 5.1 displays an adaptation of the original water balance diagram (shown in Figure 2.1), which has been customized to fit operational characteristics unique to SAWS.  Included in this updated water balance are system output quantities (column eight), which are either forms of consumption or losses in million gallons (MG) of water. Some of these system output categories are shaded yellow. The shaded quantities represent new additions or further refinement of the description of the water balance category so that it is more applicable to SAWS. Also, the deferred accounting quantities are now included in the water balance, as a means to accurately track storage and recovery volumes of Edwards Aquifer water in the operation of the ASR project. Last, column two in Figure 5.1 is a new addition to the water balance diagram. SAWS produces all of its own water from a variety of sources (SAWS does not import water), which it plans to diversify over time. The purpose of column two is to divide the system input into volumes of water acquired from each source. In the audit year, 2004, these potential sources included the Edwards Aquifer, the Trinity Aquifer, and the Carrizo-Wilcox Aquifer. In future years, this column will need to be redefined to include any new water sources. Section 5.2 explains each water balance output category (column seven of Figure 5.1) with particular emphasis on the components discussed in section 4 of this paper (UARL methodology, deferred water concept, and meter accuracy assessment).

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| System Input<br>**52, 965.2 MG** | Edwards Aquifer Newly Supplied<br>**51,731 MG** | *Water Deferred*<br>**1,809.5 MG** | *Deferred Consumption*<br>**1,809.5 MG** | *Unbilled Deferred Consumption*<br>**1,809.5 MG** | *Deferred Revenue Water*<br>**1,809.5 MG** | *Unbilled Deferred Water*<br>**1,809.5 MG** | | *1809.5* |
| | | Water Exported<br>**115.5 MG** | Authorized Consumption<br>**49,686.3 MG** | Billed Authorized Consumption<br>**49,517.9 MG** | Revenue Water<br>**49,517.9 MG** | Billed Exported Water | | 115.5 |
| | | Water Supplied<br>**51,040.2 MG** | | | | Billed Metered Consumption<br>**49,402.4 MG** | Residential | 27173.0 |
| | | | | | | | Apartment | 7663.0 |
| | | | | | | | Commercial | 11746.0 |
| | | | | | | | Industrial | 2089.0 |
| | | | | | | | City of San Antonio | 596.0 |
| | | | | | | | Fire Hydrants | 135.4 |
| | | | | | | Billed Unmetered Consumption | | 0.0 |
| | | | | Unbilled Authorized Consumption<br>**168.4 MG** | Nonrevenue Water<br>**7,882.3 MG** | Unbilled Metered Consumption | | 114.4 |
| | ***Edwards Aquifer, Previously Deferred & Now Supplied***<br>**0 MG** | | | | | Unbilled Unmetered Consumption | Line Flushing | 54.0 |
| | | | Water Losses<br>**7,713.9 MG** | Apparent Losses<br>**5,162.1 MG** | | Unauthorized Consumption | | 82.4 |
| | | | | | | Billing Adjustments | | 3590.3 |
| | | | | | | Customer Metering Inaccuracies<br>**1,489.4 MG** | Billed Exported | 4.0 |
| | | | | | | | Residential | 975.3 |
| | | | | | | | Non-Residential | 501.4 |
| | ***Native Carrizo-Wilcox Water***<br>**5 MG** | | | | | | SAWS Metered Use | 4.0 |
| | | | | | | | Fire Hydrants | 4.7 |
| | | | | Real Losses<br>**2,551.8 MG** | | Documented and Quantifiable Real Losses<br>**2,551.8 MG** | Assignment Leaks | 178.3 |
| | | | | | | | Survey Leaks | 22.7 |
| | Trinity Aquifer<br>**1,193 MG** | | | | | | ASR System Testing | 5.0 |
| | | | | | | | Leakage and Overflows at Storages | 0.2 |
| | | | | | | UARL | | 2345.5 |
| | | | | | | Undocumented Real Losses | | 0.0 |
| **52,965.2** | | **Total (MG of Water)** | | | | | | **59,210** |

**Fig. 5.1** Water balance, adapted to SAWS, with finalized system input and output volumes.

## 5.2. WATER BALANCE OUTPUT COMPONENTS

The water balance output components (column seven) are described in order from top to bottom.

### 5.2.1. Unbilled Deferred Water

This category records the volume of water that is withdrawn from the Edwards Aquifer, and then is transferred through the SAWS distribution system to the Twin Oaks ASR site for storage in the Carrizo-Wilcox Aquifer until it is needed in the future. In 2004, 1,809.5 MG of water was stored at the ASR site (Murray et al. 2006). When completing this water balance diagram for the next auditing period (FY2005), it is imperative to remember that this *unbilled deferred water* category is not a cumulative storage amount. The balance resets to zero at the end of the auditing period, however the amount of deferred water left at the conclusion of the auditing period is available for use during the next period. This water should be accounted for according to carryover principles as in Fig. 4.4. In recovery mode for the ASR project, once this *unbilled deferred water* category reaches zero and the cumulative Edwards Aquifer water stored is also zero according to Fig. 4.4, any more water pumped from the ASR site is considered to be native Carrizo-Wilcox Aquifer water and should be quantified as such in column two of Fig. 5.1.

### 5.2.2. Billed Exported Water

This category quantifies the volume of water sold and exported to other water service providers. SAWS regularly exports water to the City of Elmendorf via two six-inch diameter metered connections, and also to East Central Water Supply Corporation via three eight-inch diameter metered connections. (Martinez, personal communication, 2006, cited in Murray et al. 2006) As shown in Fig. 5.1, during 2004, SAWS exported and received revenue for a total of 115.5 MG (Murray et al. 2006).

### 5.2.3. Billed Metered Consumption

This category quantifies the volume of water consumed by registered customers whose meters are read monthly and then are appropriately billed. SAWS has six different types of billing accounts; residential, apartment, commercial, industrial, City of San Antonio, and fire hydrants. Residential, apartment, commercial, and industrial are typical metered water uses which totaled a consumption of 48,671 MG, as shown in Fig. 5.1. The City of San Antonio account type pertains to water used by city agencies such as the parks and recreation department, city buildings, etc. The volume of metered consumption by the city totaled to 596 MG of water. The fire hydrant account type is an estimate of the amount of SAWS water used at construction sites. SAWS leases fire hydrant meters monthly to contractors, who temporarily use the fire hydrants as water supply during construction processes. These fire hydrants are metered; therefore, each customer is appropriately billed for their water use. Metered fire hydrant consumption totaled to 135.5 MG for 2004 (Murray et al. 2006).

### 5.2.4. Billed Unmetered Consumption

Billed unmetered consumption quantifies the volume of water used and paid for by customers without metered connections. These customers may be charged a flat fee per month or the volume of water used may be estimated by an approved SAWS procedure and then payment is made upon the estimated consumption. Potential customers for this type of water use are city agencies such as the Parks and Recreation Department, Department of Public Works, fire departments, or other municipal government water uses. In the SAWS, this category of water use does not exist at this time; therefore the assigned consumption volume in Fig. 5.1 is zero (Murray et al. 2006). This is largely due to the fact that presently all City of San Antonio accounts are metered (per section 5.2.3). The billed unmetered consumption category is retained in this water balance in order to provide flexibility in case this category is needed in the future.

### 5.2.5. Unbilled Metered Consumption

This category quantifies the volume of water that is consumed by customers whose meters are read, however revenue is not collected. Water use that falls into this category within the SAWS is metered consumption for SAWS building facilities. SAWS had 116 metered connections, which registered a total water use of 114.4 MG for 2004 (Murray et al. 2006). Of course, SAWS does not pay itself for this water use.

### 5.2.6. Unbilled Unmetered Consumption

This category quantifies the volume of water consumed without metering or payment for its use. This type of water use occurs in the SAWS when the Operations Department uses water for line flushing after the repair of water mains and meters. Line flushing is performed by opening fire hydrants and releasing water in an effort to remove any debris from the system. Since, this use is unmetered; an estimated volume consumed for each flush is calculated with recorded information on the length of time water was discharged, the estimated line pressure, and the size of the water main supplying the fire hydrant. Information was not available for flushing estimates during FY2004; therefore data for 2005 was substituted, assuming that the consumption in 2004 would be similar. SAWS estimated 4.5 MG of water was used for line flushing in June and November of 2005. These monthly volume estimates were assumed to be representative of the unbilled unmetered monthly consumption for 2004, totaling to a yearly use of 54 MG. (Murray et al.)

### 5.2.7. Unauthorized Consumption

This category quantifies the volume of water consumed without authorization from the water utility and, of course payment is not received for its use. This category is often called “water theft”, which can occur through illicit service connections, bypassing of customer meters, tampering with meters to make them more “customer friendly”, or by installing new meters without setting up an account with the utility (Murray et al. 2006). Unauthorized consumption was estimated by collecting information from law enforcement, the SAWS customer service department, and Utility Revenue Management (a consulting firm conducting a separate project focused on revenue recovery). During 2004, twenty-eight instances of meter bypassing were discovered as well as one case of a customer using water without being registered in the billing system. This totaled to unauthorized consumption, non-revenue water losses, of 82.4 MG (shown in Fig. 5.1) (Murray et al. 2006).

### 5.2.8. Billing Adjustments

Billing adjustments are a unique addition to the original water balance diagram aimed at addressing an anomaly in the method SAWS uses to manage their billing system. SAWS customer billing system also serves as a means to reimburse or wave fees to their customers when necessary. Instead of maintaining a separate database to account for these refunds, SAWS using the billing record database and “erases” water use on customer accounts to provide appropriate refunds to their customers.

For example, a customer whose meter reads that 20,000 gallons of water was used in January 2004 is owed a $25 refund for a particular reason. When refunding the customer, SAWS subtracts an equivalent of $25 worth of water from their account for that month. Assuming that the residential retail cost of water is $0.14 per 100 gallons, the customer would owe $28 for their water usage that month. When applying the $25 refund, SAWS updates the customer’s billing record to read that only 2,143 gallons of water used in January 2004 and now charges the customer $25 less on their water bill for that month.  This is a water accounting problem because recorded water consumption in the SAWS billing records is less than the actual amount of water used by the customers.

Dr. Linthicum, an Associate Professor of Accounting at the University of Texas at San Antonio, examined SAWS billing records and was able to “recover” the amounts of water which was “erased” due to these billing procedures.  It amounted to an apparent loss of 3,590.3 MG, which is equivalent to approximately $6 million worth of refunds (Hubbard, 2005, personal communication, as cited in Murray et al. 2006).  The research team highly recommends that SAWS modifies their current accounting practice and separates consumption records from billing records so that this irregularity is not a problem in the future.

### 5.2.9. Customer Metering Inaccuracies

Customer metering inaccuracies are defined as the discrepancy between the amount of water actually consumed and the amount of water reportedly consumed due to under or over registering meters.  This type of error can be beneficial or detrimental to the utility, although typically meters tend to under-register more often then over-register. This category in the water balance is extremely important, and can pin-point a large source of revenue loss.  In a utility system which depends upon metered connections to bill the customer, completing a thorough meter accuracy analysis is essential to maintaining efficient operations.  If the analysis concludes that meters are under-registering significantly, it is imperative that the issue be addressed and more rigorous procedures for meter testing and calibration be enacted.

Fig. 5.1 divides the customer metering inaccuracy category into five groups; billed exported, residential, non-residential, SAWS metered use, and fire hydrants. The consumption values (column eight) assigned to each of these five groups were calculated first by assigning each group one of the two classifications – residential or non-residential. In section 4.4, a methodology for meter assessment was presented and Table 4.11 displayed the final accuracy results. Residential meters were determined to be 97.2% accurate and non-residential were determined to be 96.5% accurate. Next, the consumption registered for each of these five groups must be determined. This piece of information is already known, and displayed in Figure 5.1 in the category *billed metered consumption*. Once the billed metered consumption and meter accuracy rating for each group is known, equation 5.1 can be applied to calculate the amount of water "lost" due to under-registering meters in the system.

$$M_{error} = V\ (1 - A) \tag{5.1}$$

Where $M_{error}$ = Apparent losses due to meter errors (gal/year).

$V$ = Billed metered consumption (gal/year).

$A$ = Accuracy or residential or non-residential meters.

Before completing the calculation described with equation 5.1, each of the five metering inaccuracy groups must be assigned the correct consumption value from the *billed metered consumption* section of Fig. 5.1. The inputs into each *Customer Metering Inaccuracy* group's calculation as well as final results are as follows.

- **Billed Exported** apparent losses are estimated to be 4 MG. This is the loss incurred when exporting (selling) water to the two small utilities. Recall that SAWS transfers water their through six-inch and eight-inch metered connections to two smaller utilities. Since these connections are of commercial size, the non-residential meter accuracy (96.5%) was applied to the billed exported metered consumption (115.5 MG).
- **Residential** apparent losses are estimated to be 975.3 MG. Residential meter accuracy (97.2%) was applied to billed metered consumption values for both residential (27,173 MG) and apartment (7,663 MG) accounts. Apartment accounts were included here because they are normally operated by small diameter (1 to 2-inches) meters.
- **Non-Residential** apparent losses are estimated to be 501.4 MG. Non-Residential meter accuracy (96.5%) was applied to billed metered consumption values for commercial (11,746 MG), industrial (2,089 MG), and City of San Antonio (596 MG) accounts. It is obvious that commercial and industrial metered connections are large diameter and would be considered to be part of the non-residential group. Information was not readily available regarding the size of the City of San Antonio connections; therefore it was assumed that they are larger than two-inches and therefore included in this group. The City of San Antonio account is

small when compared to the others, therefore this assumption, if proved wrong, will not impact the final output significantly.

- **SAWS Metered Use** apparent losses are estimated to be 4 MG. Non-residential meter accuracy (96.5%) was applied to the unbilled metered consumption (114.4 MG). Recall that this water was metered and used at SAWS facilities, with no payment required. Information was not readily available regarding the size of the meters at SAWS facilities; therefore it was assumed they are of commercial magnitude.
- **Fire Hydrant** apparent losses are estimated to be 4.7 MG in Fig. 5.1, which is slightly misleading. According to current meter testing practices, fire hydrant meters are not tested for accuracy like customer meters. They are only tested to ensure they are in working order. Since, there is no accuracy value to associate with their measured consumption in 2004 (135.4 MG), the non-residential size meter accuracy of 96.5% was applied to fire hydrant meters. Fire hydrant meters are of a commercial size, so this is a fair assumption. It is recommended that in the future, fire hydrant meters are tested for accuracy, so a more reliable analysis can be made.

Metering inaccuracies totaled to 1489.4 MG of “lost” water, which is equivalent to approximately $2.5 million for the audit year. This determination of value uses Dr. Linthicum’s estimate for the value of water ($1678.47 per MG) delivered to customers (Murray et al. 2006).

### 5.2.10. Documented and Quantifiable Real Losses

This category in Fig. 5.1, quantifies the amount of known physical losses from the water system. Real (physical) losses are a form of non-revenue water loss and are divided into four groups in the water balance diagram – assignment leaks, survey leaks, ASR system testing, and leakage and overflows at storages. The first group, *assignment leaks*, is defined as leaks reported to SAWS by a customer or area resident. After receiving the report, SAWS will send a maintenance team out to repair the leak and then estimate the volume of water lost. In 2004, SAWS Leak Detection/Location Program reported an estimated 178.3 MG of water lost due to assignment leaks (Shipley 2005).

The second group, *survey leaks*, is defined as real losses discovered through the efforts of the SAWS Leak Detection/Location Program. These types of leaks are not normally on the surface, seen by the naked eye. Instead, they are found through the use of listening devices, leak detection equipment, and the efforts of leak task forces inspecting water lines, fire hydrants, service connections, and main valves in the system. In 2004, SAWS staff surveyed 900.56 miles (of a total of 4380 miles) of water main in the system, and measured an estimated 61,990 gallons per day of leaks (Shipley 2005). This daily leakage value was multiplied by 366 days to estimate the equivalent volume of survey leaks in 2004. This calculation process totaled an estimated 22.7 MG of survey leaks.

The third group, *ASR System Testing*, is simply a specific instance where a real loss occurred in the SAWS. During the maintenance and testing phase of the ASR project, an estimated 5 MG of water was spilled and lost (Haby 2005, personal communication, cited in Murray et al. 2006). This occurred before any Edwards Aquifer water was stored in the ASR site; therefore the water lost was native Carrizo-Wilcox Aquifer water. If there had been a positive credit of Edwards Aquifer water in the ASR system at the time of the spill, then the amount of water lost would need to be subtracted from the volume of *unbilled deferred water*.

The fourth group, *Leakage and Overflows at Storages*, is defined as the volume of water loss occurring when an above ground storage tank overflows or a possibly a system blow off valve opens and releases water. This type of real loss was estimated by examining SCADA records of measured storage tank water levels (in hourly time steps), and then comparing each tanks hourly water levels to specifications of allowable head according to records from SAWS Production Department. Through this analysis, it was determined that two above ground storage tanks overflowed during 2004. For each tank, the duration in hours of the overflow condition was multiplied by the average flow rate of water entering the tank to calculate an estimated volume of water lost due to the overflow. (Murray et al. 2006) Table 5.1 displays a summary of these real losses, which total to an estimated 0.2 MG in Fig. 5.1.

**TABLE 5.1** Estimated Real Losses At Booster Station Storage Tanks In 2004 (after Murray et al. 2006)

| SCADA Point | Description | Time of Overflow (hr) | Average Flowrate of Station (MG/hr) | Volume of Loss (MG) |
|---|---|---|---|---|
| WC2LI120 | Helotes Park 2 | 2 | 0.03 | 0.06 |
| UNILI120 | University Tank | 1 | 0.17 | 0.17 |
| | | **TOTAL ESTIMATED LOSS (MG) =** | | **0.23** |

### 5.2.11. UARL

UARL is defined as an allowable volume of real losses from the system, which estimates a volume of leaks that are undetectable or would be uneconomical to repair during the year. UARL is calculated according to an empirical equation stated in the IWA audit manual, and is sensitive to parameters such as system pressure, water main length, and density and length of service connections. Section 4.2 of this research paper defines and describes the UARL calculation process in great detail. UARL was estimated to be 2,355 MG of water for 2004, as shown in Fig. 5.1.

### 5.2.12. Undocumented Real Losses

Undocumented real losses are defined as being equivalent to total system input minus total system output. Typically, system input will exceed system output for a utility indicating that there are more real losses (leaks) in their system that have not yet been found. These extra leaks are additional to the level of UARL calculated for the particular system. In the case of SAWS, system input was deemed to be significantly underestimated. This “miss-balance” of the resulting water balance for SAWS in FY2004 leads to undocumented real losses being valued at zero in the final water balance diagram, Fig. 5.1. After system input measurement methods are hopefully reviewed, recalibrated, and recalculated in future years, SAWS should see some value attached to this category in the IWA water balance, even if it is a small one.

## 5.3. PERFORMANCE INDICATOR RESULTS

According to Alegre et al. (2002), a performance indicator (PI) is “a quantitative measure of a particular aspect of the undertaking’s performance or standard of service. It assists in the monitoring and evaluation of the efficiency and effectiveness of the undertaking, thus simplifying an otherwise complex evaluation.” Briefly, PIs are a simple method of comparing the efficiency of a utility with itself over time, or comparing between utilities anywhere.

Four of the six groups of PIs were calculated for the case of the SAWS water loss audit. The categories computed were water resources indicators, physical indicators, operational indicators, and financial indicators. (Quality of service indicators and personnel indicators were not included in this project.) The PIs, as calculated for SAWS, are included in Appendix C of this thesis. Another benefit of calculating performance indicators for various aspects of the utility system according to IWA methodology is that during the process, each piece of data used is confidence graded to reflect both the accuracy and reliability in the information collected. This confidence grading is valuable when making decisions on future resource allocation and when considering the audit results. For example, if there is little confidence in apparent loss estimates from metering inaccuracies, the first step may be to improve the data collection process before spending money on replacing meters, assumed to be faulty, throughout the system. In the remainder of section 5.3, a few of the most important PIs will be examined and compared with other utilities throughout the world. Appendix C contains a complete list of confidence graded PIs as calculated for SAWS.

### 5.3.1. Operational Indicator 25: Infrastructure Leakage Index

This PI is the most widely reported and compared indicator for utilities completing an IWA water loss audit. According to equation 5.2, the ILI is equal to the following for SAWS in 2004.

$$\text{ILI}=\frac{\text{Annual Real Losses}}{\text{UARL}} = 2{,}639.4 \text{ MG} / 2{,}345.5 \text{ MG} = 1.13 \qquad (5.2)$$

This performance indicator has been confidence graded “B3”, which corresponds to reliable data with an accuracy of +/- 10%. An ILI value of one suggests that all real losses that can feasibly be eliminated in the utility system have been located and repaired. If this indicator is taken at face value, it would suggest that SAWS is doing a very efficient job of locating and repairing real losses in its system. It is likely that the SAWS Leakage Detection Program is performing their duties very well. Theoretically, according to the ILI equation, the amount of water the utility should be able to recover with leak detection and proper maintenance and operation is the volume of real losses minus the volume of UARL. This would equal 293.9 MG or approximately 902 acre-feet for the year. According to the confidence grading system assigned to this indicator, this value may actually vary between 811 to 992 acre-feet. This amount of lost water is minimal in comparison to the additional volume that SAWS must acquire to meet its growing future needs.

Given the results of this particular audit, where system inputs were assessed to be less than system outputs, the calculated ILI performance indicator is not credible. In a more typical application of the IWA audit to a water utility, it would be expected that the system input would exceed the system output and the difference between the two volumes falls into the water balance category called *undocumented real losses* (explained in section 5.11). This means that there are leaks present in the system, that are greater than the UARL level of leakage, but these leaks have also not been located through the use of leak detection equipment. The fact that the system input is likely being significantly under measured in SAWS, translates to the real loss category of the water balance also being under measured, which finally reduces the ILI incorrectly. Until, more confidence in the system input measurements for SAWS is achieved, the calculation of the ILI performance indicator should be viewed as preliminary.

### 5.3.2. Water Resources Indicator 2: Resources Availability Ratio

The purpose of this PI is to assess the percentage of overall available water resources that the utility utilizes during the audit year. Alegre et al. (2002) encourages use of this indicator “as a management tool, particularly in rapid growing areas or areas subject to scarcity problems.” It seems that both of these issues are applicable to SAWS.

The resources availability ratio is calculated according to equation 5.3.

$$WR2 = \frac{\text{Water Produced}}{\text{Yearly Abstraction Capacity}} \times 100 = \frac{53{,}101MG}{65{,}635MG} \times 100 = 80.9\% \qquad (5.3)$$

The yearly abstraction capacity (65,634 MG) is equivalent to 234,000 acre-feet and was determined by adding the permitted Edwards Aquifer water in 2004 to the maximum amount allowed to pump from the Trinity Aquifer in 2004. (Abstracting water from the Carrizo-Wilcox Aquifer was ignored in this calculation.) According to the PI, WR2, SAWS consumed 80.9% of their available water resources. This is seen as an important PI with respect to the SAWS, because this indicates that in 2004, a very wet year, they did not use approximately 44,694 acre-feet of water that they had rights to abstract. If the ASR project had come online sooner, it is possible that more of this surplus water could have been captured and stored at the Twin Oaks ASR site for use in future years when dry conditions reduce SAWS pumping rate from the Edwards Aquifer.

### 5.3.3. Operational Indicator 23: Apparent Losses

The purpose of operational indicator 23 is to evaluate the volume of apparent losses per service connection in the utility system. This is a useful indicator to compare between utility systems, in order to ascertain if apparent losses in the utility being evaluated are normal, abnormally high, or less than average. This is useful information for a utility in two important ways. First, by comparing to other utilities, they will know what levels are achievable and what type of resource commitment it will take to reduce apparent losses. Second, the utility can compare year-on-year improvements to determine if their level of resource allocation addressing this issue is producing results. Operational indicator 23 is defined according to equation 5.4.

$$OP23 = \frac{\text{Apparent Losses}}{\text{No. of Service Connections}} = \frac{5157.4MG}{315,000} = 0.01637\ {}^{MG}\!/_{\text{service connection}} \qquad (5.4)$$

# 6. CONCLUSION

## 6.1. ANALYSIS OF SAWS IWA AUDIT RESULTS

This section examines the direct results of the water loss audit according to IWA principles for SAWS, as well as final values shown in the water balance, as shown in Fig. 5.1. Section 6.1.1 compares system input to system output. Next, sections 6.1.2 and 6.1.3 analyze results from the two non-revenue water categories; apparent and real losses. The non-revenue water category is important because it defines the aspects of a utility where system efficiency can be improved. Last, section 6.1.4 addresses issues for incorporating SAWS extensive water reuse/recycle program into the standard IWA audit.

### 6.1.1. Inequality Between System Input and Output

Upon examination of Fig. 5.1, the first and most obvious conclusion drawn is that the system inputs are much less than the system outputs. In fact, the water balance indicates that approximately six billion more gallons of water was used than was produced in SAWS for 2004, which is a disparity corresponding to about 12% of the system input. This inequality is physically not possible, SAWS water output cannot exceed its total input. Rather, this discrepancy must be attributed to the cumulative error in the measurement and estimation of all quantities in the water balance. It is most likely that the system input is significantly larger than estimated. Due to pumping restrictions set by the Edwards Aquifer Authority on SAWS, underestimating system input is a serious issue and must be carefully addressed. The TAMU research team makes the following recommendations relevant to determination of system input volume, so that in future audits greater confidence and accuracy in the system input volume can be achieved.

- *SAWS should re-evaluate available methods for determination of system input volume to achieve a goal of maximum accuracy at an acceptable cost.* At present, the runtime constant flow method is used for system input volume determination. Previous internal studies have found this method to have accuracy of "± 3 to 5%". However, the water balance inequality suggests that this accuracy could be as large as ± 12%. To put this into perspective, SAWS physical water losses are within the ± 5% range. It is difficult to have confidence in a 5% error, when it is overshadowed by a ± 12%. Therefore, the accuracy of the input measurement system is far less than the physical water losses in the system. Due to its aggressive water loss control program, SAWS's physical water losses are now within this error range. Re-installation and/or recalibration of flow meters at input points may allow much greater accuracy in determining system input volume, but at some cost. A cost-benefit analysis on this issue might be an appropriate future study.
- *SAWS should conduct annual (at minimum) inspections and recalibrations for devices needed by the preferred flow volume measurement method (runtime or metering).* At present, the runtime constant flow method for individual pumps is the primary means with which to measure system input, but pumps are inspected

and runtime constants are re-calibrated only on an "as needed" basis. This irregular schedule of inspection may allow errors to accumulate over time leading to inaccurate system input volume determination. If the runtime constant method is maintained as the preferred input calculation method, the "Pump Efficiency Program" should be re-instituted as an annual inspection program (it is likely that some energy savings would be realized as well). If flow metering is adopted as the input calculation method, meters should be inspected and calibrated on an annual basis.

- *SAWS should consider redundancy in system input volume determination by using both the runtime constant flow and flow metering.* Future audits would benefit by having redundant methods by which to calculate system input volume. The presence of flow meters and runtime constants at all input points makes this redundancy possible, but the cost of bringing both methods up to acceptable standards of accuracy must be considered.
- *SAWS should consider data entry for unmonitored stations into SCADA.* At present, 3 input stations (Bandera Road, Edison, and Lady of the Lake) are "unmonitored" and are not represented in the system's SCADA database. System input from these stations is considered negligible, but finding a way to incorporate these stations into the system's comprehensive data will lend completion to the water auditing process. Because of the very low volumes of water expected to be input at these stations, this is a low priority recommendation.

### 6.1.2. Apparent Losses

In 2004, the final water balance estimated apparent losses to be 5,157.4 MG (15,827.5 acre-feet) of water. Apparent losses are not a physical loss of water, but rather a missed opportunity for revenue. Resources should be allocated in controlling these apparent losses according to the following recommendations.

- Residential meters have an estimated accuracy of 97.2%, but need to be routinely tested for accuracy. Only a regular testing routine will provide the random sample needed to assess meter accuracy without the biases and assumptions that were included in this research. This is a high priority recommendation because residential sized meters are the largest consuming group in the system; therefore any accuracy that can be gained in this category will be a beneficial payoff with the revenue returned to the utility.
- Non-Residential meters have an estimated accuracy of 96.5%. It is recommended that they be recalibrated more often, so that more accuracy can be regained and therefore the utility will be reimbursed appropriately for the water used. This is assuming that the benefits of the recovered revenue outweigh the cost of further meter testing.
- Fire hydrant meters should be spot tested for accuracy, so a true value (and not just an assumption) can be used to determine apparent losses for this type of water use. If random spot testing is done over the next year, then a better picture of the fire hydrant meters accuracy can be assessed and it can be determined if

fire hydrant meters are or are not a significant source of revenue loss. For the 2004 audit, there was no information collected to be able to make this decision.

- The water use record system needs to be separate from the system used to bill and refund customers money. This is a high priority suggestion because sifting through billing records year after year during the IWA auditing process would be tedious. It would be better to just go ahead and separate the two systems if possible.

### 6.1.3. Real Losses

Despite the needs to better measure system input, the end result is that input and output are close to one another (assuming zero undocumented real losses). This would indicate that SAWS current leak detection and system maintenance programs are doing an effective job of controlling real losses in the system. It is recommended that the Leakage Detection/Location Program should continue at its current intensity and funding. For 2004, recoverable real losses (not including UARL) amounted to 293.9 MG (902 acre-feet) of water (using the calculated ILI value of 1.13, which is not a fully correct assumption). According to Fig. 3.3, SAWS will require new water assets in the range of tens of thousands of acre-feet to meet demand projections through 2050. The amounts of real losses not yet recovered according to this audit are minimal in comparison to what is needed for future water supply. Therefore, at this point in time, it is more important to spend resources on developing new water sources as opposed to further expanding an already efficient leak detection program.

### 6.1.4. SAWS Water Reuse and Recycling Program

SAWS has an extensive water reuse and recycling program. This program has not been mentioned or taken into account in this particular research study because it is completely separate from the potable water distribution system audited according to IWA methodology. The water reuse and recycling program has its own separate SCADA monitoring system, separate infrastructure and distribution system, and supplies recycled water for uses such as landscaping irrigation, commercial and industrial facilities, and public fountains. Recycled water is provided at a lower fee to SAWS customers than the traditional potable water supply. The SAWS recycled water system has its own separate billing account procedures as well. All of the information and data collection infrastructure is available for the water reuse and recycling program that a separate audit could be performed on the efficiency of this system. At this point in time, recycled water is not a valuable enough asset to motivate completing this task. SAWS is expected to continue expansion of its water recycling program, as it allows expansion of service with less strain on potable water supplies. As recycled water becomes a more financially important program, its need for appropriate auditing will increase.

## 6.2. IWA IS AN APPROPRIATE AUDIT MODEL FOR NORTH AMERICAN WATER UTILITIES

The IWA audit model was successfully applied in this research project to a large North American water utility, SAWS. In any model application, new challenges will arise and new circumstances will be addressed.  This research project was no exception. New and useful methodologies were developed in the study areas of:

- Defining the most accurate system input volume from multiple measurement systems and numerous input points throughout the system.
- Incorporating deferred storage consumption principles into audit methodology.
- Calculating UARL from a system spanning many pressure zones.
- Defining a methodology for assessing meter accuracy for the system.

These model developments will aide SAWS in completing the audit in future years, as well as any other utility that may encounter similar issues when conduction an IWA audit.

There are multiple benefits for performing an annual IWA audit on North American utilities.  The utility is first able to measure its' current performance by calculating non-revenue water and performance indicators.  Second, the utility can identify problem areas within its system and formulate solutions.  The utility can then allocate resources and enact new policies to address each inadequacy.  Last, in the following year's audit, the utility can determine if these new strategies are producing worthwhile results.  The audit must be conducted annually in order to benefit in this manner.

Another significant benefit for conducting an IWA audit is that all departments (conservation, meter testing, operations, production, finance, customer service, compliance, planning, leak detection, and others) within the utility are forced to communicate and work together.  This benefit is especially evident for the case of large utilities, like SAWS, where each department does not typically interact on a regular basis.  Increased communication between departments facilitates increased efficiency and better understanding of the utilities ultimate priorities and goals.

The last significant benefit that will be discussed is the platform for international comparison of audit results.  This is useful because it is likely that somewhere in the world, there is another utility with a similar problem, situation, configuration, etc.  By comparing each utilities performance with others, ideas can be shared on what types of strategies work for differing problems encountered.

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# APPENDIX A

# UARL TUTORIAL

## A.1. METHOD A: STEP-BY-STEP TUTORIAL

This sub-section provides detailed step-by-step instructions to calculate UARL for the SAWS according to Method A methodology.

### A.1.1. Required ArcView GIS Tools & Files

ArcView GIS 3.2 was used extensively in this calculation process. It is likely that ArcGIS 8.3 and 9 can also accomplish these tasks, but this tutorial was written to specifically instruct the user with ArcView GIS 3.2. In order to begin the process of determining the UARL value, the following shapefiles will need to be added to a blank ArcView project.

- **Waterline_age.shp:** This is the shapefile, provided by SAWS, that maps all water mains throughout their system. Pertinent information found in the attribute table of this shapefile is a field containing the length of each object in feet.
- **Pp.shp**: This is the shapefile containing all of the pressure points currently measured throughout the system. In addition, points have been added at booster stations to increase the number of spatially distributed points throughout the system.

The following polyline shapefiles of each pressure zone will be needed.

- **Pz2.shp**
- **Pz3.shp**
- **Pz4.shp**

- **Pz5.shp**
- **Pz6&9.shp**
- **Pz7.shp**
- **Pz8.shp**
- **Pz10&11a.shp**
- **Pz11&12 .shp**

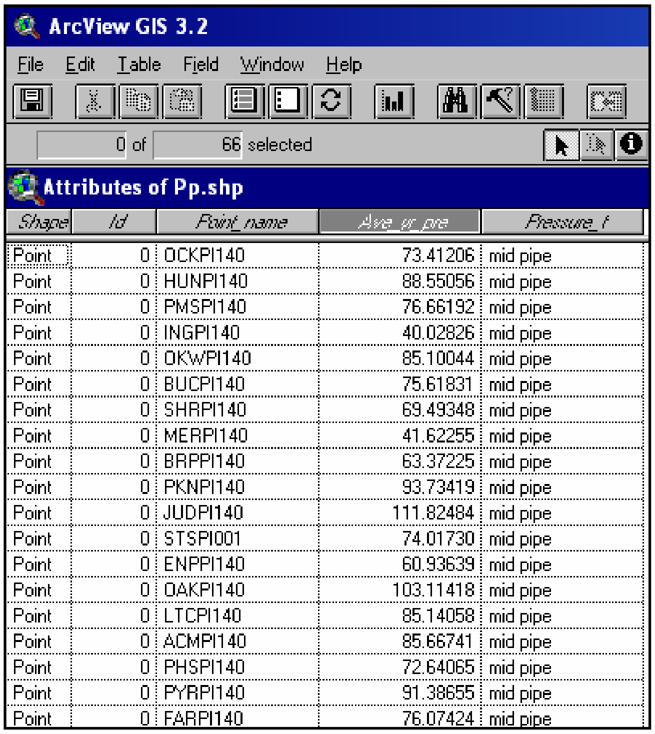
The following polygon shapefiles of each pressure zone will also be needed.

- **Pz2_polygon.shp**
- **Pz3_polygon.shp**
- **Pz4_polygon.shp**
- **Pz5_polygon.shp**
- **Pz6&9_polygon.shp**
- **Pz7_polygon.shp**
- **Pz8_polygon.shp**
- **Pz10&11a_polygon.shp**
- **Pz11&12_polygon.shp**

### A.1.2. Calculating Average System Operating Pressure

The average operating pressure of the system (in psig) must be calculated over the course of the auditing period. Average yearly pressure values are needed for each pressure point listed in the ArcView GIS shapefile **Pp.shp**. The attribute table of this shapefile has three pertinent fields; **Point_Name** (point name), **Ave_yr_pre** (average yearly pressure), and **Pressure_t** (pressure type). The field, point name, is where the unique identifier for each pressure point used in the UARL calculations is listed. This point name can be used in conjunction with the SCADA database and the program Microsoft Access to output the measured hourly pressures at that specific point for the auditing period.

The next field, average yearly pressure, is where the calculated average yearly pressure for the corresponding point name should be listed. For each pressure point, use Microsoft Access to search the SCADA database for the hourly pressures over the course of the auditing period. Copy the pressure output table to Microsoft Excel and then calculate the average pressure (simple mean) of the **Point_average_val** column for each pressure point individually. Do this by summing all values in the column and then divide by the number of values listed. This can be done using the COUNT function in Excel (this allows empty cells in the database to not be included in the average). Once the yearly average pressures have been calculated for each pressure point, enter these average values into the attribute table of the pressure point shapefile (Pp.shp) as shown in Fig. A.1.



0 of 66 selected

Attributes of Pp.shp

| Shape | Id | Point_name | Ave_yr_pre | Pressure_t |
|---|---|---|---|---|
| Point | 0 | OCKPI140 | 73.41206 | mid pipe |
| Point | 0 | HUNPI140 | 88.55056 | mid pipe |
| Point | 0 | PMSPI140 | 76.66192 | mid pipe |
| Point | 0 | INGPI140 | 40.02826 | mid pipe |
| Point | 0 | OKWPI140 | 85.10044 | mid pipe |
| Point | 0 | BUCPI140 | 75.61831 | mid pipe |
| Point | 0 | SHRPI140 | 69.49348 | mid pipe |
| Point | 0 | MERPI140 | 41.62255 | mid pipe |
| Point | 0 | BRPPI140 | 63.37225 | mid pipe |
| Point | 0 | PKNPI140 | 93.73419 | mid pipe |
| Point | 0 | JUDPI140 | 111.82484 | mid pipe |
| Point | 0 | STSPI001 | 74.01730 | mid pipe |
| Point | 0 | ENPPI140 | 60.93639 | mid pipe |
| Point | 0 | OAKPI140 | 103.11418 | mid pipe |
| Point | 0 | LTCPI140 | 85.14058 | mid pipe |
| Point | 0 | ACMPI140 | 85.66741 | mid pipe |
| Point | 0 | PHSPI140 | 72.64065 | mid pipe |
| Point | 0 | PYRPI140 | 91.38655 | mid pipe |
| Point | 0 | FARPI140 | 76.07424 | mid pipe |

**Fig. A.1.** Pressure Point attribute table (Pp.shp) in ArcView GIS 3.2, showing pertinent fields; Point_Name, Ave_yr_pre, and Pressure_type.

The last field in the attribute table, pressure type, describes the origin of the pressure points listed. The description **mid pipe** refers to points listed in the SAWS SCADA data as measured pressure points throughout their system. The descriptions **discharge** and **suction** refer to the points that were added at booster stations to increase the number of points spread throughout the system. Discharge points are measurements that are taken as water is expelled from the booster stations and are accordingly higher in pressure. Suction points are measured at the intake of the booster stations and are thus slightly lower than normal in pressure. An effort was made to choose discharge and suction points that are evenly distributed in pressure zones to ensure that results were not tainted by using mostly abnormally high or low pressures.

In future audits, if needed, pressure points can always be added or subtracted to this pressure point shapefile.  It is encouraged to use good judgment when selecting new points and to strive for balance between discharge and suction points in the system.  If more **mid pipe** pressure measurement stations are added to the system, they can always be added to this shapefile as well and will only increase the accuracy of this process.

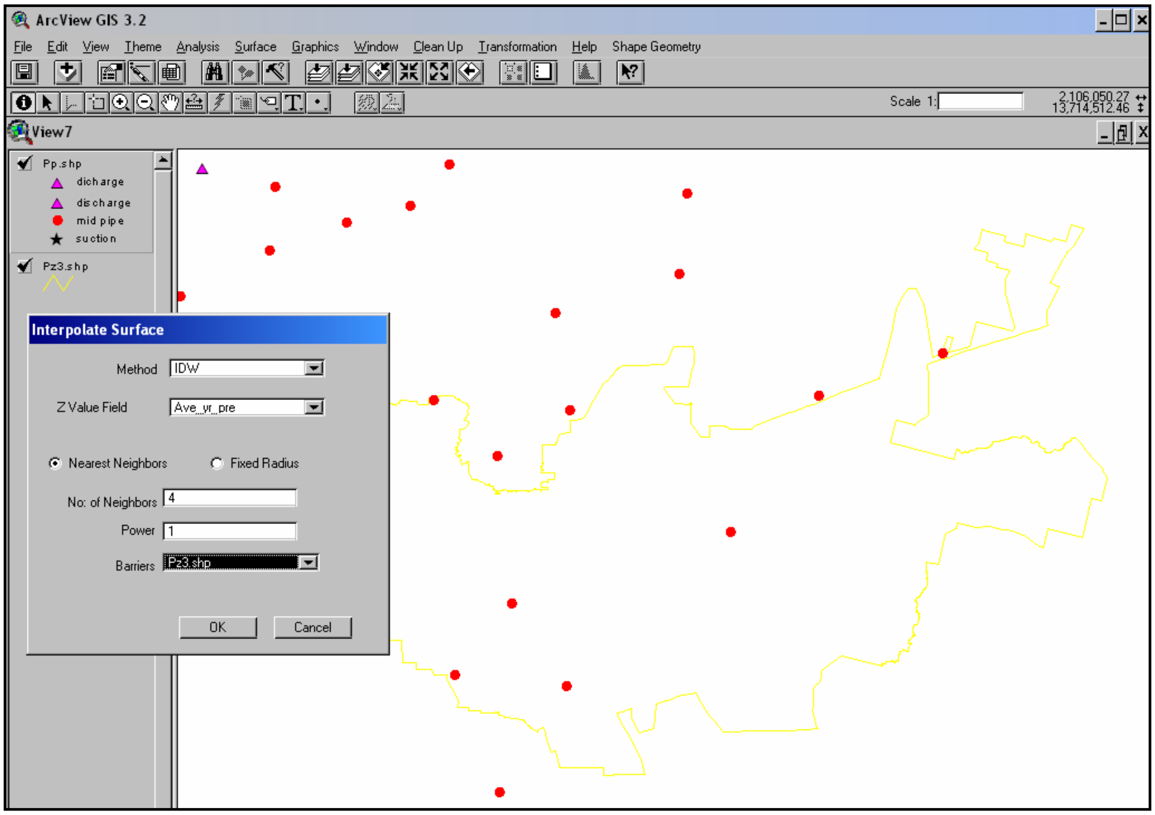
### A.1.3. Inverse Distance Weighting Method

The Inverse Distance Weighting (IDW) Method is a process used to spatially interpolate between data points.  ArcView GIS 3.2 can quickly perform this routine.  The IDW method is used on the pressure points (Pp.shp) to create a spatially distributed pressure across the entire SAWS service area using the previously calculated average yearly pressure points as inputs.  Pressure in a water distribution system is not spatially distributed across the land surface; instead it is contained in the pipes.  Unfortunately, no methods or computer programs exist that are advanced enough to take into account the pressure only traveling through the existing mains, so this IDW Method is being used to simplify the issue.  The IDW Method will be performed separately in each pressure zone where pressures are comparable.  Performing this method pressure zone by pressure zone will help to recover some of the accuracy lost by using simplifying assumptions.

For this task, the polyline shapefiles of each pressure zone will be needed.  These files are listed in the section **A.1.1. Required ArcView GIS Tools & Files** of this report.  Add each of these shapefiles to an ArcView GIS map along with the pressure point shapefile (Pp.shp).  Check the theme of one of the pressure zones and the pressure point shapefile. Select the pressure point shapefile by clicking on the theme again. Next click on the ArcView GIS "Surface" menu and then select the "Interpolate Grid" option in the sub-menu. Choose OK for the first pop-up menu that appears. In the next pop-up menu, choose the following:

- Method = IDW
- Z Value Field = Ave_yr_pre
- Select the Nearest Neighbors option
- No. of Nearest Neighbors = 4
- Power equal to 1
- Under "Barriers" choose the pressure zone name you want to work with.
- Select the OK button.

The following figure, Fig. A.2., shows what the ArcView GIS window will look like when performing the previously described tasks. Pressure zone three will be used for this example and in all of the following examples in this tutorial.



Interpolate Surface

Method: IDW

Z Value Field: Ave_yr_pre

● Nearest Neighbors ○ Fixed Radius

No. of Neighbors: 4

Power: 1

Barriers: Pz3.shp

**Fig. A.2.** Picture of the ArcView GIS viewport performing the IDW method.

Now, a new theme will appear on the left-hand side of the ArcView GIS window. Check this theme to see the pressures spatially distributed across the pressure zone. (Note, this pressure distribution will appear both outside and inside the boundaries of the pressure zone you are using. This is acceptable; however pressure values are only valid within the boundary of the zone.) It is wise to move forward to the next section before repeating the IDW method for the next pressure zone. The next figure, Fig. A.3., shows what spatially distributed pressure zone will look like.

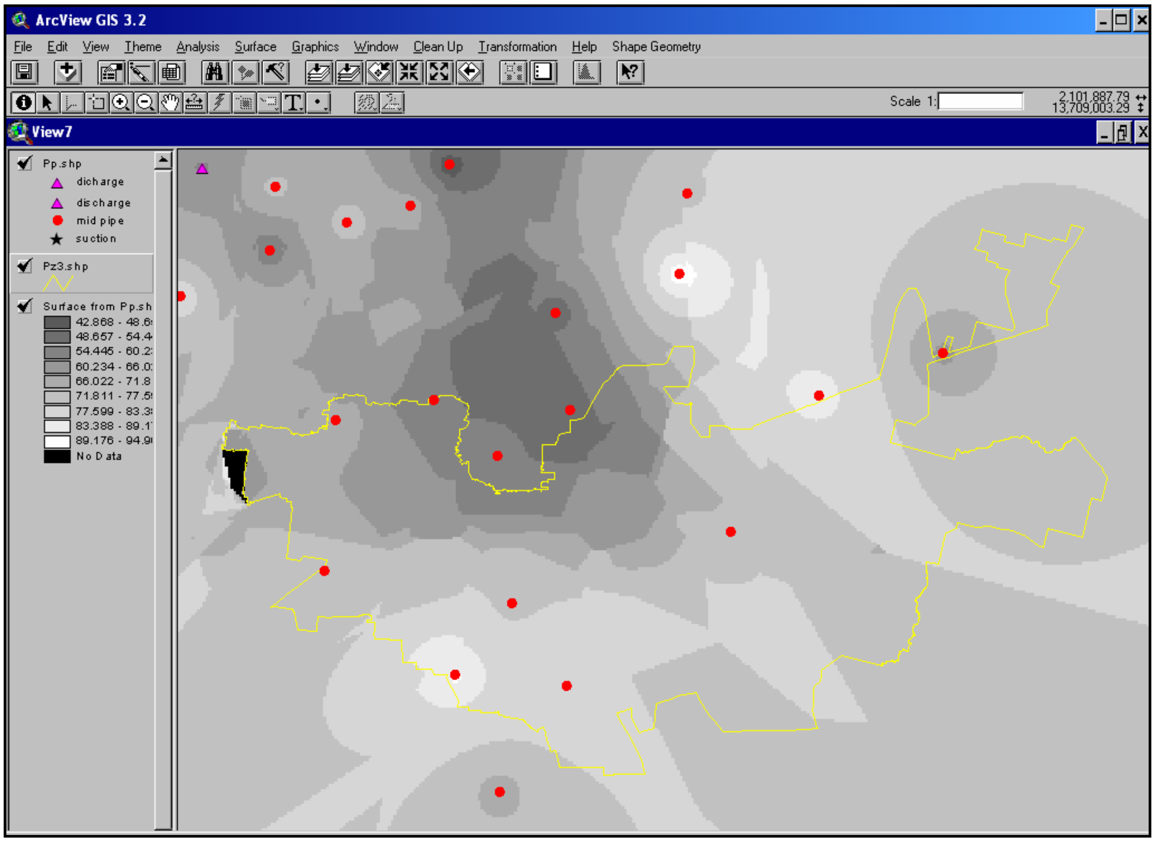
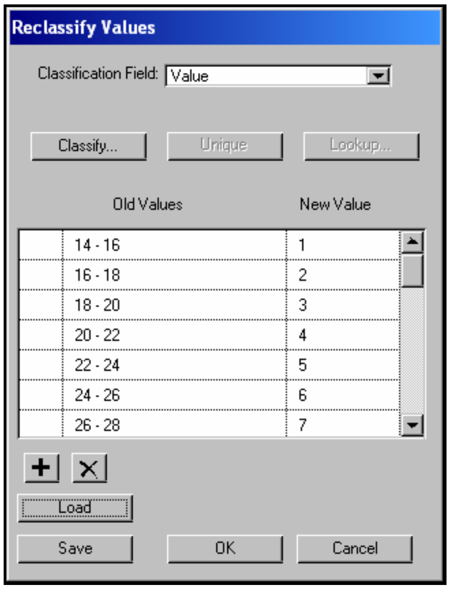


**Fig. A.3.** Pressure zone 3 with spatially distributed pressure point values.

### A.1.4. Reclassification & Conversion of Pressure Surface

The new theme just created in the above section must now be reclassified and made permanent.

Select the “Analysis” menu and then choose the “Reclassify” option on the sub-menu. Select the Load button from the pop-up menu. Search for the filename **reclass1.avc**. This file will reclassify the surface in increments of two psig. The following figure, Fig. A.4., shows the reclassification window with incremental pressure classification values.



Classification Field: Value

| Old Values | New Value |
|---|---|
| 14 - 16 | 1 |
| 16 - 18 | 2 |
| 18 - 20 | 3 |
| 20 - 22 | 4 |
| 22 - 24 | 5 |
| 24 - 26 | 6 |
| 26 - 28 | 7 |

**Fig. A.4.** ArcView GIS menu showing pressure reclassification scheme.

Before choosing OK, look at the upper and lower bounds of the average yearly pressures that have been calculated. The initial file ranges from 14 to 156 psig. Check your average yearly pressures in the pressure point shapefile and make sure none of the values fall outside of this range. If one does, you will have to create your own reclassification instead of loading this file. Assuming all pressures fall within this range, continue by selecting OK.

Another new theme will be added to your window. Check its box so that the theme is visible. (See Fig. A.5. to see what the reclassified theme will look like.) Now we want to make a common legend for this theme. Double click on the theme and a new window will appear. Select the Load button from this pop-up menu, and then search for the file named **legend1.avl**. Once it is found, highlight the filename and then select OK and a new menu will pop-up. In this new window, make sure Field equals Value and the

All box is checked. Now choose OK. Choose APPLY on the first sub-menu and then close the other menu as well.

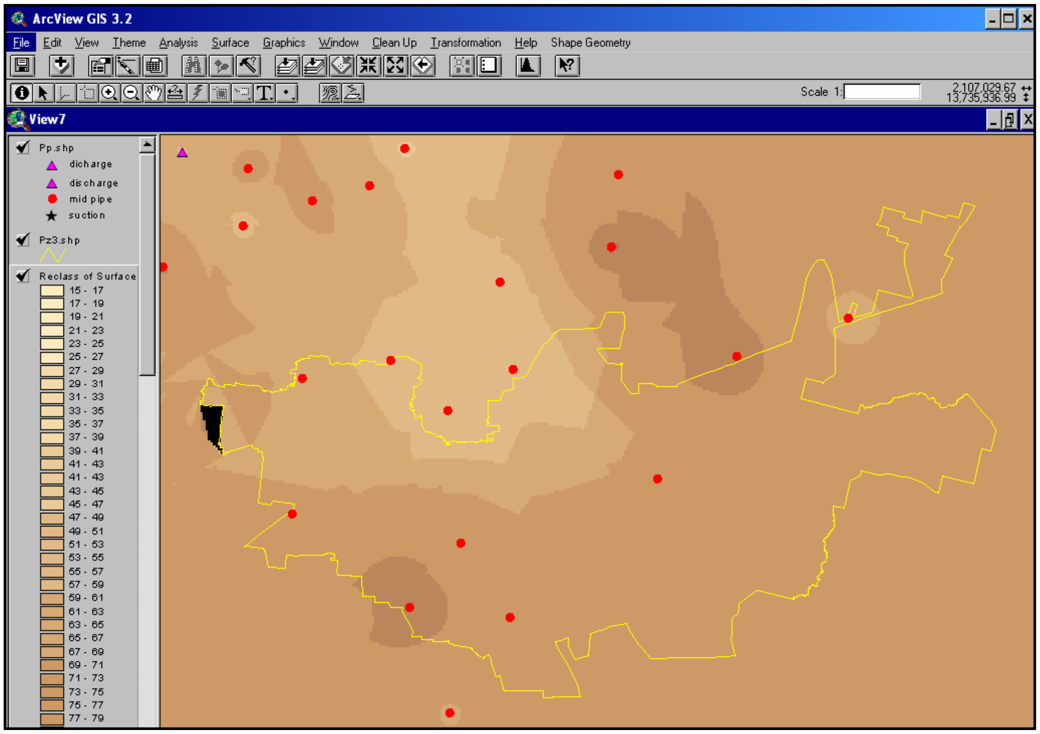
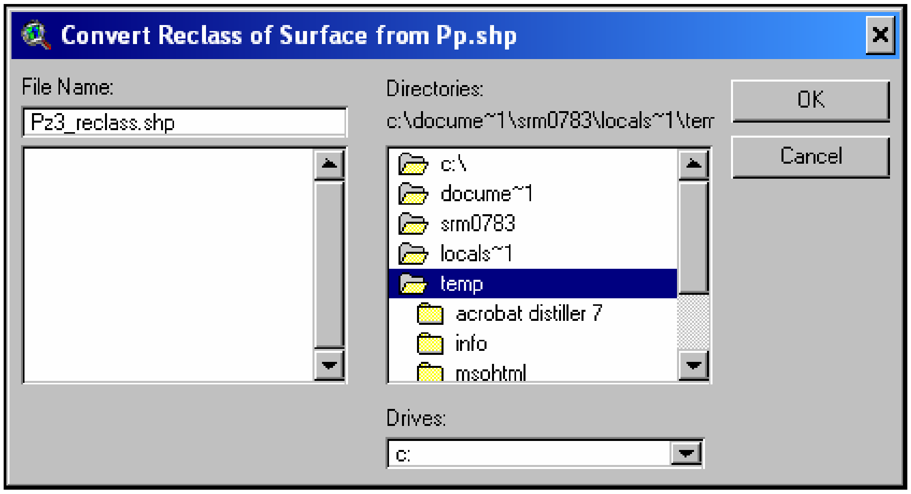


**Fig. A.5.** Reclassified pressure surface for pressure zone 3.

The next task is to convert the theme "Reclassification of Surface from Pp.shp" to a shapefile. First, click on the theme on the left hand side of the screen so that it is selected. Next, choose the "Theme" menu at the top of the screen and then select "Convert to Shapefile" on the sub-menu. A pop-up menu will appear as seen in Fig. A.6. You are in the process of creating a new shapefile, so give it an appropriate name (for this example Pz3_reclass, if you are working with pressure zone three) and choose a directory to save it. Now select OK. The converted shapefile will be added to the window and look similar to the one pictured in Fig. A.7.



File Name: Pz3_reclass.shp

Directories: c:\docume~1\srm0783\locals~1\tem

Drives: c:

**Fig. A.6.** ArcView GIS menu for converting a theme to a shapefile.

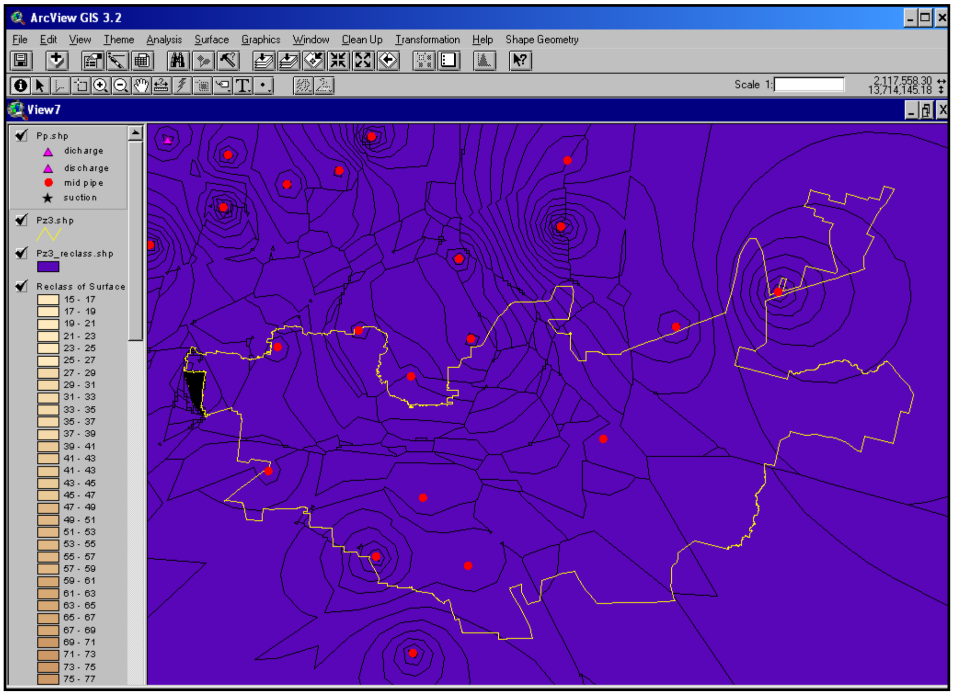
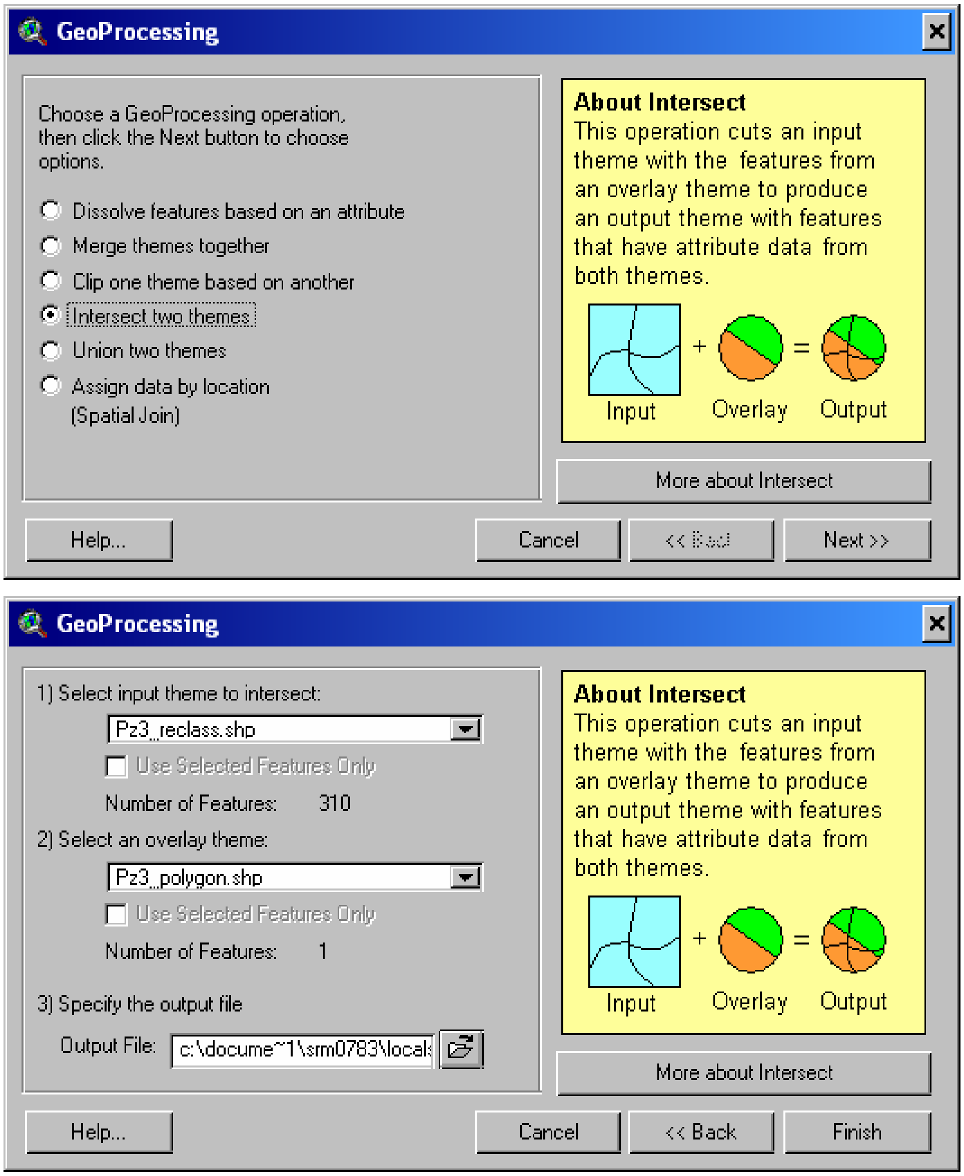


**Fig. A.7.** Converted shapefile showing the spatially weighted pressure surfaces for zone three.

This new shape (Pz3_reclass) needs to be trimmed to only the area within the corresponding pressure zone (Pz3_polygon.shp). For this task, first, the polygon shapefile of the pressure zone (named in section **A.1.1. Required ArcView GIS Tools & Files** of this report) should be added to the window. Next, choose the "View" menu at the top of the screen and then select "GeoProcessing Wizard" on the sub-menu. A pop-up menu will appear as in Fig. A.8. (a) Choose the option "intersect two themes" and then select the button Next. Choose the following options on the menu as in Fig. A.8. (b):

- First option; select the newly converted shapefile (Pz3_reclass) as the input theme to intersect.
- Second option; select the polygon shapefile for the corresponding pressure zone (Pz3_polygon.shp) as the overlay theme.
- Third option; select the correct directory and select an appropriate filename (Pz3_intersect.shp) for the new shapefile that will be created. This new theme will be added to your window.



Choose a GeoProcessing operation, then click the Next button to choose options.

○ Dissolve features based on an attribute
○ Merge themes together
○ Clip one theme based on another
● Intersect two themes
○ Union two themes
○ Assign data by location (Spatial Join)

**About Intersect**
This operation cuts an input theme with the features from an overlay theme to produce an output theme with features that have attribute data from both themes.

1) Select input theme to intersect:
Pz3_reclass.shp
☐ Use Selected Features Only
Number of Features: 310

2) Select an overlay theme:
Pz3_polygon.shp
☐ Use Selected Features Only
Number of Features: 1

3) Specify the output file
Output File: c:\docume~1\srm0783\locals

**About Intersect**
This operation cuts an input theme with the features from an overlay theme to produce an output theme with features that have attribute data from both themes.

**Fig. A.8.** (a) GeoProcessing Wizard menu. (b) Menu option choices to perform intersection task with GeoProcessing Wizard.

The spatially distributed pressure shapefile trimmed to a single pressure zone will look similar to Fig. A.9.

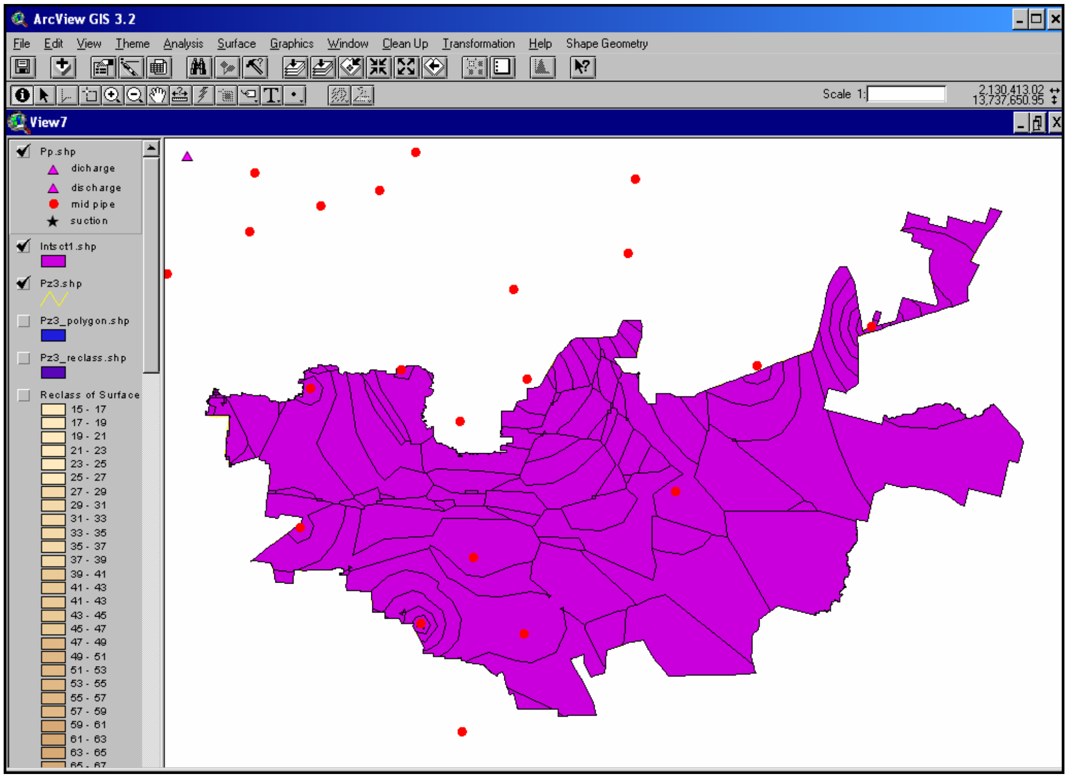


**Fig. A.9.** Spatially distributed pressures shapefile trimmed to pressure zone three.

Again, continue on to the next section before beginning to work with the next pressure zone.

### A.1.5. Intersection with Water Mains

Another, ArcView GIS task that must be completed is intersecting each trimmed reclassified and converted shapefile (Pz3_intersect.shp from the previous example) with the shapefile containing the water mains (Waterline_age.shp). Add these two files to a ArcView GIS view.

This task is accomplished by the following steps. Click on the Waterline_age.shp theme so that it is selected. Next, choose the “select feature” button from the toolbar along the top of the screen. While holding shift down, click and drag around all the water lines that overlap the pressure zone you are using. Try to minimize the region you select as much as possible because this will save processing time. (See Fig.A.10 as an example.)

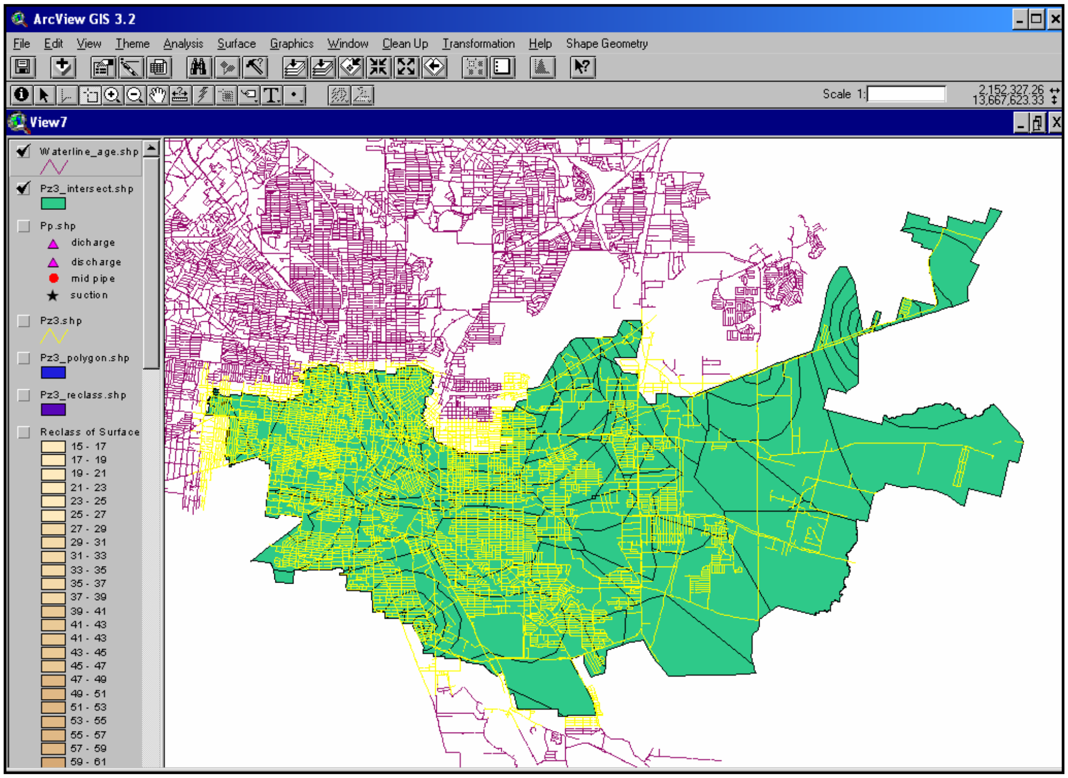
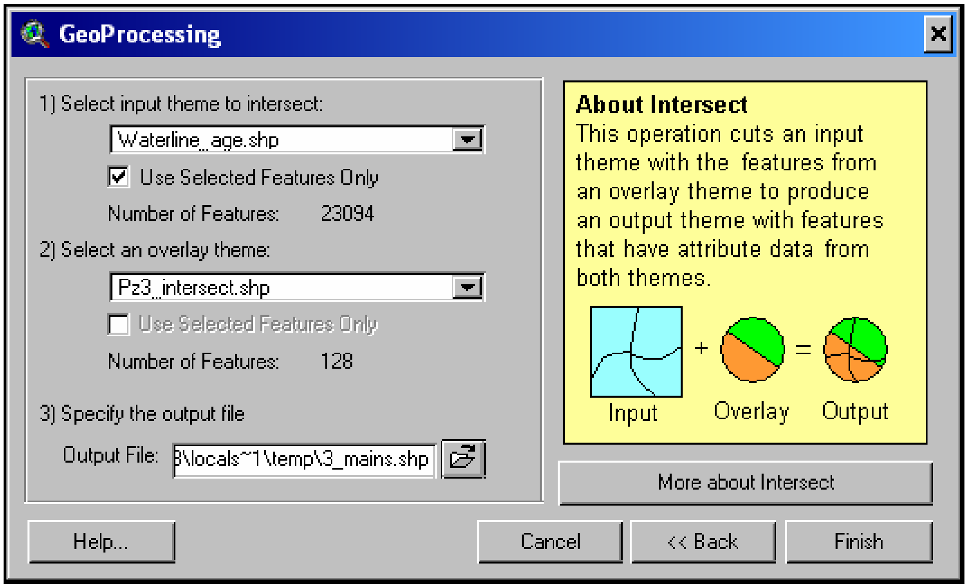


**Fig. A.10.** Selecting the water mains which overlap pressure zone three.

Next, choose the "View" menu at the top of the screen and then select "GeoProcessing Wizard" on the sub-menu. A pop-up menu will appear. Choose the option "intersect two themes" and then select the button Next. Choose the following options as also seen in Fig. A.11.:

- First option, select the shapefile (Waterline_age.shp) as the input theme to intersect. Make sure the box is checked that says "Use Selected Features Only".
- Second option, select the output shapefile from the previous intersection task (Pz3_intersect.shp) as the overlay theme.
- Option three, choose the correct directory and select an appropriate filename (3_mains.shp) for the new shapefile that will be created. This new theme will be added to your window. It will appear as in Fig. A.12.



1) Select input theme to intersect:
Waterline_age.shp
☑ Use Selected Features Only
Number of Features: 23094
2) Select an overlay theme:
Pz3_intersect.shp
☐ Use Selected Features Only
Number of Features: 128
3) Specify the output file
Output File: 3\locals~1\temp\3_mains.shp

**About Intersect**
This operation cuts an input theme with the features from an overlay theme to produce an output theme with features that have attribute data from both themes.

**Fig. A.11.** GeoProcessing Wizard menu showing intersection between water mains and a pressure zone three.

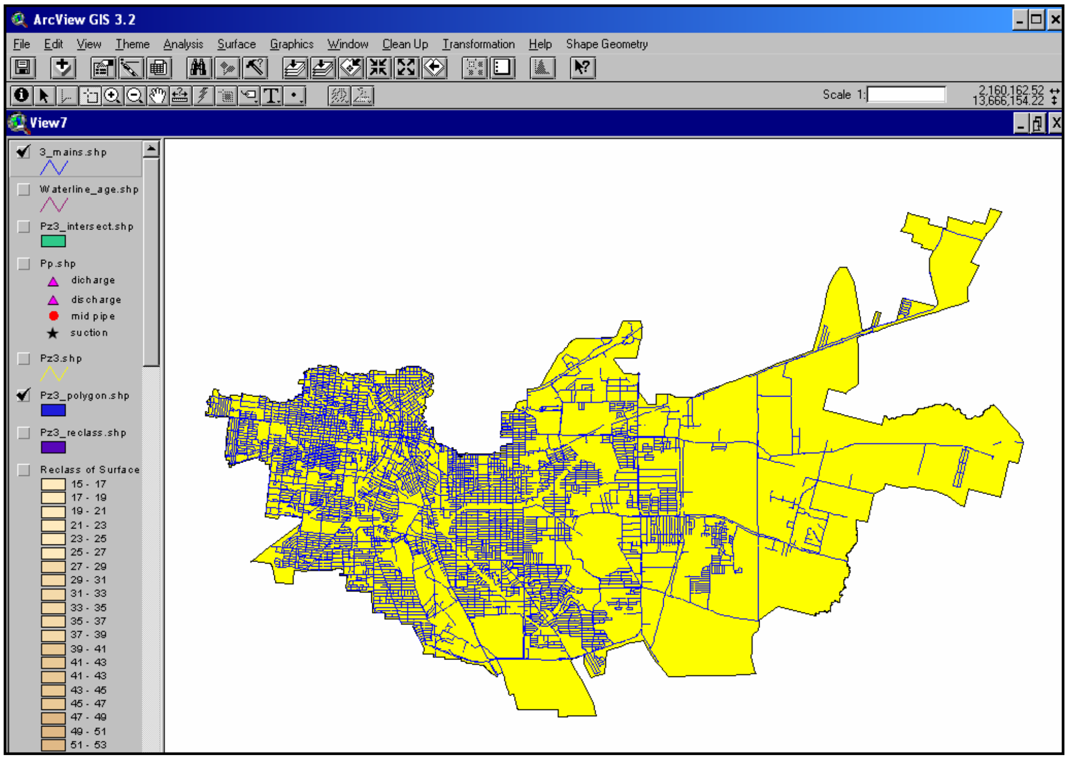
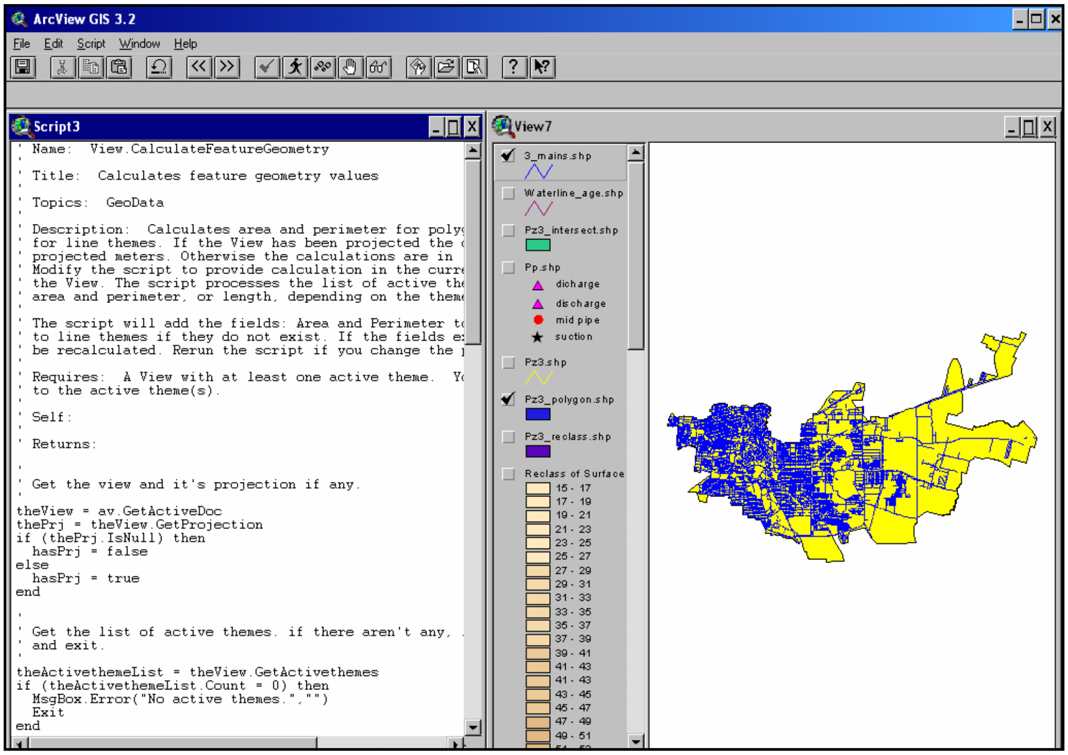


**Fig. A.12.** ArcView GIS 3.2 window showing the resulting water main shapefile intersected with pressure zone three.

One more step is required in order to calculate the length of the water mains in each pressure zone. This is because the previously described steps and resulting shapefile (3_mains.shp) does not correctly determine the truncated length of water mains which cross the boundaries of the pressure zones. In order to remedy this problem, follow these steps in ArcView GIS. Fig. A.13 is the visual representation of following these steps.

- Open script 3 (Script 3 is shown at the conclusion of this section (A.1.5).

- Manipulate your screen viewport, so that you can see both script 3 and the view you have been using that has the water main shapefiles clipped to the single pressure zones.
- Select the shapefile 3_mains.shp by checking its theme on the left hand side of the view, and click on it again to make sure this is the active theme.
- Click last on the header of script 3 to make it active.
- Select the "Run" button on the toolbar across the top of the screen.
- When the program asks you if you want to "update length", choose "Yes".



```
' Name:  View.CalculateFeatureGeometry
'
' Title:  Calculates feature geometry values
'
' Topics:  GeoData
'
' Description:  Calculates area and perimeter for poly
' for line themes. If the View has been projected the
' projected meters. Otherwise the calculations are in
' Modify the script to provide calculation in the curre
' the View. The script processes the list of active the
' area and perimeter, or length, depending on the them
'
' The script will add the fields: Area and Perimeter t
' to line themes if they do not exist. If the fields e
' be recalculated. Rerun the script if you change the
'
' Requires:  A View with at least one active theme.  Y
' to the active theme(s).
'
' Self:
'
' Returns:


'
' Get the view and it's projection if any.
'
theView = av.GetActiveDoc
thePrj = theView.GetProjection
if (thePrj.IsNull) then
  hasPrj = false
else
  hasPrj = true
end

'
' Get the list of active themes. if there aren't any,
' and exit.
'
theActivethemeList = theView.GetActivethemes
if (theActivethemeList.Count = 0) then
  MsgBox.Error("No active themes.","")
  Exit
end
```

**Fig. A.13.** ArcView GIS window showing the process used to calculate the truncated length of the water mains located within pressure zone three.

At this point, the script has successfully recalculated all the lengths of the mains within pressure zone three, and accounted for even the mains whose lengths were truncated as they crossed zone boundaries. This theme (3_mains.shp) is the final product and its attribute table contains all the necessary information to calculate UARL.

Export the table from the final product shapefile (3_mains.shp) to Microsoft Excel. This table contains several columns, two being important in this procedure. The “Length” column lists the length of each water main in feet and the “Gridcode” column lists the average yearly pressures of each corresponding water main. Note, there is another column named “Shape_Length”. This column’s length does not get updated during the previously described GIS procedures; therefore do not use its values for subsequent calculations. Finally, this same process can be repeated with all the other shapefiles of the water mains intersecting the other pressure zones.

Script 3, used in the calculation of the truncated lengths of the water lines is as follows (http://support.esri.com/index.cfm?fa=downloads.geoprocessing.scripts).

```
' Name:  View.CalculateFeatureGeometry
'
' Title:  Calculates feature geometry values
'
' Topics:  GeoData
'
' Description:  Calculates area and perimeter for polygon themes and length
' for line themes. If the View has been projected the calculations are in
' projected meters. Otherwise the calculations are in 'native' map units.
' Modify the script to provide calculation in the current report units of
' the View. The script processes the list of active themes to calculate
' area and perimeter, or length, depending on the theme type.
'
' The script will add the fields: Area and Perimeter to polygon themes, Length
' to line themes if they do not exist. If the fields exist their values will
' be recalculated. Rerun the script if you change the projection of the view.
'
' Requires:  A View with at least one active theme.  You must have write access
```

```
' to the active theme(s).
'
' Self:
'
' Returns:

'
' Get the view and it's projection if any.
'
theView = av.GetActiveDoc
thePrj = theView.GetProjection
if (thePrj.IsNull) then
  hasPrj = false
else
  hasPrj = true
end

'
' Get the list of active themes. if there aren't any, let the user know
' and exit.
'
theActivethemeList = theView.GetActivethemes
if (theActivethemeList.Count = 0) then
  MsgBox.Error("No active themes.","")
  Exit
end

'
' Loop through the list of active themes. if you can't edit the theme
' inform the user.
'
For Each thetheme in theActivethemeList
  theFTab = thetheme.GetFTab
  if (theFTab.CanEdit.Not) then
    MsgBox.Info("Cannot edit table for theme:"++thetheme.AsString,"")
    Continue
  end
  '
  ' Make the FTAB editable, and find out which type of feature it is.
  '
  theFTab.SetEditable(TRUE)
  theType = theFTab.FindField("shape").GetType
  if (theType = #FIELD_SHAPEPOLY) then
    '
    ' if it's polygonal check for the existence of the fields "Area" and
    ' Perimeter. if they do not exist, create them.
    '
    if (theFTab.FindField("Area") = nil) then
      theAreaField = Field.Make("Area",#FIELD_DOUBLE,16,3)
      theFTab.AddFields({theAreaField})
    else
      ok = MsgBox.YesNo("Update Area?", "Calculate", true)
      if (ok.Not) then
```

```
    continue
  end

  theAreaField = theFTab.FindField("Area")
 end

 if (theFTab.FindField("Perimeter") = nil) then
  thePerimeterField = Field.Make("Perimeter",#FIELD_DOUBLE,16,3)
  theFTab.AddFields({thePerimeterField})
 else
  ok = MsgBox.YesNo("Update Perimeter?", "Calculate", true)
  if (ok.Not) then
    continue
  end

  thePerimeterField = theFTab.FindField("Perimeter")
 end

 '
 ' Loop through the FTAB and find the projected area and perimeter of each
 ' shape and set the field values appropriately.
 '
 theShape = theFTab.ReturnValue(theFTab.FindField("shape"),0)
 For Each rec in theFTab
  theFTab.QueryShape(rec,thePrj,theShape)

  theArea = theShape.ReturnArea
  thePerimeter = theShape.ReturnLength

  theFTab.SetValue(theAreaField,rec,theArea)
  theFTab.SetValue(thePerimeterField,rec,thePerimeter)
 end

elseif (theType = #FIELD_SHAPELINE) then
 '
 ' if the data source is linear, check for the existence of the
 ' field "Length". if it doesn't exist, create it.
 '
 if (theFTab.FindField("Length") = nil) then
  theLengthField = Field.Make("Length",#FIELD_DOUBLE,16,3)
  theFTab.AddFields({theLengthField})

 else
  ok = MsgBox.YesNo("Update Length?", "Calculate", true)
  if (ok.Not) then
    continue
  end

  theLengthField = theFTab.FindField("Length")
 end

 '
 ' Loop through the FTAB and find the projected length of each shape and set
```

```
    ' the field values appropriately.
    '
    theShape = theFTab.ReturnValue(theFTab.FindField("shape"),0)
    For Each rec in theFTab
      theFTab.QueryShape(rec,thePrj,theShape)

      theLength = theShape.ReturnLength

      theFTab.SetValue(theLengthField,rec,theLength)
    end

  end

  theFTab.SetEditable(FALSE)
end
```

### A.1.6. Calculating UARL: Water Mains

The following UARL calculation is for water mains only, and is completed one pressure zone at a time. Mains are pipes that are accounted for in the SAWS GIS water main shapefile. The UARL constant for mains is 5.4 gallons/miles of mains/day/psig of pressure according to the UARL equation. To carry out the UARL calculation for this detailed method A, add a new column to the previously described table exported into Microsoft Excel from ArcView GIS. Title this new column UARL. Create the following formula, equation A.1, in this column.

$$\text{UARL}_{Mains} = 5.4 \times \frac{\text{Shape Length}}{5280\ {}^{\text{ft}}\!/\!_{\text{mi}}} \times \text{Ave. Yearly Pressure in psi} \times 365\ \frac{\text{days}}{\text{year}} \qquad \text{(A.1)}$$

Sum this column to attain the total UARL value for each particular pressure zone. Repeat procedure for remaining pressure zones and then sum all of these subtotaled UARL values together to attain the total UARL values for all the water mains in the SAWS.

### A.1.7. Calculating UARL: Service Lines & Pipes between Curb Stops & Meters

Since the ArcView GIS files contain only information about the water mains and not the service lines or underground pipes between the curb stops and customer meters, there was not adequate information available to calculate these UARL values using the same detailed method as with the water mains. Therefore, a couple of assumptions had to be made in order to estimate the UARL values for these other infrastructure components. First, these two infrastructure components are directly connected to the water mains and therefore will have very similar pressures as the main itself. This assumption requires an average system pressure (in psig) to be calculated. Do this according to the following equation (Alegre et al. 2000 and Kunkel 2002):

$$P_{Average} = \left(UARL_{Mains} \times 365\right) / 5.4 / \text{Total Miles of Mains} \tag{A.2}$$

The second assumption is that the average length of service connections in SAWS is 50 feet. The following equation A.3 (Alegre et al. 2000 and Kunkel 2002) calculates the UARL for amount of service lines in the system and for the underground pipes which run between the curb stop and the customer meters.

$$UARL_{\text{Service Conn \& Curb Stops}} = P_{Average} \times N_C \times 365 \times \left(0.13 + 7.5 L_P\right) \tag{A.3}$$

In the previous equation:

- $UARL$ is calculated in units of gallons per year.
- $P$ is the average operating pressure of the system, in units of psig as calculated in previous equation.
- $N_C$ is the number of service connections in the system.
- $L_P$ is the average length per service connections in miles.

The final amount of UARL for this system, according to this detailed method, is the sum of the two previous UARL infrastructure calculations. These calculations for the 2004 auditing period produced an UARL volume of 2.355 billion gallons of water per year.

In SAWS Comprehensive Annual Financial Report for the year 2004, they estimate that 52.588 million gallons of water was pumped that year. In comparison with the previous results, the UARL account for roughly 4.48% of the total pumped volume. This UARL estimate appears reasonable.

## A.2. METHOD B: STEP-BY-STEP TUTORIAL

Method B is a compromise between methods A and C. It is the preferred method because it produces very similar results to method A while using simplifying procedures. Using method B, the UARL volume for the 2004 auditing period only differs by 0.4 % when compared to method A calculations. This method is much faster because it does not require as extensive use of ArcView GIS. Also, positively, this method continues to consider the impacts of the pressure zones on the SAWS and the average pressure calculations by using a weighted average pressure according to the mileage of water mains in each pressure zone. The following sub-sections describe the procedures for calculating UARL according to this simplified method.

### A.2.1. Calculating the Average Pressure per each Zone

See the section **A.1.2. Calculating Average System Operating Pressure** from the Method A procedures to learn how to calculate $P_{Average}$ for each individual pressure zone.

### A.2.2. Calculating Miles of Main per each Zone

This task involves using ArcView GIS to intersect the shapefile "Waterline_age.shp" with each individual pressure zone, so that that the total miles of water main per zone can be calculated. First add the shapefile "Waterline_age.shp" and the following polygon shapefiles of each pressure zone.

- **Pz2_polygon.shp**
- **Pz3_polygon.shp**
- **Pz4_polygon.shp**
- **Pz5_polygon.shp**
- **Pz6&9_polygon.shp**
- **Pz7_polygon.shp**
- **Pz8_polygon.shp**

- **Pz10&11a_polygon.shp**
- **Pz11&12_polygon.shp**

Now, continue with the following steps. Begin by turning on the waterline shapefile and one of the pressure zone shapefiles, in this example pressure zone two (Pz2_polygon.shp) will be used. Choose the "select feature" button on the ArcView GIS toolbar. While holding shift down, click and drag around all the water lines that overlap the pressure zone you are using. Try to minimize the region you select as much as possible because this will save processing time. Next, choose the "View" menu at the top of the screen and then select "GeoProcessing Wizard" on the sub-menu. A pop-up menu will appear. Choose the option "intersect two themes" and then select the button Next. Choose the following options:

- First option, select the shapefile (Waterline_age.shp) as the input theme to intersect. Make sure the box is checked that says "Use Selected Features Only".
- Second option, select the output shapefile from the previous intersection task (Pz2_polygon.shp) as the overlay theme.
- Option three, choose the correct directory and select an appropriate filename (PZ2_mains.shp) for the new shapefile that will be created. This new theme will be added to your window.

One more step is required in order to calculate the length of the water mains in each pressure zone. This is because the previously described steps and resulting shapefile (PZ2_mains.shp) does not correctly determine the truncated length of water mains which cross the boundaries of the pressure zones. In order to remedy this problem, follow the following steps in ArcView GIS 3.2.

- Open script 3.
- Manipulate your screen viewport, so that you can see both script 3 and the view you have been using that has the water main shapefiles clipped to the single pressure zone.
- Select the shapefile PZ2_mains.shp by checking its theme on the left hand side of the view, and click on it again to make sure this is the active theme.
- Click last on the header of script 3 to make it active.
- Select the “Run” button on the toolbar across the top of the screen.
- When the program asks you if you want to “update length”, choose “Yes”.

At this point, the script has successfully recalculated all the lengths of the mains within pressure zone 2, and accounted for even the mains whose lengths were truncated as they crossed zone boundaries. This theme (PZ2_mains.shp) is the final product. Export the attribute table from the shapefile (PZ2_mains.shp) to Microsoft Excel. This table contains several columns, the important one being the column named “Length”. This column lists the length of each water main in feet. Be careful to choose the correctly named column, because there is another column named “Shape_Length” which does not get its truncated lengths updated during the previously run ArcView GIS procedure using Script 3. In Microsoft Excel, sum the “Length” column and then divide it by 5,280 feet/mile to determine the total mileage of water mains in the pressure zone.

Repeat this same process for each pressure zone, so that the miles of main encompassed by each pressure zone is known.

### A.2.3. Calculating UARL

Use Microsoft Excel to multiply the miles of Main ( $L_M$ ) in each pressure zone by the average pressure ( $P_{Average}$ ) in the corresponding pressure zone. Then, sum these individual values of ( $L_M \times P_{Average}$ ) all together. Divide this summed value by the total value of all miles of water main in the SAWS. This results in a weighted average system pressure ( $P_{weighted}$ ) in units of psig.

Now, use the following equation, described in the introduction of this section, to calculate the UARL of the system (Alegre et al. 2000 and Kunkel 2002).

$$UARL = P_{weighted} \times N_C \times 365 \left[ \left( \frac{5.4 L_M}{N_C} \right) + 0.13 + 7.5 L_P \right] \tag{A.4}$$

Using this method produced an UARL value of 2.344 billion gallons per year.

# APPENDIX B

## SUMMARY OF SYSTEM INPUT ANALYSIS

### Primary Pumping Stations: HSP

| Station | Point_Name | Metered Flow | Metered Flow (MG/year) | Point_Name | Runtime Flow | Runtime Flow (MG/year) | Point_Name | Runtime Total Flow (MG/year) |
|---|---|---|---|---|---|---|---|---|
| 34th Street | 34SFI010 | x | 455.825748 | 34SMN001 | x | 536.6447917 | 34SSL3FL | 166.19643 |
| | 34SFI020 | x | 999.064332 | 34SMN002 | x | 1225.947 | 34SSL4FL | 1899.828356 |
| | 34SFI030 | x | 139.576014 | 34SMN003 | x | 119.536 | | |
| | 34SFI040 | x | 47.883255 | 34SMN004 | x | 71.71541667 | | |
| | 34SFI050 | x | 118.614801 | 34SMN005 | x | 93.048 | | |
| Total | | | 1760.96415 | | | 2046.891208 | | 2066.024786 |
| Anderson St. | AN1FI010 | x | 1079.590828 | AN1MN001 | x | 1140.334708 | AN1SLFL | 6677.163273 |
| | AN1FI020 | x | 973.234619 | AN1MN002 | x | 972.388125 | | |
| | AN1FI030 | x | 1141.260821 | AN1MN003 | x | 1115.572708 | | |
| | AN1FI040 | x | 1091.752915 | AN1MN004 | x | 1055.56875 | | |
| | AN1FI050 | x | 1032.353049 | AN1MN005 | x | 1166.183333 | | |
| | AN1FI060 | x | 1172.446901 | AN1MN006 | x | 1171.183 | | |
| Total | | | 6490.639133 | | | 6621.230625 | | 6677.163273 |
| Artesia St. | ARTFI010 | x | 81.615811 | ARTMN001 | x | 786.465625 | ARTMSLFL | 2375.298348 |
| | ARTFI020 | x | 483.738826 | ARTMN002 | x | 656.2066667 | ARTSLFL | 2158.306172 |
| | ARTFI030 | x | 303.022817 | ARTMN003 | x | 708.6695 | | |
| | ARTFI040 | x | 91.129773 | ARTMN004 | x | | | |
| Total | | | 959.507227 | | | 2151.341792 | | 2158.306172 |
| Basin St. | BSNFI010 | x | 524.259691 | BSNMN001 | x | 456.707 | BSNSLFL | 5877.477168 |
| | BSNFI020 | x | 2252.425213 | BSNMN002 | x | 2584.375 | | |
| | BSNFI030 | x | 15.919177 | BSNMN003 | x | 0 | | |
| | BSNFI040 | x | 1273.687821 | BSNMN004 | x | 931.8458333 | | |
| | BSNFI050 | x | 1148.318628 | BSNMN005 | x | 1039.483333 | | |
| | BSNFI060 | x | 973.566951 | BSNMN006 | x | 840.225 | | |
| Total | | | 6188.177481 | | | 5852.636167 | | 5877.477168 |
| Maltsberger | MALFI010 | x | 894.815671 | MALMN001 | x | 1044.558917 | MALSLFL | 5068.737634 |
| | MALFI020 | x | 509.57182 | MALMN002 | x | 769.3656667 | | |
| | MALFI030 | x | 671.88775 | MALMN003 | x | 773.39 | | |
| | MALFI040 | x | 656.399351 | MALMN004 | x | 714.4208333 | | |
| | MALFI050 | x | 57.470246 | MALMN005 | x | 62.01033333 | | |
| | MALFI060 | x | 536.303118 | MALMN006 | x | 726.0490833 | | |
| | MALFI070 | x | 891.367373 | MALMN007 | x | 951.4505 | | |
| Total | | | 4217.815329 | | | 5041.245333 | | 5068.737634 |
| Marbach | MARFI010 | x | 69.302941 | MARMN001 | x | 259.2308333 | MARSLFL | 724.003236 |
| | MARFI020 | x | 222.718039 | MARMN002 | x | 4.595083333 | | |
| | MARFI030 | x | 261.995003 | MARMN003 | x | 18.06358333 | | |
| | MARFI040 | x | 174.729942 | MARMN004 | x | 9.074541667 | | |
| | MARFI050 | x | 157.188414 | MARMN005 | x | 428.9891667 | | |
| Total | | | 885.934339 | | | 719.9532083 | | 724.003236 |
| Micron Drive | MICFI010 | x | 8.892469 | MICMN001 | x | 5.479166667 | MICSL5FL | 153.5956 |
| | MICFI020 | x | 134.205985 | MICMN002 | x | 148.1583333 | MICSL7FL | 13.4676 |
| | MICFI030 | x | -0.014785 | MICMN003 | | | | |
| | MICFI040 | x | -0.014782 | MICMN004 | | | | |
| | MICFI050 | x | -0.014782 | MICMN005 | | | | |
| | MICFI060 | x | 0.594134 | MICMN006 | x | 12.14583333 | | |
| | MICFI070 | x | 0.747565 | MICMN007 | x | 1.279166667 | | |
| | MICFI080 | x | -0.014777 | MICMN008 | | | | |
| | MICFI090 | x | 0.023501 | MICMN009 | | | | |
| | MICFI110 | x | 0 | MICMN010 | | | | |
| Total | | | 144.404528 | | | 167.0625 | | 167.0632 |
| Market St. | MKTFI010 | | | MKTMN001 | x | 1069.507083 | MKTSLFL | 3736.441 |
| | MKTFI020 | | | MKTMN002 | x | 862.3295833 | | |
| | MKTFI030 | | | MKTMN003 | x | 1196.474583 | | |
| | MKTFI040 | | | MKTMN004 | x | 590.5533333 | | |
| Total | | | | | | 3718.864583 | | 3736.441 |
| Mission St. | MSNFI010 | x | 327.461151 | MSNMN001 | x | 349.9272917 | MSNSLFL | 3125.450596 |
| | MSNFI020 | x | 798.418128 | MSNMN002 | x | 813.9408333 | | |
| | MSNFI030 | x | 4.603535 | MSNMN003 | x | 0.2375 | | |
| | MSNFI040 | x | 801.142971 | MSNMN004 | x | 818.5441667 | | |
| | MSNFI050 | x | 710.270237 | MSNMN005 | x | 652.9431667 | | |
| | MSNFI060 | x | 676.366933 | MSNMN006 | x | 481.674125 | | |
| Total | | | 3318.262955 | | | 3117.267083 | | 3125.450596 |
| Nacodoches(1) | NC1FI010 | x | 268.042669 | NC1MN001 | x | 441.1591667 | NC1SL5AFL | 1641.413749 |
| | NC1FI020 | x | 475.662987 | NC1MN002 | x | 504.9415 | NC1SL6FL | 2516.185903 |
| | NC1FI030 | x | 261.473325 | NC1MN003 | x | 383.0433333 | NC1SL5FL | 0 |
| | NC1FI040 | x | 198.255617 | NC1MN004 | x | 389.489 | | |
| | NC1FI050 | x | 280.583634 | NC1MN005 | x | 766.5504167 | | |
| | NC1FI060 | x | 795.940315 | NC1MN006 | x | 581.8020833 | | |
| | NC1FI070 | x | 276.512737 | NC1MN007 | x | 347.0541667 | | |
| | NC1FI080 | x | 559.708334 | NC1MN008 | x | 592.8791667 | | |
| | NC1FI090 | x | 68.686655 | NC1MN009 | x | 99.99166667 | | |
| Total | | | 3184.866273 | | | 4106.9105 | | 4157.599652 |

### Primary Pumping Stations: HSP (continued)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Nacodoches(2) | NC2FI010 | x | 432.306097 | NC2MN001 | x | 498.3966667 | NC2SL9FL | 1320.561303 |
| | NC2FI020 | x | 7.904245 | NC2MN002 | x | 0 | | |
| | NC2FI030 | x | 43.637624 | NC2MN003 | x | 39.85833333 | | |
| | NC2FI040 | x | 624.83541 | NC2MN004 | x | | | |
| Total | | | 1108.683376 | | | 538.255 | | 1320.561303 |
| Piper's Meadow | PMSFI010 | x | 130.090833 | PMSMN001 | x | 104.6745833 | PMSSLFL | 181.820409 |
| | PMSFI020 | x | 77.122319 | PMSMN002 | x | 76.89583333 | | |
| Total | | | 207.213152 | | | 181.5704167 | | 181.820409 |
| Randolph | RANFI010 | x | 85.991171 | RANMN001 | x | 132.2021667 | RANSL4FL | 1919.783483 |
| | RANFI020 | x | 77.297879 | RANMN002 | x | 118.0744583 | RANSL6FL | 252.583311 |
| | RANFI030 | x | 820.208366 | RANMN003 | x | 1135.905 | | |
| | RANFI040 | x | 628.743125 | RANMN004 | x | 762.1625 | | |
| Total | | | 1612.240541 | | | 2148.344125 | | 2172.366794 |
| Seale Road | SELFI010 | x | 69.302941 | SELMN001 | x | 182.9882875 | SELSLFL | 589.981166 |
| | SELFI020 | x | 222.718039 | SELMN002 | x | 145.50625 | | |
| | SELFI030 | x | 261.995003 | SELMN003 | x | 257.9992917 | | |
| | SELFI040 | x | 174.729942 | SELMN004 | | | | |
| | SELFI050 | x | 157.188414 | SELMN005 | | | | |
| Total | | | 885.934339 | | | 586.4938292 | | 589.981166 |
| Turtle Creek 2 | TC2FI001 | | | TC2MN001 | x | 15.41979167 | TC2SLFL | 45.045658 |
| | TC2FI002 | | | TC2MN002 | x | 27.563375 | | |
| | TC2FI003 | | | TC2MN003 | x | 2.000166667 | | |
| | TC2FI004 | | | TC2MN004 | | | | |
| Total | | | | | | 44.98333333 | | 45.045658 |
| Wurzbach | WURFI010 | x | 1097.01765 | WURMN001 | x | 860.031 | WURSL5FL | 2535.192588 |
| | WURFI020 | x | 1065.894018 | WURMN002 | x | 1154.696667 | WURSL7FL | 5145.664453 |
| | WURFI030 | x | 612.293036 | WURMN003 | x | 505.44375 | | |
| | WURFI040 | x | 1116.613774 | WURMN004 | x | 494.415625 | | |
| | WURFI050 | x | 1152.309654 | WURMN005 | x | 539.0898333 | | |
| | WURFI060 | x | 1305.825178 | WURMN006 | x | 1755.187542 | | |
| | WURFI070 | x | 893.097907 | WURMN007 | x | 792.1675 | | |
| | WURFI080 | x | 1047.844687 | WURMN008 | x | 1526.84625 | | |
| Total | | | 8290.895904 | | | 7627.878167 | | 7680.857041 |
| San Geronimo | | | | SGAMN001 | | | SGASLFL | 4.373288 |
| | | | | SGAMN002 | | | | |
| Total | | | | | | | | 4.373288 |
| S&S Hills | | | | SSHMN001 | | | SSHSLFL | 6.85571 |
| | | | | SSHMN002 | | | | |
| Total | | | | | | | | 6.85571 |
| Concept Therapy | | | | CTIMN001 | x | 1.374053542 | CTISLFL | 2.145107 |
| | | | | CTIMN002 | x | 1.572176667 | | |
| Total | | | | | | 2.946230208 | | 2.145107 |
| Culebra | | | | CULMN001 | | | CULSLFL | 34.21278 |
| | | | | CULMN002 | | | SL5FL | |
| | | | | CULMN003 | | | | |
| | | | | CULMN004 | | | | |
| Total | | | | | | | | 34.21278 |
| Trinity Aquifer Wells | | | | TRYSLFL | x | 1193.215929 | | |

### Secondary Pumping Stations: HSP

| Station | Point_Name | Metered Flow | Metered Flow (MG/year) | Point_Name | Runtime Flow | Runtime Flow (MG/year) | Point_Name | Runtime Total Flow (MG/year) |
|---|---|---|---|---|---|---|---|---|
| Turtle Creek 3 | TC3FI001 | x | 617.556688 | TC3MN001 | | | TC3SLFL | 152.423881 |
| Babcock Rd. | BBCFI001 | x | 0.012756 | BBCMN001 | | | BBCSLFL | 0 |
| Barbet #1 | BB1FI001 | x | 0.291865 | BB1MN001 | | | BB1SLFL | 0 |
| Barbet #2 | BB2FI001 | x | 541.614899 | BB2MN001 | | | BB2SLFL | 447.606545 |
| Basse Rd. | BSEFI001 | x | 0.89548 | BSEMN001 | | | BSESLFL | 0 |
| Brackenridge (Well #13) | B13FI001 | x | 218.488356 | B13MN001 | | | | |
| Brackenridge (Well #14) | BKGFI001 | x | 191.952544 | BKGMN001 | | | BKGSLFL | 565.099705 |
| Dover | KW2FI001 | x | 254.645894 | KW2MN001 | | | KW2SLFL | 0 |
| Dreamhill | DRMFI001 | x | 389.865055 | DRMMN001 | | | DRMSLFL | 737.831907 |
| Stahl Road | STSFI001 | x | 0.672984 | STSMN001 | | | STSSLFL | 0 |
| Lackland City #3 | LC3FI001 | x | 119.840396 | LC3MN001 | | | LC3SLFL | 0 |
| Lackland City #6 | LC6FI010 | x | 379.665738 | LC6MN001 | | | LC6SLFL | 0 |
| Lackland City #6a | LC6FI020 | x | 515.414476 | LC6MN002 | | | LCSLFL | |
| Stapleton Park | KW4FI001 | x | 39.921813 | KW4MN001 | | | KW4SLFL | 0 |
| Lindbergh Park | KW1FI001 | x | 41.724336 | KW1MN001 | | | KW1SLFL | 25.315092 |
| Sutton | SUTFI001 | x | 114.833663 | SUTMN001 | | | SUTSLFL | 121.428508 |
| Loma Linda | LLSFI001 | x | 331.968256 | LLSMN001 | | | LLSSLFL | 526.663041 |
| Sunshine | SUNFI001 | x | 141.980218 | SUNMN001 | | | SUNSLFL | 149.543014 |
| Ramsey Road | RAMFI001 | x | 2.641144 | RAMMN001 | | 0 | RAMSLFL | 0 |
| Klaus Road | KLSFI001 | x | 698.537839 | KLSMN001 | | | KLSSLFL | 752.05924 |
| Woodlake | WLKFI001 | x | 177.46435 | WLKMN001 | | | WLKSLFL | 76.683818 |
| West Avenue | WSTFI001 | x | 5.407793 | WSTMN001 | | | WSTSLFL | 0 |
| Walzem | WLZFI001 | x | 93.930331 | WLZMN001 | | | WLZSLFL | 80.575022 |
| Northwood Station | NRSFI001 | x | 858.645637 | NRSMN001 | | | NRSSLFL | 792.182273 |
| Upsom Park | KW5FI001 | x | 46.915139 | KW5MN001 | | | KW5SLFL | 0 |
| Gateway #1 | GATFI001 | x | 0.356467 | GATMN001 | | | | |
| Gateway #2 | GATFI002 | | | GATMN002 | | | GATSLFL | 112.339377 |
| Kelly Wells Total | | | | | | | KWSLFL | 395.365954 |

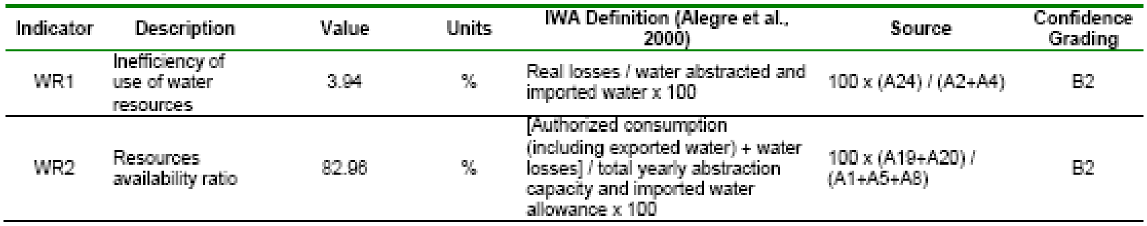
***Unmonitored Stations:***

*Bandera Road*
*Edison*
*Lady of the Lake*

# APPENDIX C

# PERFORMANCE INDICATORS

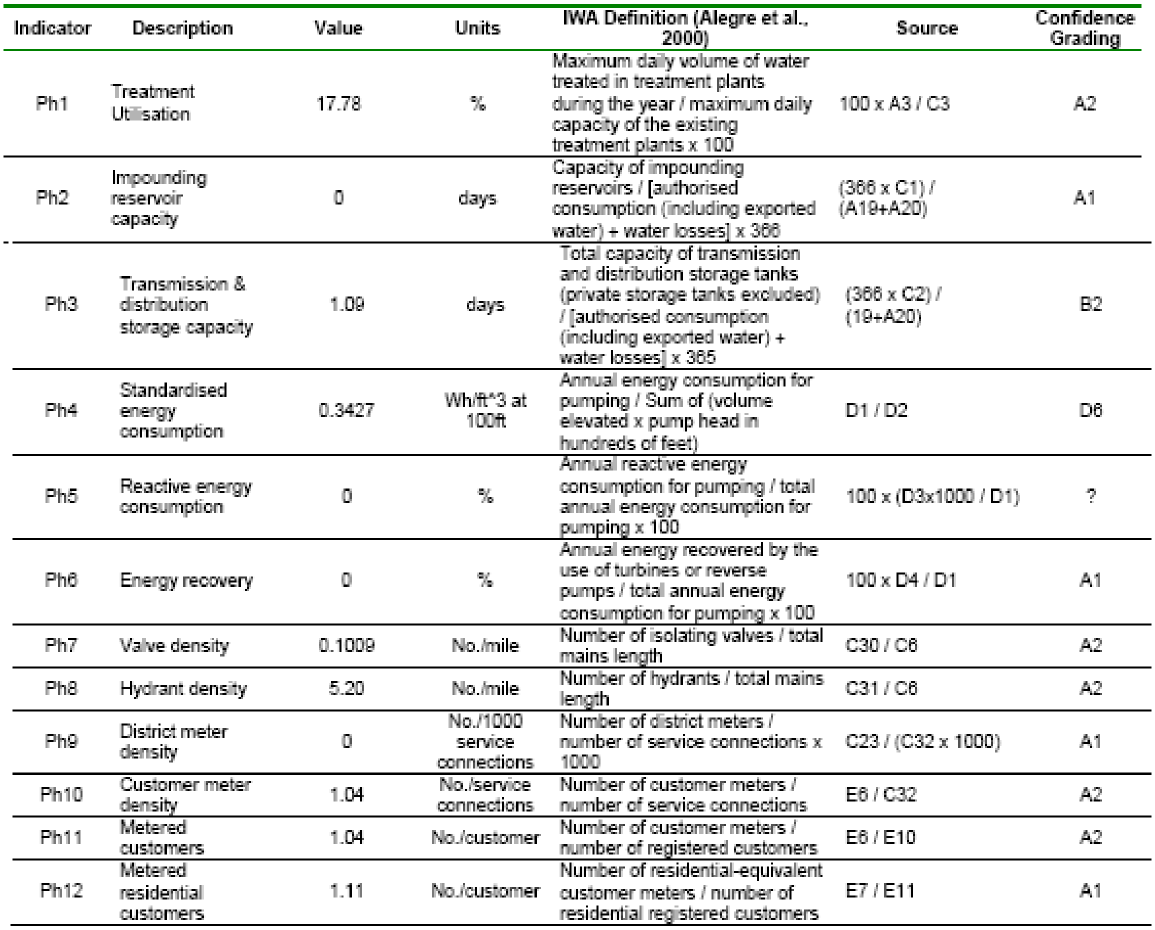
**TABLE C.1.** Water Resources Performance Indicators*



| Indicator | Description | Value | Units | IWA Definition (Alegre et al., 2000) | Source | Confidence Grading |
|---|---|---|---|---|---|---|
| WR1 | Inefficiency of use of water resources | 3.94 | % | Real losses / water abstracted and imported water x 100 | 100 x (A24) / (A2+A4) | B2 |
| WR2 | Resources availability ratio | 82.98 | % | [Authorized consumption (including exported water) + water losses] / total yearly abstraction capacity and imported water allowance x 100 | 100 x (A19+A20) / (A1+A5+A8) | B2 |

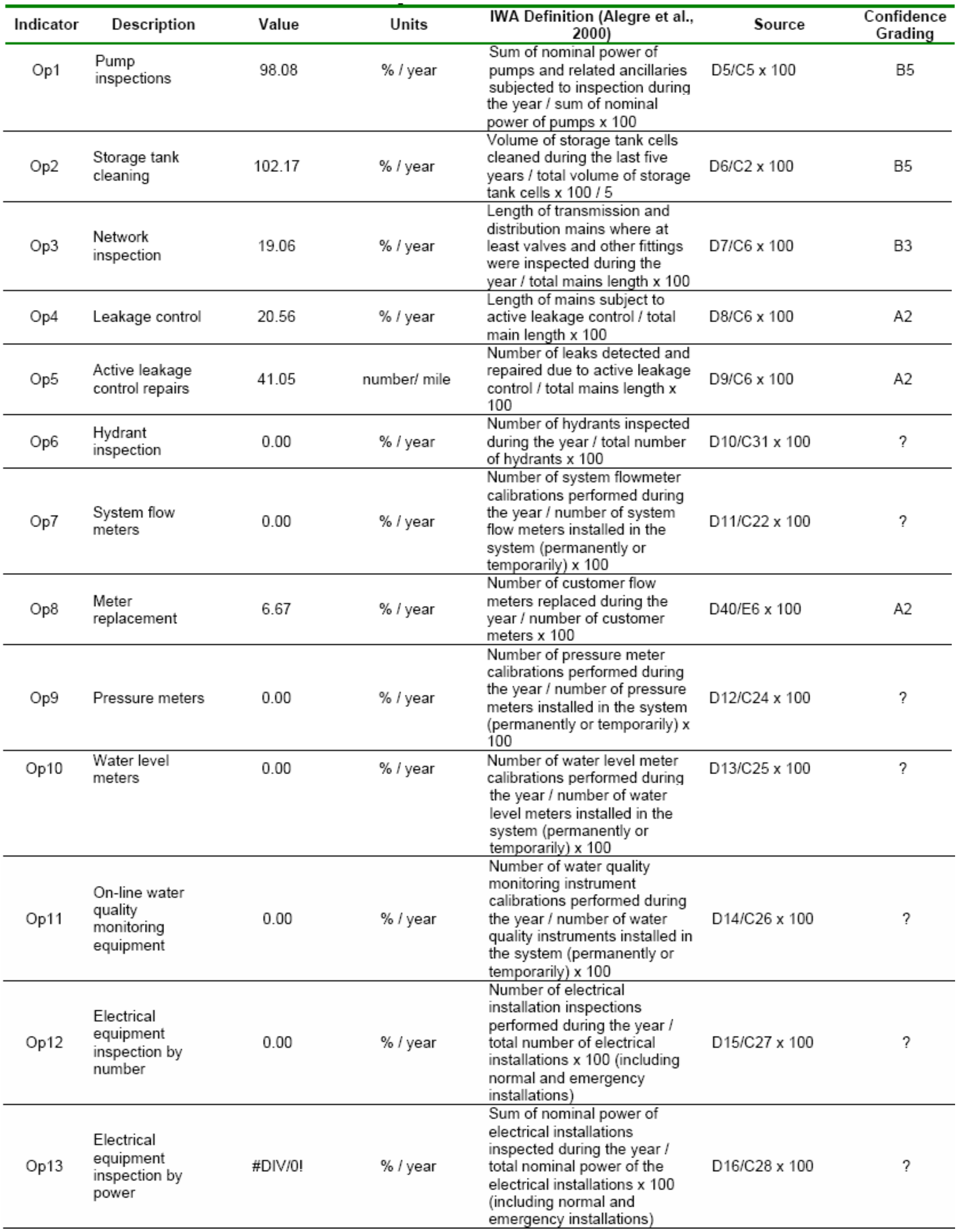
* Some Performance Indicator calculations are not complete.

**TABLE C.2.** Physical Performance Indicators*



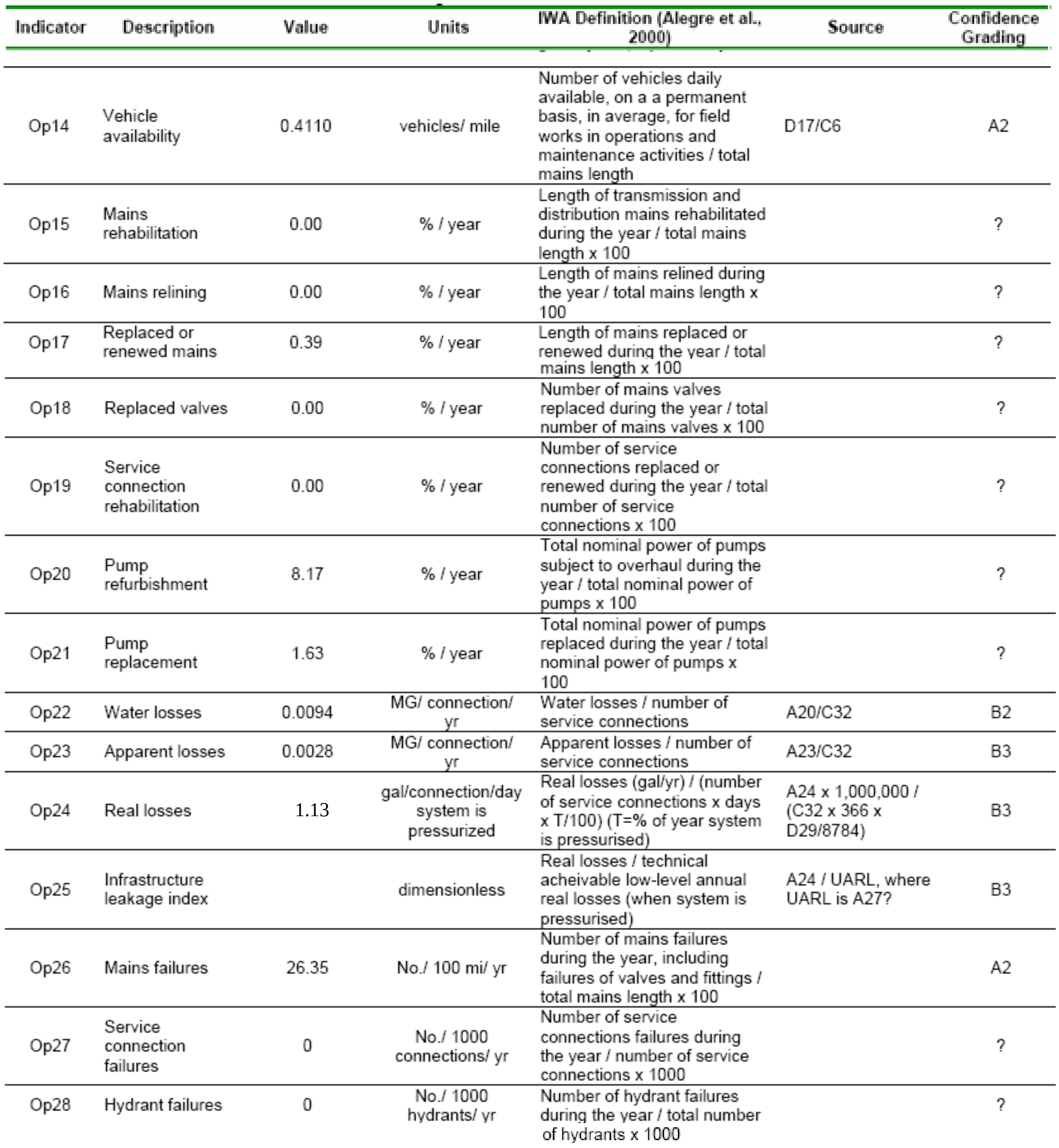
| Indicator | Description | Value | Units | IWA Definition (Alegre et al., 2000) | Source | Confidence Grading |
|---|---|---|---|---|---|---|
| Ph1 | Treatment Utilisation | 17.78 | % | Maximum daily volume of water treated in treatment plants during the year / maximum daily capacity of the existing treatment plants x 100 | 100 x A3 / C3 | A2 |
| Ph2 | Impounding reservoir capacity | 0 | days | Capacity of impounding reservoirs / [authorised consumption (including exported water) + water losses] x 366 | (366 x C1) / (A19+A20) | A1 |
| Ph3 | Transmission & distribution storage capacity | 1.09 | days | Total capacity of transmission and distribution storage tanks (private storage tanks excluded) / [authorised consumption (including exported water) + water losses] x 365 | (366 x C2) / (19+A20) | B2 |
| Ph4 | Standardised energy consumption | 0.3427 | Wh/ft^3 at 100ft | Annual energy consumption for pumping / Sum of (volume elevated x pump head in hundreds of feet) | D1 / D2 | D6 |
| Ph5 | Reactive energy consumption | 0 | % | Annual reactive energy consumption for pumping / total annual energy consumption for pumping x 100 | 100 x (D3x1000 / D1) | ? |
| Ph6 | Energy recovery | 0 | % | Annual energy recovered by the use of turbines or reverse pumps / total annual energy consumption for pumping x 100 | 100 x D4 / D1 | A1 |
| Ph7 | Valve density | 0.1009 | No./mile | Number of isolating valves / total mains length | C30 / C6 | A2 |
| Ph8 | Hydrant density | 5.20 | No./mile | Number of hydrants / total mains length | C31 / C6 | A2 |
| Ph9 | District meter density | 0 | No./1000 service connections | Number of district meters / number of service connections x 1000 | C23 / (C32 x 1000) | A1 |
| Ph10 | Customer meter density | 1.04 | No./service connections | Number of customer meters / number of service connections | E6 / C32 | A2 |
| Ph11 | Metered customers | 1.04 | No./customer | Number of customer meters / number of registered customers | E6 / E10 | A2 |
| Ph12 | Metered residential customers | 1.11 | No./customer | Number of residential-equivalent customer meters / number of residential registered customers | E7 / E11 | A1 |

**TABLE C.3**. Operational Performance Indicators*



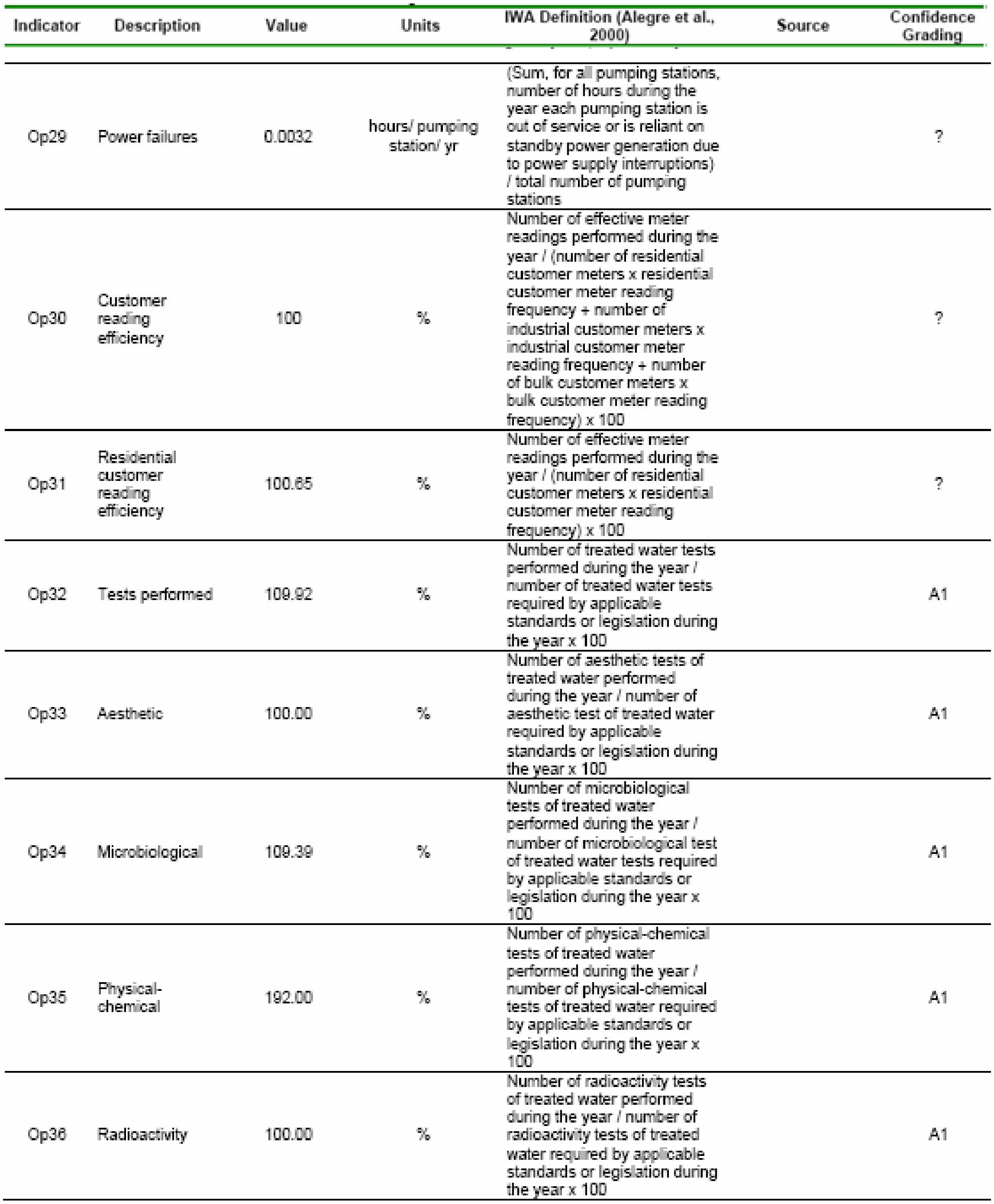
| Indicator | Description | Value | Units | IWA Definition (Alegre et al., 2000) | Source | Confidence Grading |
|---|---|---|---|---|---|---|
| Op1 | Pump inspections | 98.08 | % / year | Sum of nominal power of pumps and related ancillaries subjected to inspection during the year / sum of nominal power of pumps x 100 | D5/C5 x 100 | B5 |
| Op2 | Storage tank cleaning | 102.17 | % / year | Volume of storage tank cells cleaned during the last five years / total volume of storage tank cells x 100 / 5 | D6/C2 x 100 | B5 |
| Op3 | Network inspection | 19.06 | % / year | Length of transmission and distribution mains where at least valves and other fittings were inspected during the year / total mains length x 100 | D7/C6 x 100 | B3 |
| Op4 | Leakage control | 20.56 | % / year | Length of mains subject to active leakage control / total main length x 100 | D8/C6 x 100 | A2 |
| Op5 | Active leakage control repairs | 41.05 | number/ mile | Number of leaks detected and repaired due to active leakage control / total mains length x 100 | D9/C6 x 100 | A2 |
| Op6 | Hydrant inspection | 0.00 | % / year | Number of hydrants inspected during the year / total number of hydrants x 100 | D10/C31 x 100 | ? |
| Op7 | System flow meters | 0.00 | % / year | Number of system flowmeter calibrations performed during the year / number of system flow meters installed in the system (permanently or temporarily) x 100 | D11/C22 x 100 | ? |
| Op8 | Meter replacement | 6.67 | % / year | Number of customer flow meters replaced during the year / number of customer meters x 100 | D40/E6 x 100 | A2 |
| Op9 | Pressure meters | 0.00 | % / year | Number of pressure meter calibrations performed during the year / number of pressure meters installed in the system (permanently or temporarily) x 100 | D12/C24 x 100 | ? |
| Op10 | Water level meters | 0.00 | % / year | Number of water level meter calibrations performed during the year / number of water level meters installed in the system (permanently or temporarily) x 100 | D13/C25 x 100 | ? |
| Op11 | On-line water quality monitoring equipment | 0.00 | % / year | Number of water quality monitoring instrument calibrations performed during the year / number of water quality instruments installed in the system (permanently or temporarily) x 100 | D14/C26 x 100 | ? |
| Op12 | Electrical equipment inspection by number | 0.00 | % / year | Number of electrical installation inspections performed during the year / total number of electrical installations x 100 (including normal and emergency installations) | D15/C27 x 100 | ? |
| Op13 | Electrical equipment inspection by power | #DIV/0! | % / year | Sum of nominal power of electrical installations inspected during the year / total nominal power of the electrical installations x 100 (including normal and emergency installations) | D16/C28 x 100 | ? |

**TABLE C.3**. Continued*



| Indicator | Description | Value | Units | IWA Definition (Alegre et al., 2000) | Source | Confidence Grading |
|---|---|---|---|---|---|---|
| Op14 | Vehicle availability | 0.4110 | vehicles/ mile | Number of vehicles daily available, on a a permanent basis, in average, for field works in operations and maintenance activities / total mains length | D17/C6 | A2 |
| Op15 | Mains rehabilitation | 0.00 | % / year | Length of transmission and distribution mains rehabilitated during the year / total mains length x 100 | | ? |
| Op16 | Mains relining | 0.00 | % / year | Length of mains relined during the year / total mains length x 100 | | ? |
| Op17 | Replaced or renewed mains | 0.39 | % / year | Length of mains replaced or renewed during the year / total mains length x 100 | | ? |
| Op18 | Replaced valves | 0.00 | % / year | Number of mains valves replaced during the year / total number of mains valves x 100 | | ? |
| Op19 | Service connection rehabilitation | 0.00 | % / year | Number of service connections replaced or renewed during the year / total number of service connections x 100 | | ? |
| Op20 | Pump refurbishment | 8.17 | % / year | Total nominal power of pumps subject to overhaul during the year / total nominal power of pumps x 100 | | ? |
| Op21 | Pump replacement | 1.63 | % / year | Total nominal power of pumps replaced during the year / total nominal power of pumps x 100 | | ? |
| Op22 | Water losses | 0.0094 | MG/ connection/ yr | Water losses / number of service connections | A20/C32 | B2 |
| Op23 | Apparent losses | 0.0028 | MG/ connection/ yr | Apparent losses / number of service connections | A23/C32 | B3 |
| Op24 | Real losses | 1.13 | gal/connection/day system is pressurized | Real losses (gal/yr) / (number of service connections x days x T/100) (T=% of year system is pressurised) | A24 x 1,000,000 / (C32 x 366 x D29/8784) | B3 |
| Op25 | Infrastructure leakage index | | dimensionless | Real losses / technical acheivable low-level annual real losses (when system is pressurised) | A24 / UARL, where UARL is A27? | B3 |
| Op26 | Mains failures | 26.35 | No./ 100 mi/ yr | Number of mains failures during the year, including failures of valves and fittings / total mains length x 100 | | A2 |
| Op27 | Service connection failures | 0 | No./ 1000 connections/ yr | Number of service connections failures during the year / number of service connections x 1000 | | ? |
| Op28 | Hydrant failures | 0 | No./ 1000 hydrants/ yr | Number of hydrant failures during the year / total number of hydrants x 1000 | | ? |

**TABLE C.3**. Continued*

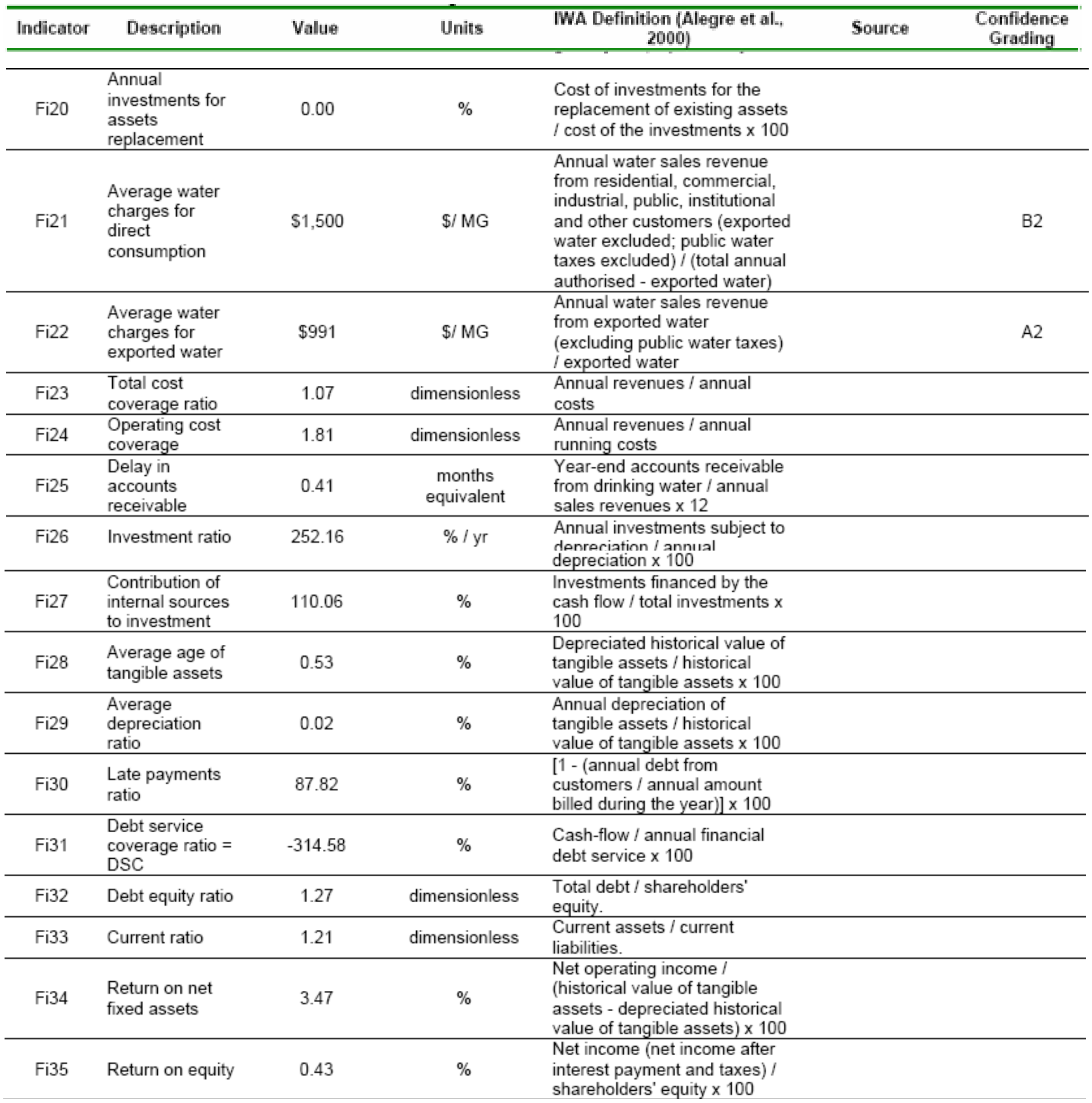


| Indicator | Description | Value | Units | IWA Definition (Alegre et al., 2000) | Source | Confidence Grading |
|---|---|---|---|---|---|---|
| Op29 | Power failures | 0.0032 | hours/ pumping station/ yr | (Sum, for all pumping stations, number of hours during the year each pumping station is out of service or is reliant on standby power generation due to power supply interruptions) / total number of pumping stations | | ? |
| Op30 | Customer reading efficiency | 100 | % | Number of effective meter readings performed during the year / (number of residential customer meters x residential customer meter reading frequency + number of industrial customer meters x industrial customer meter reading frequency + number of bulk customer meters x bulk customer meter reading frequency) x 100 | | ? |
| Op31 | Residential customer reading efficiency | 100.65 | % | Number of effective meter readings performed during the year / (number of residential customer meters x residential customer meter reading frequency) x 100 | | ? |
| Op32 | Tests performed | 109.92 | % | Number of treated water tests performed during the year / number of treated water tests required by applicable standards or legislation during the year x 100 | | A1 |
| Op33 | Aesthetic | 100.00 | % | Number of aesthetic tests of treated water performed during the year / number of aesthetic test of treated water required by applicable standards or legislation during the year x 100 | | A1 |
| Op34 | Microbiological | 109.39 | % | Number of microbiological tests of treated water performed during the year / number of microbiological test of treated water tests required by applicable standards or legislation during the year x 100 | | A1 |
| Op35 | Physical-chemical | 192.00 | % | Number of physical-chemical tests of treated water performed during the year / number of physical-chemical tests of treated water required by applicable standards or legislation during the year x 100 | | A1 |
| Op36 | Radioactivity | 100.00 | % | Number of radioactivity tests of treated water performed during the year / number of radioactivity tests of treated water required by applicable standards or legislation during the year x 100 | | A1 |

**TABLE C.4**. Financial Performance Indicators*

| Indicator | Description | Value | Units | IWA Definition (Alegre et al., 2000) | Source | Confidence Grading |
|---|---|---|---|---|---|---|
| Fi1 | Unit total costs | $4,439 | $/ MG | (Annual running costs + annual capital costs) / authorised consumption (including exported water) | | |
| Fi2 | Unit running costs | $2,613 | $/ MG | Annual running costs / authorised consumption (including exported water) | | |
| Fi3 | Unit capital costs | $1,826 | $/ MG | Annual capital costs / authorised consumption (including exported water) | | |
| Fi4 | Internal manpower costs ratio | 55.30 | % | Annual internal manpower costs / annual running costs x 100 | | |
| Fi5 | External services costs ratio | 51.37 | % | Annual external services costs / annual running costs x 100 | | |
| Fi6 | Imported (raw & treated) water costs ratio | 5.28 | % | Annual imported (raw and treated) water costs / annual running costs x 100 | | |
| Fi7 | Energy costs ratio | 5.36 | % | Annual energy costs / annual running costs x 100 | | |
| Fi8 | Other costs ratio | 0.00 | % | (Purchased merchandises + leasing and rentals + taxes, levies & fees + exceptional earnings & losses + other operating expenditures) / annual running costs x 100 | | |
| Fi9 | Management and support cost ratio | 0.00 | % | Annual running costs of management and support / total annual running costs x 100 | | |
| Fi10 | Financial and commercial costs ratio | 0.00 | % | Annual running costs of financial and commercial / annual running costs x 100 | | |
| Fi11 | Custormer service costs ratio | 0.00 | % | Annual running costs of customer service / annual running costs x 100 | | |
| Fi12 | Technical services costs ratio | 0.00 | % | Annual running costs of the technical services: planning, design, construction, operations and maintenance / annual running costs x 100 | | |
| Fi13 | Depreciable costs ratio | 64.09 | % | Annual depreciation costs / annual capital costs x 100 | | |
| Fi14 | Net interest costs ratio | 35.55 | % | (Interest expenses costs - interest income) / annual capital costs x 100 | | |
| Fi15 | Unit annual revenue | $4,731 | $/ MG | (Annual operating revenues - capitalised costs of self constructed assets) / authorised consumption (including exported water) | | |
| Fi16 | Sales revenues | 107.82 | % | (Sales revenues / annual revenues) x 100 | | |
| Fi17 | Other revenues | -1,278.72 | % | Other revenues not coming from sales/annual revenues x 100 | | |
| Fi18 | Unit Investment | $3,278 | $/ MG | Annual cost of investments (expenditures for plant and equipment) / authorised consumption (including exported water) | | |
| Fi19 | Annual investments for new & upgrading assets | 0.00 | % | Cost of investments for new assets (or upgrading of existing ones) / total cost of the investments x 100 | | |

**TABLE C.4.** Continued*



| Indicator | Description | Value | Units | IWA Definition (Alegre et al., 2000) | Source | Confidence Grading |
|---|---|---|---|---|---|---|
| Fi20 | Annual investments for assets replacement | 0.00 | % | Cost of investments for the replacement of existing assets / cost of the investments x 100 | | |
| Fi21 | Average water charges for direct consumption | $1,500 | $/ MG | Annual water sales revenue from residential, commercial, industrial, public, institutional and other customers (exported water excluded; public water taxes excluded) / (total annual authorised - exported water) | | B2 |
| Fi22 | Average water charges for exported water | $991 | $/ MG | Annual water sales revenue from exported water (excluding public water taxes) / exported water | | A2 |
| Fi23 | Total cost coverage ratio | 1.07 | dimensionless | Annual revenues / annual costs | | |
| Fi24 | Operating cost coverage | 1.81 | dimensionless | Annual revenues / annual running costs | | |
| Fi25 | Delay in accounts receivable | 0.41 | months equivalent | Year-end accounts receivable from drinking water / annual sales revenues x 12 | | |
| Fi26 | Investment ratio | 252.16 | % / yr | Annual investments subject to depreciation / annual depreciation x 100 | | |
| Fi27 | Contribution of internal sources to investment | 110.06 | % | Investments financed by the cash flow / total investments x 100 | | |
| Fi28 | Average age of tangible assets | 0.53 | % | Depreciated historical value of tangible assets / historical value of tangible assets x 100 | | |
| Fi29 | Average depreciation ratio | 0.02 | % | Annual depreciation of tangible assets / historical value of tangible assets x 100 | | |
| Fi30 | Late payments ratio | 87.82 | % | [1 - (annual debt from customers / annual amount billed during the year)] x 100 | | |
| Fi31 | Debt service coverage ratio = DSC | -314.58 | % | Cash-flow / annual financial debt service x 100 | | |
| Fi32 | Debt equity ratio | 1.27 | dimensionless | Total debt / shareholders' equity. | | |
| Fi33 | Current ratio | 1.21 | dimensionless | Current assets / current liabilities. | | |
| Fi34 | Return on net fixed assets | 3.47 | % | Net operating income / (historical value of tangible assets - depreciated historical value of tangible assets) x 100 | | |
| Fi35 | Return on equity | 0.43 | % | Net income (net income after interest payment and taxes) / shareholders' equity x 100 | | |

# VITA

Sarah Ruth Meyer earned a Bachelor of Science degree in civil engineering in May 2005 from Texas A&M University. Since then, she has worked towards a Master of Science degree also from Texas A&M University, focused in water resources engineering.

Sarah's graduate studies have been supported by a research assistantship funded by San Antonio Water System, a teaching assistantship, and by award of the Texas Section ASCE Hawley Fellowship. Throughout the course of her college career, Sarah has interned with a couple of engineering consulting firms. These internships include working with the hydrology and hydraulics group at Lockwood, Andrews, and Newnam Inc. (Summer 2005 and 2006) and a land development firm, Bury + Partners, Inc. (Summer 2004). These internship opportunities helped motivate her to pursue graduate level studies as well as focus her learning upon engineering and management of Texas critical water resources. Upon receipt of her Master's Degree in December 2006, she will be working as a consulting civil engineer with an emphasis in water resources.

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