THE ROLE OF GIS IN ASSET MANAGEMENT:
INTEGRATION AT THE OTAY WATER DISTICT

by

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LIST OF ACRONYMS

ASCE . . . . .American Society of Civil Engineers

AWWA . . . . . . American Water Works Association

CIP. . . . . Capital Improvement Project

CMMS. . . . . . . Computerized Maintenance Management Systems

EAM . . . . Enterprise Asset Management

EPA . . . . .U.S. Environmental Protection Agency

ESRI . . . . Environmental Systems Research Institute

GAO . . . . U.S. General Accounting Office

GASB . . . . Governmental Accounting Standards Board

GIS . . . . Geographic Information System

GPS . . . . .Global Positioning System

GUI . . . . Graphic User Interface

IIMM. . . . . . . .International Infrastructure Management Manual

MCC. . . . . Motor Control Cabinet

NAMS . . . . . . Australia and New Zealand's National Asset Management Steering

O&M. . . . . . . Operations and Maintenance

OWD . . . . Otay Water District

RDMS. . . . . . . Relational Database Management System

SCADA . . . . . Supervisory Control and Data Acquisition System

SQL. . . . . Sequential Query Language

WIN . . . . Water Infrastructure Network

ABSTRACT

This study demonstrates the integration of Geographic Information Systems (GIS) with asset management. There are few existing studies or demonstrations of the integration of GIS technology with asset management systems, especially for vertical assets at water utilities. A model is developed using Otay Water District (OWD) as a case study. The case study expands upon a GIS model that already contains horizontal assets (e.g., pipelines). The new model includes vertical assets (e.g., pump stations). In the past, non-spatial vertical assets, such as pump stations and their components were represented only by a point and could not be plotted against spatial data variables. In the expanded model, spatial and non-spatial asset risk variables are measured and scored for the 79 pumps within the 20 pump stations at the district. Each pump is assigned criticality and probability scores, which are then multiplied to give an overall risk factor score. Model scores were plotted on a point symbology map and expert confirmation was conducted with OWD water operations staff. A sensitivity analysis of the model reveals that manipulating model parameters to increase overall scoring accuracy of some pumps can also have a negative impact on the scoring of others. Further study is needed to plan and implement schemes that allow vertical assets at utilities to inherit asset management scores based on their positions within larger horizontal networks.

CHAPTER 1 – INTRODUCTION

All water utilities are made up of assets. The physical assets of a water distribution system include pipelines, storage reservoirs, pump stations, hydrants, valves, meters, manholes, and any other components that make up the system. Assets can be categorized as either horizontal or vertical. Vertical assets are those that are primarily above the ground, such as pumps, reservoirs, and treatment facilities. The horizontal assets are usually the buried assets such as the water mains that form the backbone of the water distribution and wastewater collection systems (New Mexico Environmental Finance Center, 2006). Assets can contain other assets. For example, a pump station can house important assets such as motors and an electrical system that support the pumps (Zhao and Stevens, 2011).

As the U.S. water distribution system ages and deteriorates, the assets of the system generally lose value and costs of operation and maintenance increase. Asset management is concerned with strategic approaches to optimize cost effectiveness with decisions that balance new investment and maintenance activities. In 2008, the U.S. Environmental Protection Agency (EPA) referred to asset management as maintaining a desired level of service for a given set of assets at the lowest cycle cost (U.S. EPA, 2008a). Lowest cycle cost is the least cost for rehabilitating, repairing, or replacing an asset over a given amount of time (U.S. EPA, 2008a). For a water utility, the management of assets plays a significant role in overall financial performance.

An effective asset management system must include an effective maintenance management system which is focused on reducing the maintenance cost while extending the useful life of the asset (Shamsi, 2005). Many utilities use a react- to-crisis management approach in dealing with infrastructure problems. This is usually not the best approach given the additional costs of emergency crews and property damage. With the use of effective asset management, it is possible to reduce overall infrastructure costs instead of waiting until the assets fail incurring higher than necessary costs (Shamsi, 2005).

This is especially important because at present, aging water and wastewater infrastructures in the United States are in critical stages of deterioration requiring billions of dollars for renovation (ASCE, 2009). Many systems are not getting the necessary maintenance and repairs needed to keep them working properly because of insufficient funding. In 2009, the American Society of Civil Engineers (ASCE) released its annual report card for America's infrastructure in which the nation's wastewater and drinking water systems each received a grade of D minus. The ASCE reported that U.S. water systems have at least an $11-billion annual investment shortfall to replace aging facilities and comply with existing and future federal safe drinking water regulations. The shortfall does not account for any growth in drinking water demand in the next 20 years (ASCE, 2009).

According to the American Water Works Association (AWWA), the cost of repairing and expanding the United States drinking and water infrastructure will total more than $1 trillion between 2011 and 2035 and exceed $1.7 trillion by 2050. The need will double from about $13 billion a year today (2012) to almost $30 billion (in 2010 dollars) annually by the 2040's (AWWA, 2012). The $1 trillion estimate covers buried drinking water assets only. Above ground drinking water facilities such as storage tanks, reservoirs and treatment plants will add to the total.

In 2001, the Water Infrastructure Network (WIN), a consortium of industry, municipal and non-profit associations, reported that the use of innovations in technology and management by utility companies has cut operations and maintenance costs by 15% to 40% (WIN, 2001). One of these innovative technologies is GIS which helps to analyze and communicate geographic or spatial information associated with physical assets. According to Shamsi (2005), except for the computer itself, no technology has so revolutionized the water industry as GIS. Another innovation is a Computerized Maintenance Management System (CMMS). It can be implemented for the more efficient maintenance of a utility because it accurately tracks problems within the utility network. GIS and CMMS integration can facilitate proactive (preventative) maintenance. Global Positioning System (GPS) is a key technology because it is used to increase the accuracy of existing system maps by verifying and correcting locations of system components. Also maps for new water systems can be created if they do not exist and water system attributes can be collected for populating a GIS databases.

Along with budgetary constraints, there are increased governmental requirements that affect the management of water utilities. For example, Rule 34 of the Governmental Accounting Standards Board (GASB), requires cities to adequately account for and report their capital asset inventory in a complete, accurate, and detailed manner. Because of the higher standards, GASB Rule 34 is an important factor toward improved asset management. Congress has been considering making utilities develop comprehensive plans as a condition for future funding (GAO, 2004).

1.1 - GIS and Asset Management

GIS had been proven to be an effective and powerful tool in the water distribution industry. According to the AWWA, as of 2002, 90% of water agencies were at least partially using GIS to assist in applications (Shamsi, 2005). An application is an applied use of technology which bridges the gap between pure science and applied use. An example for use in the water utility is a CMMS. It can have many functions. For example, it can provide maintenance cost and history along with providing asset inspection data and asset condition assessment. Integrating with a GIS can improve the capabilities of a CMMS by supporting spatial analysis and locating geographically dispersed facilities in the water system. A GIS is a special type of information system in which the database of spatially distributed features and procedures collect, store, retrieve, analyze, and display geographic data. GIS relates database records and associated attribute data to a physical location, creating a "smart map" (Vanier, 2004). A GIS is also a means of effectively analyzing large amounts of spatially related data. Making informed infrastructure maintenance decisions requires large amounts of diverse information on a continuing basis. GIS integrates all kinds of information from disparate sources into one manageable system so better and informed decisions can be based on all relevant factors.

With the integration of information from a variety of sources, it is possible to determine important geospatial relationships and factors on which utility maintenance would be based. For example, water main failure could be caused not only by age, but also by pipe material, surrounding soil, water pressure, and street traffic. By analyzing these factors and other related factors, it would be possible to determine which assets are the "hot spot" areas and constitute a priority for maintenance activities.

According to Shamsi (2002), the use of GIS technology can be an ideal solution for the effective management of water industry infrastructure because it offers the power of both geography and information systems. The key element of information used by a water utility its location to geographic features and objects. According to some estimates, more than 80% of all information used by water utilities is georeferenced making GIS technology especially applicable as a management tool (Shamsi, 2002).

Spatial location is typically a major common aspect of all the data at a water utility. A GIS can locate the exact position of a utilities infrastructure such as valves, hydrants, meters, pumps, and manhole covers displaying them on a computerized map. It can also store important data about each asset, including manufacturer, year of installation, repair history, size volume, water quality data or almost any other type of information. Efficient management must include location information so good decisions can be made relative to the surrounding area and affected assets. With the use of GIS in the area of asset management, it is possible to visualize and understand the geographical context of an asset and improve the efficiency of asset management.

1.2 - GIS Implementation at Otay Water District

The Otay Water District began implementing its GIS in 1995 and wanted to make the most of its investment by fully realizing the potential of GIS (Zhao and Stevens, 2002). Major data needed by the district were collected. The database was significant in size capturing the major attributes of the facility infrastructure such as diameter, material, as-built number, facility page number, etc. For its business operations, the district needed to keep a complete and detailed inventory, including location and condition of all assets. GIS has been shown to be a state-of-the-art technology which can efficiently perform the district's data related processes (Zhao and Stevens, 2003).

An Arc Internet Map Server (ArcIMS) based GIS web application was developed which could be used by the District staff through the internet. A customized ArcIMS application was developed with a similar Graphic User Interface (GUI) of ArcView desktop providing consistent user interface for field laptop and other desktop applications. The interactive maps allow users to query the data to derive more information. Also the web portal is a cost efficient way to distribute geographic information to the GIS user. Before the implementation of the GIS, obtaining records involved physically going into the record room and manually searching for the needed information. This process was inefficient, error-prone and hindered the productivity of the water district (Zhao and Stevens, 2003).

While collecting GIS data over several years, the district saw the need to integrate a variety of information and applications with a geographic component into one manageable system. The focus of GIS became one of a centralized asset for sharing and managing information rather than a cartographic tool. The result was the District's enterprise solution which was implemented in 2002 (Zhao and Stevens, 2002).

Enterprise GIS is an organizational approach that integrates various departmental projects into a centralized GIS which serves as a foundation in integrating other tabular database systems within the district. The core of the integrated systems for the district relates to customers, financial management, work management, and GIS. Also included are important systems of Supervisory Control And Data Acquisition (SCADA) for fuel and plant specific systems. SCADA is a computer system for gathering and analyzing real time data. In 2003, the district adopted Lucity as its CMMS mainly as the work order management tool. It is still in use. (Zhao and Stevens, 2009).

A key component in the enterprise GIS is the database design. The district used Esri's water utilities data model as the prototype to design the enterprise GIS database--including the potable water, recycled water, wastewater and land-based systems. The (Structured Query Language) SQL-based Geodatabase served as the basis for the district-wide enterprise system integration. The open platform of this database structure made it possible for the district's GIS system to integrate with other systems. Between-system integration is essential to make the most of enterprise GIS (Zhao and Stevens, 2009).

During 2007 and 2008, the district reevaluated the GIS architecture including hardware, servers, storage, network, applications from different systems, database requirements and user requirements (Zhao and Stevens, 2009). The current system architecture is now designed to accomplish the district's goal of higher availability, and better performance with current and future enterprise integration.

Compared with the GIS technology capability of a decade ago, new GIS technology is enterprise enabled and the district is headed in that direction (Zhao and Stevens, 2009). With the enterprise approach, all operational data should be available and integrated. As part of Otay Water District's strategic plan, the district wants to leverage its GIS investment with an enterprise integration strategy (Zhao and Stevens, 2009). This includes a GIS-centric management system which expands the existing water model of horizontal assets to integrate vertical assets. This initiative is the inspiration for this thesis study which was undertaken with the cooperation of the district.

1.3 - Study Objective at Otay Water District

The purpose of this study is to demonstrate and evaluate the integration of GIS and utility asset management in Otay Water District. The district, located in the southern part of San Diego County is the second largest in the county encompassing 125 square miles and serves the water and/or sewer needs of a population of approximately 206,000 (OWD, 2011). The project involves the expansion of the district's asset management system, composed of horizontal assets, to include its vertical assets in detail. Even though the majority of the district's water utility assets are horizontal, the vertical assets can be over 50% of the district's capital expenditures in cost maintenance, repair, or replacement (Zhao and Stevens, 2011). It is important to develop ways to try to economize with these expensive assets. One of the district's GIS strategic plan objectives is to develop and implement an asset management program plan to extend the useful life of the capital assets (Otay Water District, 2008). Another objective is to develop and test a criticality analysis (composed of measures of consequence and risk of failures) for the 79 potable pumps within the district's 20 pump stations.

CHAPTER 2 – BACKGROUND

Literature in the area of asset management in water utilities comes from a variety of sources, including government publications, trade magazines, and conference proceedings. The development of asset management approaches with water utilities originated around 2000. Literature relevant to providing background for this study includes both an overview of work done in asset management with water utilities and the narrower topic of the integration of GIS with asset maintenance management--specifically CMMS. This section also includes the reviews of the few articles found concerning the use of vertical assets, CMMS, and asset risk--the focus of the thesis study.

2.1 - Asset Management and Water Utilities

The use of asset management in water utilities is a relatively new concept. Until around 2000, it was relatively unknown in North America (Lutchman, 2006). The term originally described the management of financial assets. In the past decade, an interest in asset management for water and water utilities has grown mainly due in part to an aging water utility infrastructure. Many professional and government organizations have defined asset management and developed plans for the practice and implementation of asset management in the area of water utilities (Sinha, n.d.).

In 2007, the U.S. Environmental Protection Agency (EPA) and six national water and wastewater associations collaborated on a guide promoting effective utility management. The guide discusses ten attributes of effectively managed water utilities. It concludes that effective asset management can enhance the infrastructure, improve performance in many critical areas, and respond to current and future challenges (EPA, 2008b). The EPA also works with water utilities to provide technical assistance to help utilities implement asset management (EPA, 2008a).

A report by the United States General Accounting Office (GAO) discusses the benefits of comprehensive asset management for drinking water and wastewater utilities. It also addresses the challenges of implementation and the federal government's role in encouraging utilities to use it (GAO, 2004). Utilities reviewed by the GAO reported that collecting accurate data about their assets in areas like maintenance, rehabilitation, and replacement costs can lead to better investment decisions. The challenges include collecting and managing needed data and integrating information and decision making across departments. Also, it is reported that the shorter-term focus of those in charge of utilities can hamper long-term planning efforts. The federal government has invested billions of dollars in drinking water and wastewater infrastructure and wants to protect its investment by having future funds go to those utilities which implement comprehensive asset management plans (GAO, 2004).

One of the goals of asset management is to replace reactive maintenance with planned maintenance with more practices geared toward predictive and condition maintenance (Harlow, 2000, part 1). Good asset management must minimize long-term asset costs and at the same time insure reliable customer service. Effective asset management must be based on practices that are easily implemented, cost effective, and sustainable in the long run (Lutchman, 2006). Lutchman (2006) also believes that good asset management needs to be focused on economic, social and environmental concepts and not just the financial bottom line.

A typical asset management framework consists of the following four parts: 1.) Facilities inventory; 2.) Condition assessment; 3.) Operations, maintenance, repair and replacement management; 4.) Analysis and evaluation (Doyle and Rose, 2001). Facilities inventory is a description of each asset. Condition assessment classifies each asset as to its capability to perform its intended function. That function being operations, maintenance, repair and replacement management tracks and records data about work orders and customer complaints. It also issues and tracks preventative and predictive maintenance schedules, generating crew assignments and work-site maps. Analysis and evaluation prioritizes work effort, analyzes cost effectiveness, and optimizes asset performance.

Asset management was first done by the water, wastewater and public works utilities in New Zealand and Australia. They set the general direction and standards for asset management in these industries. In the mid 1980's and 1990's, the government directed the utilities to become business based, customer focused, more transparent and accountable. Policies and regulations were set and the utilities were mandated to meet them. During a 12 year period, the 24 largest Australian water and wastewater utilities achieved almost a 20 percent savings per customer account. Savings involved capital and operations/maintenance costs with no changes in service levels to the customer. A large regional and wastewater utility (Hunter Water located in New South Wales, Australia) achieved far more savings and is widely viewed as having developed one of the most effective and advanced asset management programs in the world (Sinha, n.d.).

Australia and New Zealand's National Asset Management Steering (NAMS) group have developed an international infrastructure management manual which is considered to be one of the best sources for public utility asset management information (Harlow, 2000, part 4). It was first introduced in 2000, followed by a number of revisions including the latest 4th edition of the manual (NAMS, 2011). The manual includes five sections beginning with an introduction to the concepts of total asset management and lifecycle asset management. The other sections include: implementing asset management, implementation techniques, asset management information system and data management. There is also country specific information with best practices for not only Australia and New Zealand, but also other countries such as the United States and Canada (Sinha, n.d.).

The Seattle Public Utilities imported the asset management concept in the early 2000s. They became one of the first in the United States to implement a formal asset management program. Computerized asset management systems can cost $1million to $2 million for a large utility. But the Seattle utility company estimates its computerized asset management system has saved the city more than $180 billion (AWI, 2010).

2.2 - GIS and Asset Management

Even though GIS technology began in the 1960s, GIS applications for the water industry did not evolve until the late 1980s. In the early 1990s, the water industry started to use GIS in mapping, modeling, facilities management and work- order management plans. By the end of 2000, approximately 90% of the water utilities in the United States were using GIS technology in some form (Shamsi, 2005). The use of GIS as a management tool has grown since the 20th century and the number of users has increased substantially. Utilities that are using GIS successfully have seen increased productivity and increased efficiency which saves time and money. The Environmental Systems Research Institute (Esri), the leading GIS software company in the world, has been a significant contributor to GIS applications in the water industry. In 2009, Esri started a Water Utility Resource Center for the utility needs of over 300,000 worldwide users (Baird, 2011). The website is: (http://resources.arcgis.com/content/water-utilities).

As shown in Figure 1 from Esri, asset management is one of the core business patterns commonly used by water utilities. Others include: planning and analysis, field mobility, operational awareness and stakeholder engagement (Crothers, 2011). The use of GIS can be an important part of each of these patterns.

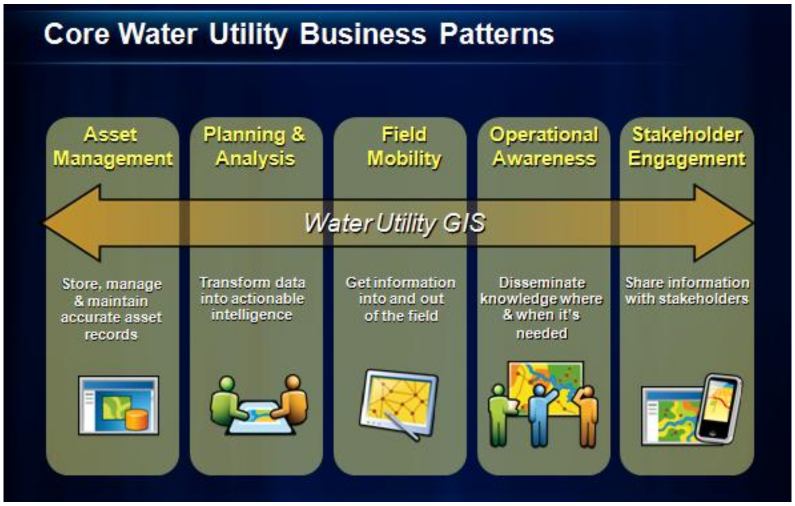


Figure 1 - Core Water Utility Business Patterns.
Source: Crothers, 2011. Esri.

The basis of effective asset management at a water utility is good asset information. GIS manages asset information by storing, managing, and maintaining accurate asset records that can be shared by the whole utility. Many times, a water utility will have complete information about an asset stored in multiple systems. The GIS stores the location, connectivity to other assets and basic attributes. The CMMS stores extended information about the work history for an asset. Other systems could include a financial system and a customer information system.

There should be integration among all of the multiple systems that store information about an asset so data about its location, connectivity, status, history and description can be easily accessed. A GIS has information that can be shared across an entire utility and used to support many of its information needs. Utilities can significantly increase their return in a GIS investment by sharing it around the entire utility and using it to support its many business patterns (Crothers, 2010).

Asset data in a GIS can be used to support the planning needs of a utility through spatial analysis. Water utilities are involved in short term planning and long term planning. For short term planning, GIS is used in creating and optimizing reactive and proactive work orders. Long term planning involves the use of asset data, performance data and GIS analysis to understand how an individual utility is performing. This information is used to help determine where to best spend capital funds to maximize the value of a utility's assets (Crothers, 2011).

GIS supports the field mobility business pattern by providing field crews with maps and applications that can be rapidly updated and are easy to use. It also enables field crews to capture GIS data and send it back to the central office. The operational awareness business pattern involves the performance of assets, utility networks and personnel and how they are affecting each other. Utility managers can then make decisions based on accurate and up to date information. GIS supports this by enabling utilities to have an interactive map of the current state of operations. An interactive map is an easy way to take information from many systems and present it through a common application (Crothers, 2011).

The final business pattern, stakeholder engagement, involves sharing information with stakeholders such as customers, elected officials, regulatory agencies, and other utilities in the service area. The trend is for water utilities to actively engage with stakeholders through public outreach programs providing accurate information that minimizes misinterpretation. GIS is used by utilities by creating static and interactive maps. Mapping applications for stakeholders include customer self service, capital project coordination, service interruption management and transparency into utility performance (Crothers, 2011).

2.3 - Computerized Maintenance Management Systems and Enterprise Asset Management

Enterprise Asset Management (EAM) Systems and CMMS are being implemented by a growing number of water and wastewater utilities and their use in these areas appears to be growing. A CMMS is a software package which maintains a computer database about a utility's maintenance operations. The terms asset management and maintenance management are often used interchangeably. Even though they are related, they are different processes with different objectives. Asset management is focused on reducing the maintenance cost of ownership, while maintenance management is focused on reducing the maintenance cost while extending the useful life of an asset (McKibben and Davis, 2002). An effective asset management system must include an effective maintenance management system and is considered the most important core of an asset management system (Shamsi, 2005).

An EAM is a CMMS focused on maintenance work orders and performance combined with an asset registry or inventory. A CMMS and asset registry are the center of an asset management program. A growing trend is for the GIS geodatabase to be the starting point for an asset management program and the asset inventory. Utilities need to know the location and condition of their assets. GIS is the best place for gathering asset data because spatial location is typically an important aspect of the data at a water utility. The GIS geodatabase combined with the CMMS forms a comprehensive customer request, asset inventory and work management system and becomes the foundation for the EAM. This combination captures asset data, work history and condition assessments necessary for cost-effective, condition and predictive maintenance programs (Baird, 2011).

McKibben and Davis (2002) give many reasons for the integration of GIS and CMMS. GIS can significantly enhance a CMMS by providing the ability to access, use, display, and manage spatial data. This is important for utilities with geographically dispersed networks. Also it can provide access to other spatial data. It can provide maps of the utility that can be used in locating facilities included in work orders. It can be used to effectively schedule and assign maintenance work crews to certain work locations, saving time and cost. Baird (2011) points out that using a GIS with full functionality, beyond just map-making, will result in lower maintenance costs and a lower cost EAM.

At the time of their study, McKibben and Davis (2002) found there were only six CMMS vendors that had links to ESRI GIS software. Of these, only three, Azteca Systems (Cityworks), GBA Master Series, and Hansen Information Technologies (Hansen's Citizen Relationship Software) had useful CMMS systems for water and wastewater utilities.

There are two methods of integrating GIS with the CMMS and these are based on where the asset data is stored--the CMMS or the GIS. GBA and Hansen maintain the asset data in the CMMS database and GIS software is used to access the asset data or provide information stored in the CMMS. GIS features are linked to the CMMS database. Adding a new asset requires the addition of the asset to both the GIS and CMMS databases. The work order and maintenance data is stored in the CMMS (McKibben and Davis, 2002).

Azteca's Cityworks uses the other method which stores the asset data in the GIS database. All assets and the related data are maintained in the GIS database. The addition of new assets in the GIS database does not require an adjustment to the Citywork's database. Work orders and maintenance management functions are maintained in a series of Cityworks tables and all of the maintenance management functions are provided as extensions of ESRI's GIS software (McKibben and Davis, 2002). Azteca's Cityworks, with its GIS-centric approach, is considered by many to be one of the best asset and maintenance management systems (Baird, 2011). It has been in use for 15 years and has over 400 clients. According to Baird (2011), a solid CMMS is a necessary part of asset management. Therefore, a CMMS with a GIS-centric approach is considered to be a necessary part of asset management.

As previously mentioned in the introduction, water utilities own two major types of assets--horizontal and vertical. Horizontal assets are geographically dispersed in the distribution system and vertical assets are concentrated in a pump station or water treatment plant. Pump stations and water treatment plants have a much larger number of assets and maintenance activities than those of distribution systems (McKibben and Davis, 2002). McKibben and Davis 2002 stated that the use of GIS data within vertical assets may be beneficial, but requires more research and development. The integration of GIS and Azteca's City Works CMMS eliminates the need to implement two maintenance management systems because it does not require its own database repository. Instead it directly accesses the asset management geodatabase.

Few studies exist on expanding horizontal asset management for CMMS-GIS into vertical assets. Zhao and Stevens (2011) discuss expanding the Otay District's water model of horizontal assets to integrate the districts vertical assets within a pump station. They also state that with the present state of GIS software and technology, GIS has not been used to capture the information within pump stations and treatment plants graphically. The model development and assessment in this study contributes to the literature in this area.

2.4 - Asset Risk, Condition and Criticality

The concepts of asset condition, criticality and risk are important in the area of water utility asset management. Asset risk is based on condition (probability of failure) and criticality (consequence of failure). Two articles were found relating these concepts to vertical assets with the use of water utilities. Hyer (2010) discusses the implementation of a pilot project at Florida's Toho Water Authority demonstrating the collection and calculation of asset data. The data included information on asset condition, consequence of failure, risk of failure and replacement cost for all vertical assets in the water utility. The data analysis provided information for future renewal and replacement costs based on asset risk and remaining useful life. With the model, the rest of the vertical assets could be evaluated in a systematic way utilizing information for capital and O&M budgeting and planning.

Hyer (2011) discusses in detail the use of condition, consequence of failure and risk scoring with the building of a comprehensive asset management program for the Austin Water

Utility in Texas. The pilot project began with a vertical pilot asset inventory, determination of the asset hierarchy and required asset attributes. Vertical asset condition scoring standards, criticality scoring standards and risk-calculation scoring are also included. The asset condition assessment scoring evaluated all aspects of asset failure to establish its probability. The assessment provided information to determine specific short-and long-term capital needs based on asset risk and remaining useful life. By establishing a specific scoring system, future condition assessments can be performed consistently. By completing the pilot program, the rest of the vertical assets can be evaluated in a systematic way. The scoring criteria and guides that were developed can be adapted for other water utilities with simple revisions.

The two articles did not specifically discuss spatial factors in determining an asset's criticality. An example would be customers that have water distributed to them by a pump station. A customer is represented by the water meter which is located where the customer resides. This would also be the same for other spatial variables such as fire hydrants, schools, hospitals, fire stations that have water distributed to them by a pump station.

Also the articles were not specific as to how the vertical assets were represented in GIS. They could be represented as having a spatial location or represented by a non-spatial table that relates to a spatial feature. An example of the latter would be a pump data table with no spatial location. The pump data table can be represented by pump station using a point data to a given location. However since the pump station is only represented by a point, the service area of the pump would not be able to be plotted correctly without further data. The non-spatial data tables on vertical assets need to be related to spatial data with close coordination of data systems. This thesis develops and reports on such data integration for the Otay Water District.

CHAPTER 3 - METHODOLGY OF CASE STUDY OF OTAY WATER DISTRICT (OWD)

The purpose of the case study is to demonstrate the integration of GIS with asset management in a water utility. The project involves the expansion of OWDs current asset maintenance management system of horizontal assets to include its vertical assets in detail. Currently, the district's vertical assets, including pump stations, reservoirs, and a single treatment plant, are represented as a point feature in the GIS. Developing the database for spatial attributes associated with vertical assets is necessary to perform criticality analysis and score for asset risk. Specifically, the objective is to develop a criticality analysis for use with the pumps within the pump stations in order to determine proactive maintenance and replacement schedules.

3.1 - Scope of Study

As a pilot study for vertical assets, the study focuses on all the pumps within the district's potable pump stations. Figure 2 provides a visual orientation for all the potable pump stations. Pump stations help transport water through the mains located at different elevations through increased pressure. Most of the district's pump stations are located in the hilly elevations in the northern part of the district. Some of the district's pump stations are considered more pertinent than others because they directly pump water to other pump stations. If the pump stations that provide water to others were to fail then the pump stations that rely on other pump stations for water would be greatly affected.

There are a variety of spatial factors that raise or lower the criticality of a pump or pump station in the network. These include whether they serve hospitals, have more customers, contain more fire infrastructure, and whether they serve many high consumption users. Another criticality factor for pump stations are those that serve water within a municipality. Major municipalities tend to have a higher population, more businesses and contain more infrastructure than pump stations that serve unincorporated regions of the county.

There are also non-spatial parameters that raise or lower the criticality of a pump or pump station. These include pump redundancy, and the estimated time to restore a pump service after failure or maintenance has occurred. The objective of this study is to explore whether spatial factors can assist in determinations regarding which pumps need to be replaced, and which pumps take precedence above others when failure or replacement occurs at the same time.

3.2 - Database Design

The design of the database structure is very important in implementing this project. Relationships must be established correctly between spatial feature classes and non-spatial feature classes maintained by the district. When data are plotted correctly, classes of both spatial and non-spatial features will be accessible in GIS. This combined horizontal and vertical data structure provides for a GIS-centric management system. This strategy combines a CMMS with a GIS geodatabase, creating the foundation for an EAM approach. The district's strategic plan emphasizes the enterprise approach to GIS with the interdepartmental sharing of data meeting the needs of many departments. The district's ultimate goal is cost effective business processes in the managing of infrastructure assets (Zhao and Stevens, 2009).

A key component in the enterprise GIS is the database design. The district used Esri water utilities data model as the prototype to design the enterprise GIS database--including the potable water, recycle water, sewer collections and land-based systems (Esri, 2011). A series of interviews were conducted among the different departments to make sure the design would fit the end users' requirements. The SQL-based geodatabase serves as the basis for district-wide enterprise system integration. The open platform of this database structure makes it possible for the district's GIS system to integrate with other systems e.g., Azteca’s City Works and Riva’s Modeling Software. Such integration is essential to make the most of enterprise GIS (Zhao and Stevens, 2009).

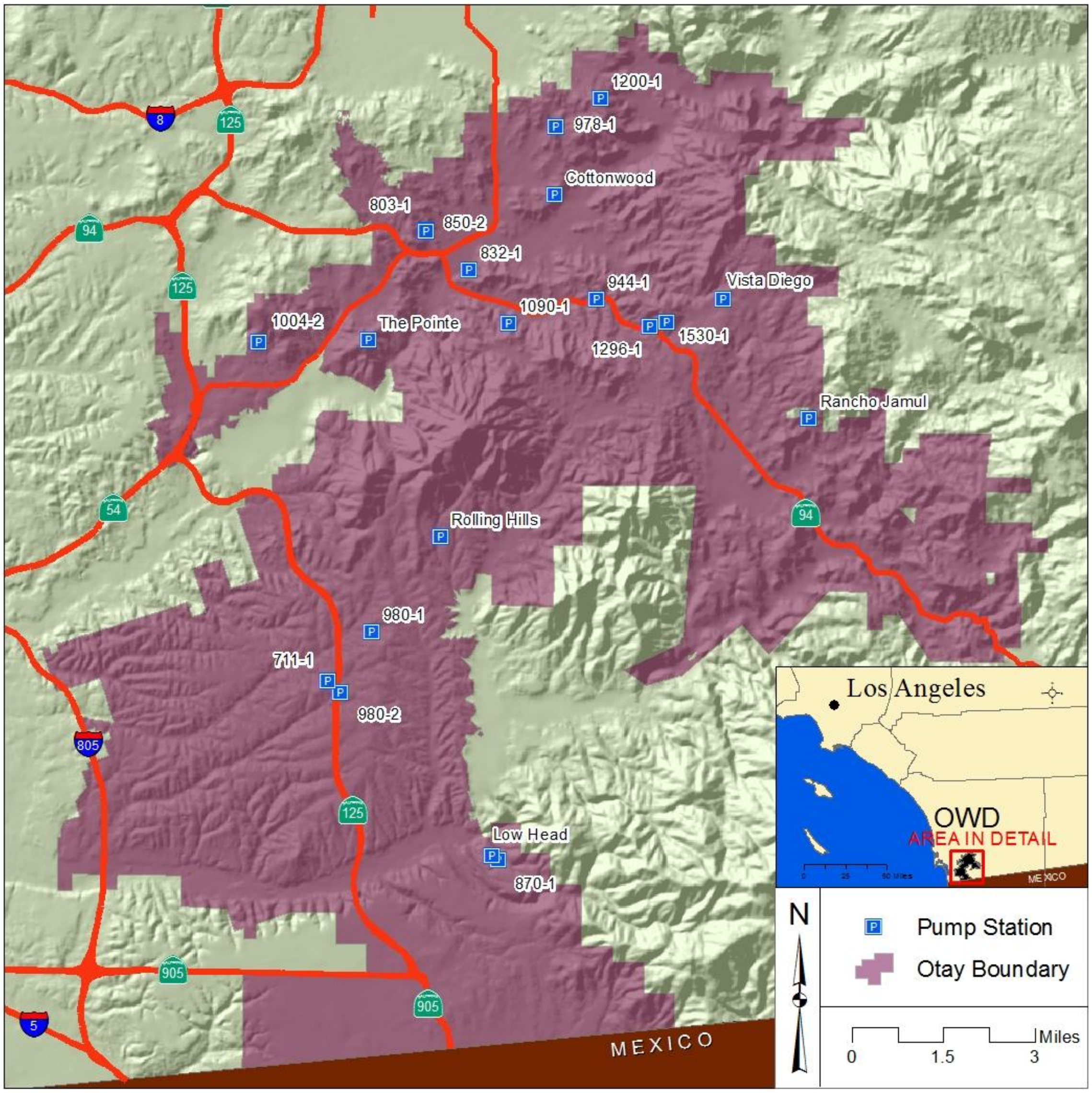
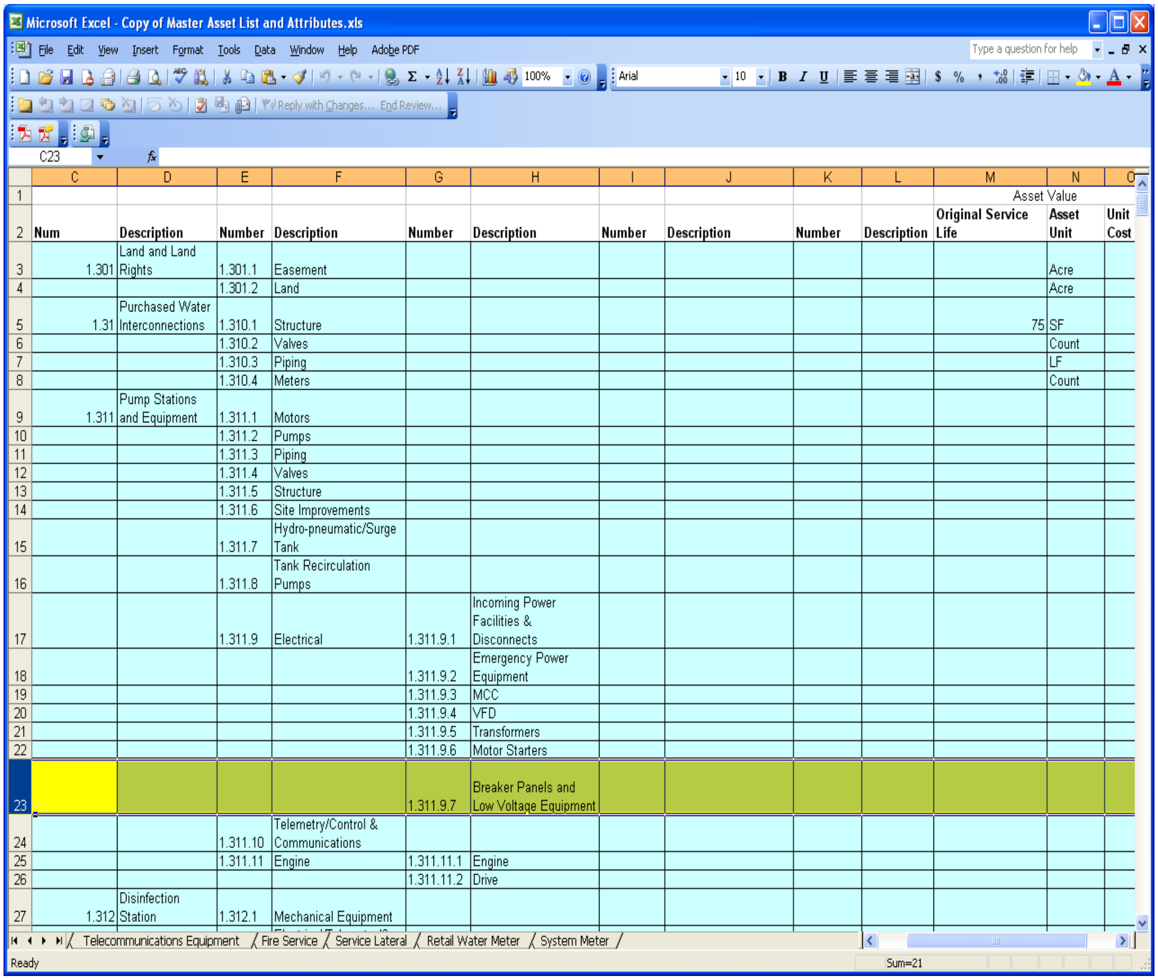


Figure 2 - Current operating pump stations in the Otay Water District. Source: Alexander Schultz, Otay Water District (2012).

Currently, pump stations along with reservoirs and the treatment plant are represented as a point feature in GIS. Figure 3 displays an orthophoto of a pump station. Prior to the database development in this study, selecting the pump station would result in the attributes of the pump station only without any of the vertical assets contained within it. With the present state of GIS software and technology, GIS has not been used extensively to capture the information within pump stations (Zhao and Stevens, 2011). Even though the pump station is represented by a point feature, in reality, the pump station contains other important assets that are not currently represented in GIS such as motors, vessels, and an electrical system. The electrical system then may consist of one or many other assets like a transformer and a Motor Control Cabinet (MCC) board.

Figure 3 – Pump Station 711-1. Source: Otay Water District (2010).

An engineering consulting firm was contracted by the district to conduct a baseline asset management assessment. The study reviewed the existing district data, general preventative maintenance practices and established a fixed asset hierarchy schedule. The information for this study was primarily taken from the district's infrastructure management system (IMS). It was put into an Access spreadsheet format. The following Figure 4 is part of the asset account detail structure.



	C	D	E	F	G	H	I	J	K	L	M	N	O
1											Asset Value		
2	Num	Description	Number	Description	Number	Description	Number	Description	Number	Description	Original Service Life	Asset Unit	Unit Cost
3	1.301	Land and Land Rights	1.301.1	Easement								Acre	
4			1.301.2	Land								Acre	
5	1.31	Purchased Water Interconnections	1.310.1	Structure							75	SF	
6			1.310.2	Valves								Count	
7			1.310.3	Piping								LF	
8			1.310.4	Meters								Count	
9	1.311	Pump Stations and Equipment	1.311.1	Motors									
10			1.311.2	Pumps									
11			1.311.3	Piping									
12			1.311.4	Valves									
13			1.311.5	Structure									
14			1.311.6	Site Improvements									
15			1.311.7	Hydro-pneumatic/Surge Tank									
16			1.311.8	Tank Recirculation Pumps									
17			1.311.9	Electrical	1.311.9.1	Incoming Power Facilities & Disconnects							
18					1.311.9.2	Emergency Power Equipment							
19					1.311.9.3	MCC							
20					1.311.9.4	VFD							
21					1.311.9.5	Transformers							
22					1.311.9.6	Motor Starters							
23					1.311.9.7	Breaker Panels and Low Voltage Equipment							
24			1.311.10	Telemetry/Control & Communications									
25			1.311.11	Engine	1.311.11.1	Engine							
26					1.311.11.2	Drive							
27	1.312	Disinfection Station	1.312.1	Mechanical Equipment									

Figure 4 - Access database table showing asset account data structure. Source: Otay Water District (2011)

The database design was created in Visio by Nader AlAlem, GIS Contractor from Halax2 INC. and Ming Zhao, Otay Water District's GIS Manager and later exported to Universal Modeling Language (UML). The database structure was imported into an empty geodatabase. Using the account detail spreadsheet and integration concepts, Nader AlAlem and Ming Zhao created a UML diagram that was finally integrated with the existing Esri GIS data water model.

An important aspect of the database development is the relationship between the abstract classes and the other asset feature classes. Abstract classes are those that cannot be instantiated and cannot be used on their own but must be first inherited by a feature class. When a feature class is linked to the abstract classes that feature class inherits the abstract class attributes. In the model, multiple feature classes are sharing the same attribute classes. Install date, facility id, as-built, and set id are attributes all used by feature classes pipes, valves and meters. Instead of creating an attribute for each feature class, an abstract class is created that contains these attributes. An example of this is shown in Figure 5.

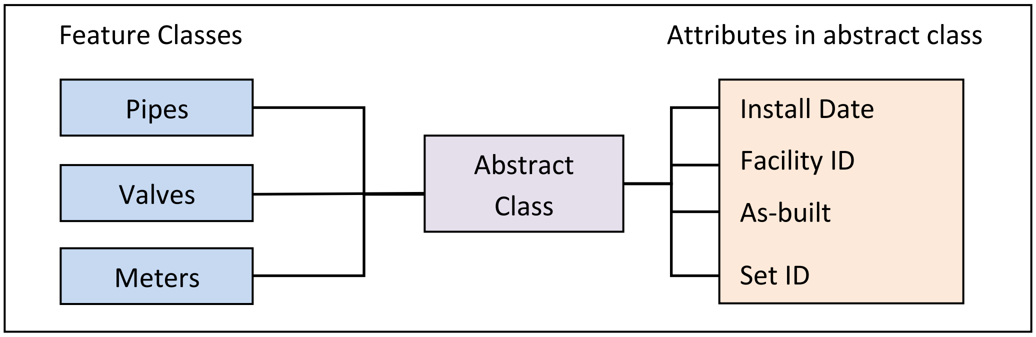


Figure 5 – Example of feature classes inheriting abstract class attributes. Source: Alexander Schultz (2012)

Figure 6 shows the basic idea of how GIS feature classes such as pump stations and system valves would have corresponding tables in the asset management system. The GIS data base relates to the asset management system on a one to one relationship. This is accomplished by joining the fields GlobalID that are shared between the GIS and Asset Management System (AMS).

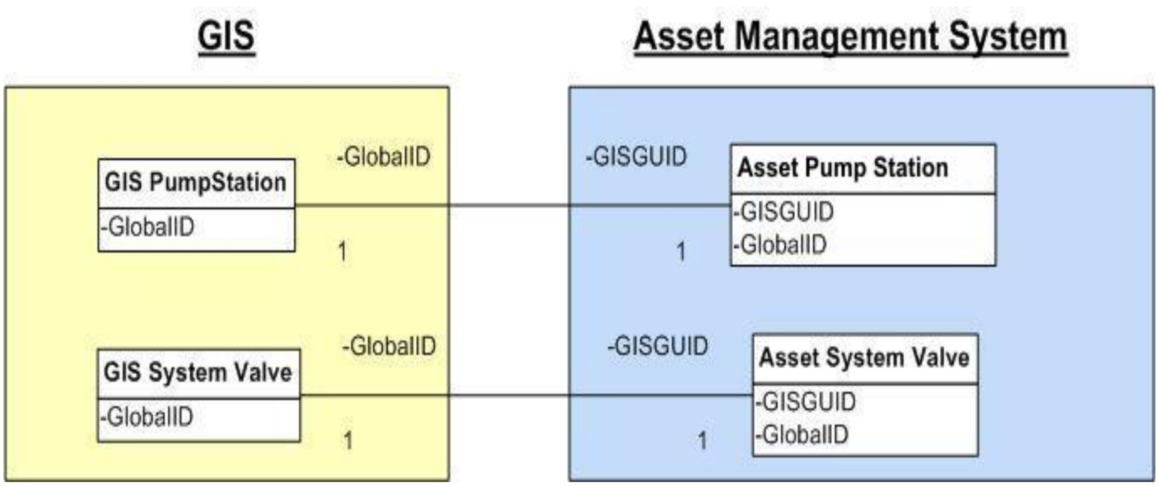


Figure 6 - Integration of GIS and asset management. Source: Otay Water District (2011)

Figure 7 shows the integration of the GIS feature class pump station with its corresponding asset management system data. It also shows the asset hierarchy for pump station contained in the AMS. The asset management table was created in the same GIS relational database management system (RDBMS) using RDBMS Sequential Query Language (SQL) statements. The new table was then registered with the geodatabase in ArcCatalog. Next, relationships were established between these assets and the assets within each pump station. The GIS feature class and the asset management table are related through a common Global ID. This process was repeated to cover all the GIS feature classes.

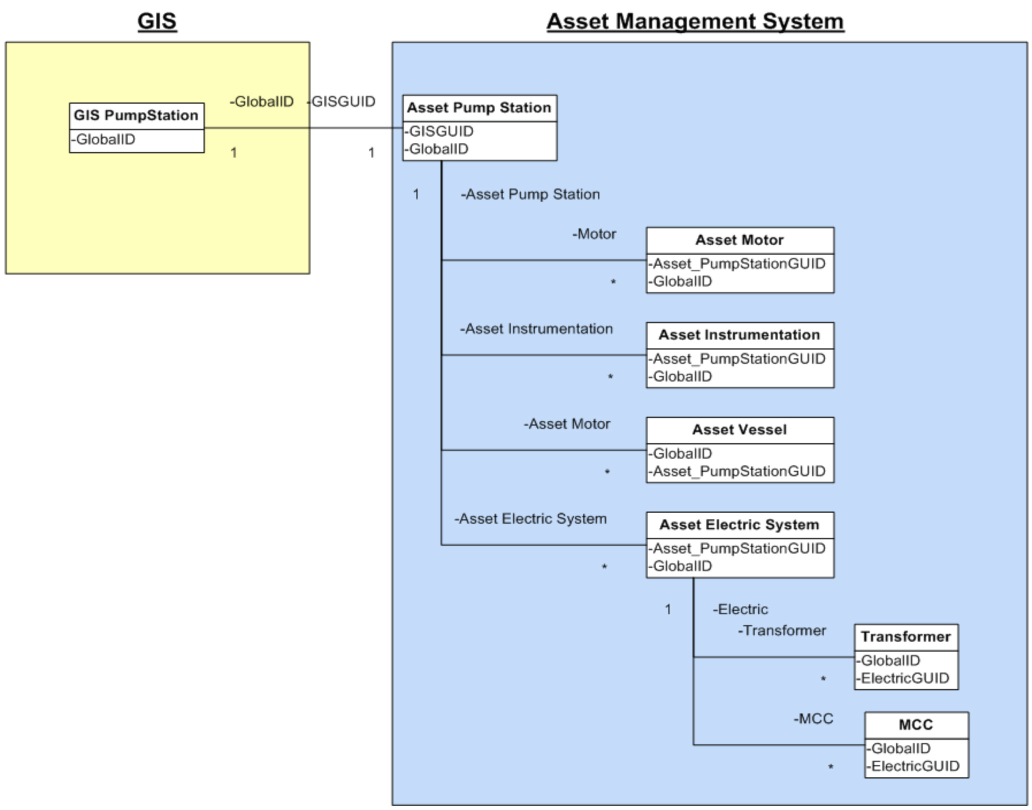


Figure 7 - GIS and asset management system with vertical assets. Source: Otay Water District (2011)

After these steps the vertical asset data is successfully integrated into the GIS data structure. To test the success of the integration, when the pump station is selected using the identify tool, the system will display the table showing GIS pump station with the asset database features contained within it.

3.3 - Populating the Database

Work crews from the OWD Operations Department initially collected the vertical asset data while in the field. Excel spreadsheets were printed to record the data. After the crews returned from the field, the data were input into the asset management database. Before the pump station data were fully populated, GIS programmer Dongxing Ma developed an asset management data entry form using Visual Basic.Net technology. The entry forms provided multiple levels hierarchies of an individual facility for the field staff to enter the asset information.

Following that, I populated the non-spatial data tables for this study by opening the asset management data entry form installed on a desktop computer. Once the form was opened, a parent asset facility (pump station, reservoir, treatment plant etc.) for the vertical asset was opened (Refer to Appendix C). Then the specific facility for the vertical asset was selected from a drop down menu. The tab for the vertical facility that needed to be added to the database was selected (Refer to Appendix D).

By repeating this process for each vertical asset, the assets' attributes were populated into the form. The new data were pushed over into the AMS. Selecting the pump station feature class with the editor tool and opening the attribute table on the editor tool bar then allow us to view the newly populated data.

Figure 8 demonstrates the data structure for a single pump station with three pumps, three control valves and two engines. It also has a single electrical system, which consists of one emergency power supply and two MCC boards. This further subdivision of the assets in the pump station is shown in Appendix B. This illustrates the need to structure the integration of the GIS and the asset databases carefully so that all the vertical assets within a given point feature will be related to the correct asset feature tables.

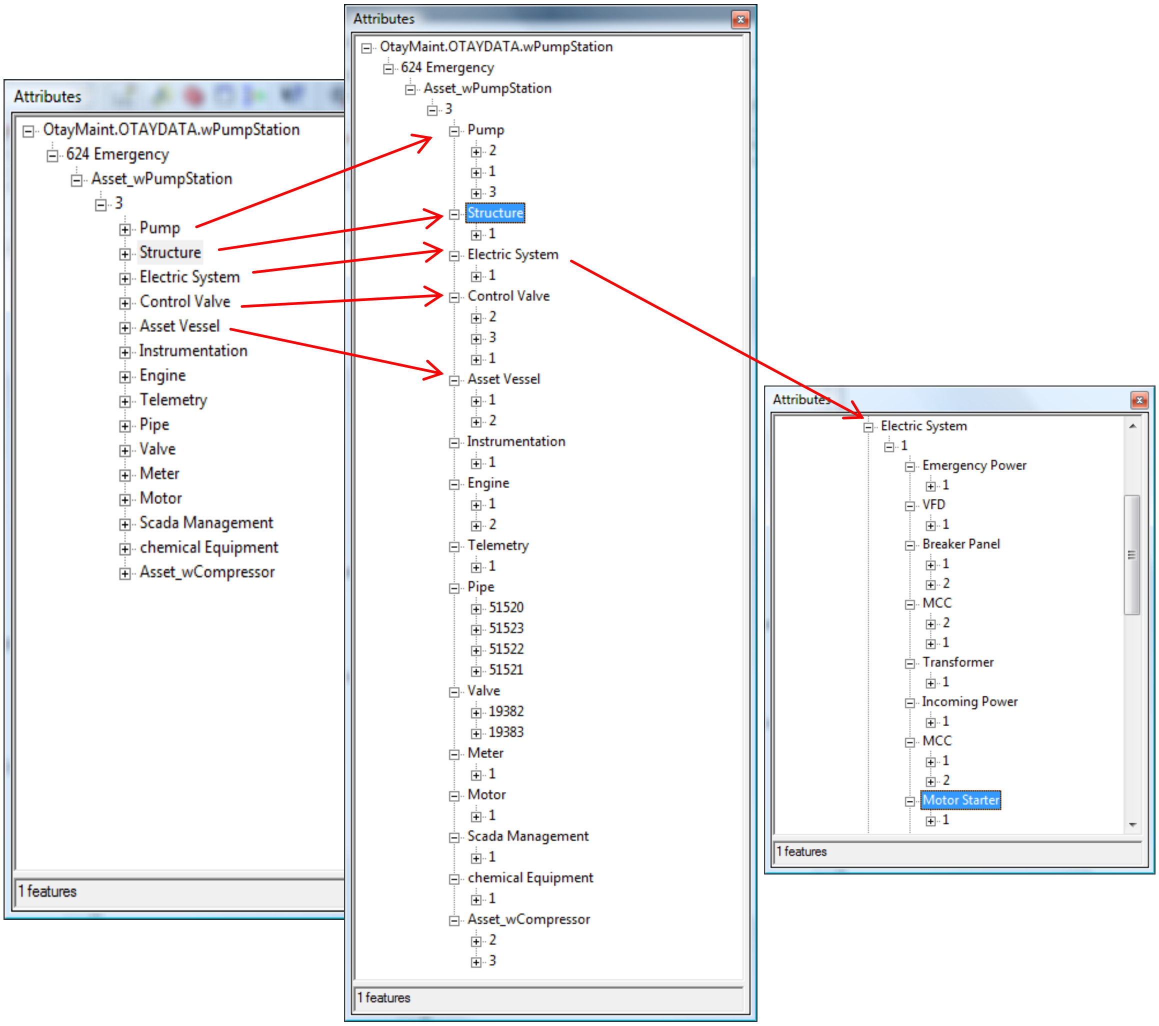


Figure 8 - Detail of pump station data structure. Source: Otay Water District (2011)

3.4 - Risk Factor Analysis

The core method in this case study uses OWD data and SanGIS data to determine asset risk factors for both spatial and non-spatial variables. To calculate risk factors, a model was constructed in ArcGIS ModelBuilder to generate results for individual pumps that are housed in pump stations throughout the district. After the results were calculated, a field study was conducted to confirm results for a few pump stations in consultation with experts at OWD.

The two parameters that make up the asset risk factors are probability and criticality. Criticality is defined as the consequence of asset failure or the severity of the impact. This is based on an expert estimation of the consequences of failure-- who or what is affected if an asset fails. There are both spatial and non-spatial aspects to criticality, including the redundancy of pumps in the system. Probability is defined as the likelihood that a given asset (i.e., a pump) will fail in a given length of time. In this study, probability is measured by the condition and age of an asset. The overall risk factor is determined by multiplying asset criticality and the probability of asset failure.

Criticality measures the consequence of failure. It is based on an assessment of how the failure of a particular asset will affect a utility's ability to meet its service goals. Criticality is used to assist in prioritizing repair/replacement decisions, condition assessment and maintenance activities. In this case study, the formula for the total criticality score is the addition of all spatial and non-spatial parameters' scores following Hyer (2011).

3.5 - Spatial Parameters

The spatial parameters for criticality include: customers served by a pump station (number of water meters), number of fire hydrants served by a pump station, number of schools, and number of high consumption users. There are also parameters for the presence or absence of fire stations, hospitals, and major municipalities in a pump zone. These are ranked numerically. A higher number means a pump is more critical and a lower number means less critical. The spatial parameters that are ordinal variables and scoring ranges are displayed in Table 1. These include: customers served by a pump station, number of hydrants served by a pump station, number of schools, and number of high consumption users. The spatial parameters that are binomial or trinomial are displayed in Table 2. These include: fire stations, major municipalities, and hospitals.

The spatial parameters are determined by spatially joining to the pressure zone layer. The pressure zone layer is used because each pressure zone represents an area served by a pump station. After the layers have been spatially joined, the frequency for each feature class is generated. The features for each feature class are then ranked from 1 to 10 using equal intervals for the nominal variables in Table 1. The equal interval classification is used so the attributes will be grouped into an equal range of values. If there is a hospital or major municipality in the pump zone, criticality will score a 10. The one spatial variable that is trinomial, fire stations is displayed in Table 2. Fire stations are scored 0 if there are no fire stations present, 5 if one fire station is present, and 10 if two or more are present. The hypothetical minimum score for spatial parameters of criticality is 4 and the hypothetical maximum score for criticality is 70.

Table 1 – Scoring range for nominal spatial parameters.

Criticality factor	Customers served by pump station	Number of hydrants served by pump station	Number of schools	Number of high consumption users
Ranking	1 - 10	1- 10	1 - 10	1 - 10

Table 2 – Scoring range for binomial or trinomial parameters.

Criticality factor	Has a hospital	Is in a major municipality	Multiple Fire Stations
Ranking	0 or 10	0 or 10	0 or 5 or 10

3.5.1 **-** *Customers served by pump station*

The data that were used to determine the customers served by pump station comes from Otay's meter feature class. The number of customers served by a pump station is measured by the number of meter services found in each pump stations pump zone. A higher number of meter services mean greater criticality of the pump within the pump station. For example, to find the customers served by pump station 711, 711 pressure zone is used because that is the zone that the pump station serves. Table 3 shows the scoring range for customers served.

Table 3 – Scoring range for customers served by pump station served.

Data Range	Score
2 - 1264	1
1264 - 2526	2
2526 - 3788	3
3788 - 5050	4
5050 - 6312	5
6312 - 7574	6
7574 - 8836	7
8836 - 10098	8
10098 - 11360	9
11360 - 12623	10

3.5.2 - *Hydrants served by pump station*

The data to determine the number of hydrants found within each pressure zone come from Otay's hydrant layer. The zone that contains the most hydrants is found to be the most critical. The hydrant's scoring range is found in Table 4.

Table 4 – Scoring range for number of hydrants served.

Data Range	Score
4 - 118	1
118 - 234	2
234 - 349	3
349 - 464	4
464 - 580	5
580 - 695	6
695 - 810	7
810 - 925	8
925 - 1040	9
1040 - 1156	10

3.5.3 - Schools served by pump station

The data to measure the number of schools come from joining the SanGIS' schools layer to Otay's pressure zone layer. The pressure zone with the highest number of schools is the most critical. Equal interval is used to classify the pumps by number of users per each zone. Rankings are based on a 1 to 10 scale. The schools' scoring range is in Table 5.

Table 5 – Scoring range for number of schools.

Data Range	Score
1 - 2	1
2 - 3	2
3 - 4	3
4 - 5	4
5 - 7	5
7 - 8	6
8 - 9	7
9 - 10	8
10 - 11	9
11 - 13	10

3.5.4 - Number of High Consumption Users

Users that eclipse the 100,000 cubic gallons per year threshold are considered high consumption users. Using consumption data from the district, the customers that use over 100,000 cubic gallons per year were queried out and joined to district's parcel layer. It was then spatially joined to the pump zone layer. The pump stations that have a larger number of high consumption users were given a higher ranking. Otay's Water Conservation Manager reports that there were only 5 to 10 customers that the district considers high consumption users. To generate a larger sample of users, this study identifies customers that exceed the 100,000 cubic gallons as high consumption users (Granger, 2012). To identify these users a query was created by OWD's Database Administrator to generate a spreadsheet of all users exceeding 100,000 cubic gallons by pump zone. The scoring for number of high consumption users scoring range is located in Table 6.

Table 6 – Scoring range for number of high consumption users.

Data Range	Score
1 - 9	1
9 - 18	2
18 - 27	3
27 - 36	4
36 - 45	5
45 - 54	6
54 - 63	7
63 - 72	8
72 - 81	9
81 – 90	10

3.5.5 - Presence of a Hospital

Pressure zones were measured as to whether or not they contain a hospital. If a pressure zone contains a hospital it would be considered relatively critical for consequences of failure. The data for this layer were downloaded from SanGIS and spatially joined to the pressure zone layer to determine which pressure zone contained a hospital. It was either scored as 0 for no hospital or 10 for hospital.

Table 7 – Scoring range for hospitals.

Data Range	Score
0	0
1	10

3.5.6 - Serves a Major Municipality

Pressure zones are measured if any portion of the zone includes a major municipality such as the city of Chula Vista or alternatively if zone only includes only unincorporated San Diego County. Major municipalities are an indication of criticality because they typically contain more customers and infrastructure than unincorporated areas. Pumps were scored either a 1 when serving only an unincorporated area and 10 when serving any portion of a major municipality.

Table 8 – Scoring ranges for municipalities.

Data Range	Score
0	0
1	10

3.5.7 - Multiple Fire Stations

The uninterrupted flow of water at fire stations is crucial for pumping water into the trucks prior to going out to fight fires. The fire station data layer is downloaded from the SanGIS website. The fire station layer is spatially joined to the pump zone layer. The results are a trinomial variable. If a pump station has more than one fire station within its pump zone then it is scored as 10. If a pump station has one fire station or less then the pump station is scored as a 5. If the pump station has no fire stations it is scored as a 0.

Table 9 – Scoring ranges for fire stations.

Data Range	Score
0	0
1	5
2	10

3.6 - Non-spatial Parameters for Criticality

The non-spatial parameters of criticality include: pump redundancy lost, pump station redundancy, reservoir redundancy, and time to restore service. The non-spatial parameters and their scoring range are displayed in Table 10. Because these parameters are non-spatial their scores had to be input manually into the pump's layer.

Table 10 – Scoring ranges for non-spatial features.

Criticality Factor	Pump Redundancy Lost	Pump Station Redundancy	Reservoir Redundancy	Time to restore service
Ranking	2 - 10	0 - 10	0 - 10	5 - 10

3.6.1 - Pump Redundancy Lost

Pump redundancy is the amount of power needed by the other pumps to compensate if one of the pumps fails. Not all pumps are working at the same time. For instance, if there are six pumps in a pump station, usually only five will be working and the other pump is a backup in case one of the other pumps fails. The spare pump is routinely rotated in and out with the other pumps. There is not a specific spare pump. For instance, if there are three pumps in a pump station and pump three is being used as the spare that does not mean it is always non operational in normal conditions. It is rotated in and out and when it is working either pump one or pump two would be used as the spare pump. (Stalker, 2012). In a pump station that requires the full capacity of all pumps to operate in normal conditions, there is no back up if one of the pumps goes down. Thus pump stations that have fewer pumps working at full capacity are considered more critical than pump stations that have more pumps than needed to fulfill normal demands.

The scoring for redundancy lost divides the number of spare pumps and by the number of working pumps. The formula for this process is spare pumps / functioning pumps = pump redundancy lost. For example, in the case of pump station 944-1 it has four pumps, three working and one spare (i.e., 1/3 = 0.33). The scoring range for Pump Redundancy Lost is found in Table 11.

Table 11 – Scoring for Pump Redundancy Lost

Data Range	Score
.20	2
.25	4
.33	6
.50	8
1	10

3.6.2 - Pump Station Redundancy

Pump Station Redundancy scores how many pump stations are affected when a pump fails in another pump station. This is scored by each pump station that is served directly by another pump station. For each pump station that is served, two points are added to the score. In Figure 9, the 944-1 pump station located in the Regulatory System shows that the 944-1 pump station in red is the water source for 4 other pump stations. Since each pump station is scored a 2, the score for the 944 would be 10. This process is repeated for all pumps in the district. Table 12 displays the scoring range for Pump Station Redundancy.

Table 12 – Scoring for Pump Station Redundancy.

Data Range	Score
0	0
1	2.5
2	5
3	7.5
4	10

3.6.3 - Reservoir Redundancy

Reservoir Redundancy scores how many reservoirs are affected when a pump failure occurs. Pumps that pump into reservoirs are less critical than those that pump to pump stations. Unlike pump stations, reservoirs have a tank to retain water and can still distribute water even when the pump station that pumps water to it has failed. Pumps that pump to more reservoirs than others receive a low score because if a pump were to fail a greater volume of water has been retained as opposed to a pump that pumped to fewer reservoirs. Table 13 displays the scoring range for Reservoir Redundancy.

Table 13 – Scoring for Reservoir Redundancy

Data Range	Score
0	10
1	6.66
2	3.33
3	0

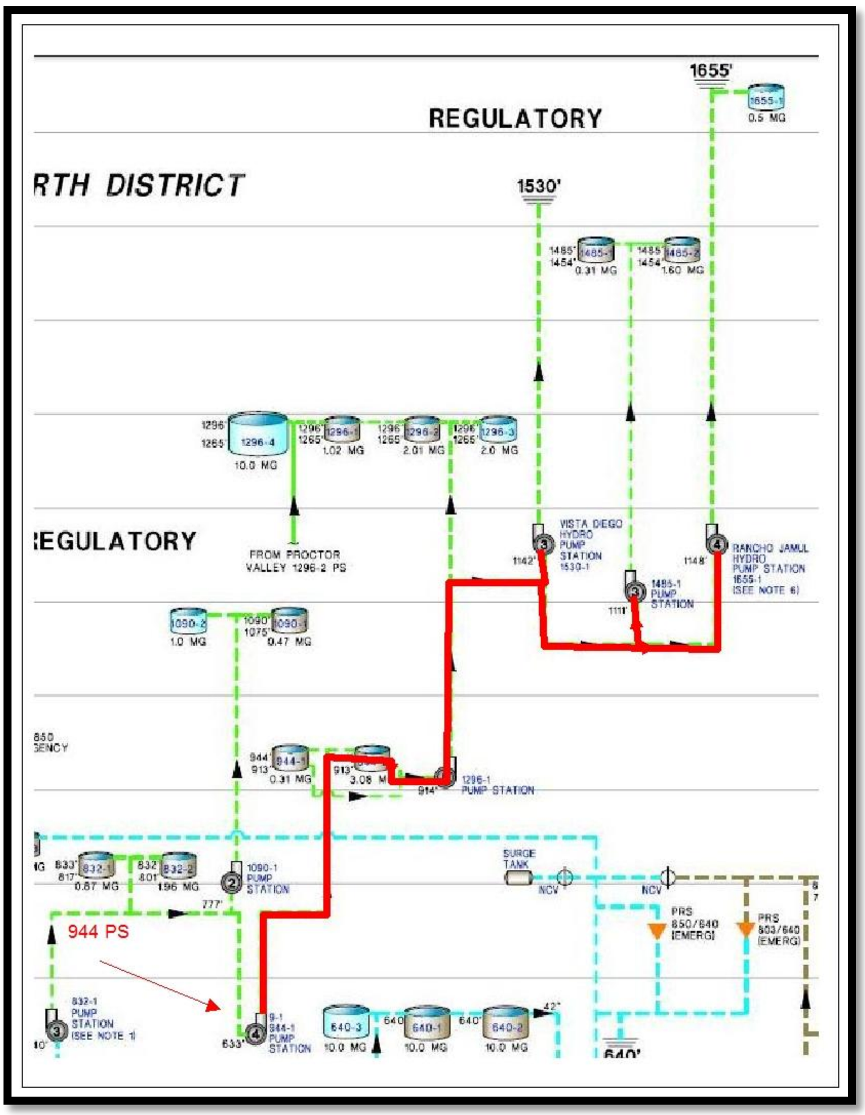


Figure 9 - Partial view of the Potable Hydraulic Profile Schematic. Source: Otay Water District (2011)

3.6.4 - Time to restore service

The time to restore service is the time that it will take the district to restore service to the pump. The type of pump is the main factor because some pumps take longer to replace than others. The two types of pumps found in the pump stations are Vertical Turbine and Centrifugal. Centrifugal pumps usually take longer to replace than vertical turbine pumps. Thus, for criticality centrifugal pump will be scored as a 10 and vertical turbine pumps will be scored as a 5. The scoring range for Time to Restore Service is located in Table 14.

Table 14 – Scoring for time to restore service.

Data Range	Score
Vertical Turbine Pump	5
Centrifugal Pump	10

The scoring range for criticality was determined by totaling all the scores for spatial and non-spatial parameters. The data ranges were classified using equal interval classification.

Table 15 - Scoring range for criticality.

Data Range	Score
12 - 19	1
19 - 25	2
25 - 32	3
32 - 38	4
38 - 45	5
45 - 52	6
52 - 58	7
58 - 65	8
65 - 71	9
71 - 78	10

3.7 - Probability Scoring

The probability score measures how likely an asset is to fail. It is measured in terms of the age of the asset. Using age as probability is a simple proxy for many aspects of mechanical condition. Unfortunately, more detailed assessments of pump condition could not be included in scoring for probability, because mechanical engineers did not assess the pumps during data collection. The estimate of condition based on age is determined by subtracting the pump's age from its life expectancy. The life expectancy for all pumps is assumed to be 15 years on average. The following formula calculates probability for each pump: (year installed – present year) / 15. Higher scores indicate a pump nearing the end of life expectancy with a greater likelihood to fail.

One spatial parameter that might have been considered for probability is the pressure zone of a pump. One might hypothesize that higher pressure zones make pumps more likely to fail than lower pressure zones. However, the pressure zone was not scored because pumps and other infrastructure are each built to withstand the pressure it will incur no matter what zone it is in.

Table 16 – Scoring range for probability

Data Range	Score
.06 - .41	1
.41 - .76	2
.76 – 1.10	3
1.10 - 1.45	4
1.45 - 1.80	5
1.80 – 2.14	6
2.14 – 2.49	7
2.49 – 2.84	8
2.84 – 3.18	9
3.18 – 3.54	10

3.8 - Asset Risk Determination Using ModelBuilder

Using ModelBuilder, a spatial model was created to automate the GIS process used to determine the spatial factors for each pump. The spatial factors are determined for each pump using ArcGIS ModelBuilder. According to Allen (2011), ModelBuilder has evolved from a simple tool into one with many functions. The use of ModelBuilder in this case study demonstrates some of these advancements in the tool. (For a model builder diagram developed for this study, see Appendix

F.) ModelBuilder was particularly useful in this study, due to its ability to automate multiple geoprocessing tasks. To determine the risk factor, 70 geoprocessing tasks were run. Doing each geoprocessing task individually would have been tedious and time consuming. With the ModelBuilder all 70 tasks for this study were completed within minutes. ModelBuilder was also used in this study as a decision support system. The non-spatial parameters were input into the pump's layer prior to running the model. ModelBuilder then calculated the non-spatial parameters and spatial parameters to determine criticality. Once criticality and probability were determined, the two factors were multiplied to determine the pumps risk factor (Hyer, 2011). After the risk factor results for the pumps were calculated, the results were analyzed to determine the accuracy of the scores. For the overall risk factor the possible scores range from a minimum of 1 to a maximum of 100.

CHAPTER 4 – RESULTS

The model developed for this thesis evaluates each of the functioning 79 potable pumps in the OWD in terms of asset risk. The potable pumps are housed within the district's 20 pump stations. Each station contains from 2 to 6 pumps. This information is to be used to determine priorities for maintenance and need of repair. In Figure 10, the location of each of the 20 pump stations is shown by a histogram in which each bar indicates the risk level of individual pumps at each individual station. Each pump falls within one of five scoring categories after scores were calculated by the model. In addition to displaying the pump stations, the map also displays OWD boundary and pump zones. This map was printed out and presented to Water Systems Supervisor.

The Water System Systems Supervisor said that the redundancy for the district is very good, but there are a few areas that would need to be addressed immediately if pump failure were to occur. Some of the district's pump stations are considered more pertinent than others because they directly pump water to other pump stations. If the pump stations that provide water to others were to fail then the pump stations that rely on other pump stations for water would be greatly affected. Those areas are where the 944-1 pump station provides water to four other pump stations. The other pump station is the Low Head which provides water to all of Otay Mesa. If these two pump stations experienced some type of shutdown or failure, thousands of people could be without water (Vaclavek, 2012).

The spatial scores were calculated according to the formula presented in Chapter 3. Complete results are provided in Appendix A.

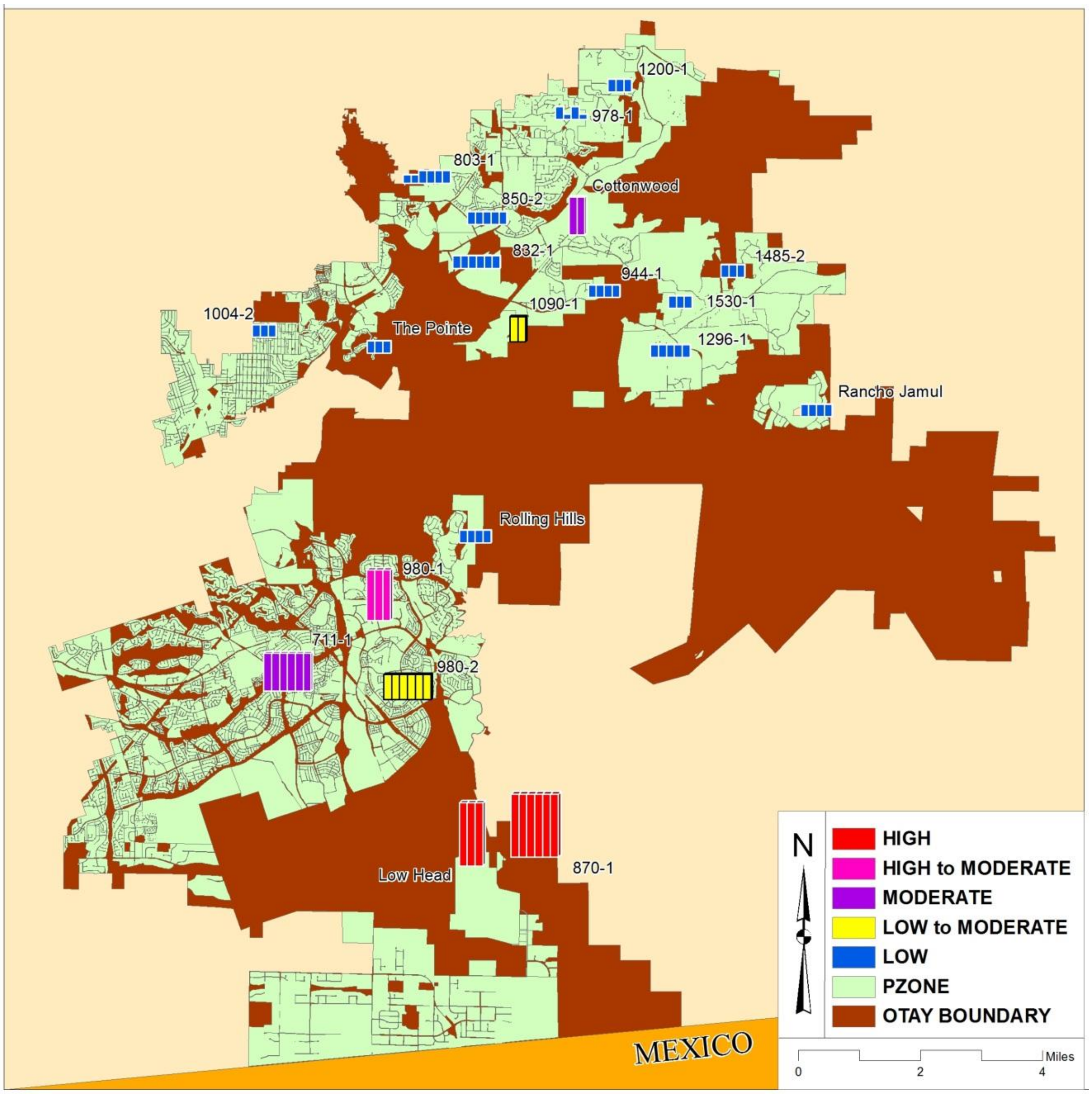


Figure 10 – Results for risk factor using equal interval rankings. Each of the 20 pump stations are represented by a histogram and each bar represents a pump in the pump station. Source: Alexander Schultz (2012)

Table 17 – Scoring for Risk Factor for equal interval classification.

Data Range	Score
1 - 15	LOW
15 - 29	LOW TO MODERATE
29 - 43	MODERATE
43 - 57	MODERATE TO HIGH
57 - 72	HIGH

4.1 - Detailed Results

To illustrate the results, the scores for five pumps from five different pump stations that received different risk factor scores in categories ranging from high to low are displayed below in Figure 11.

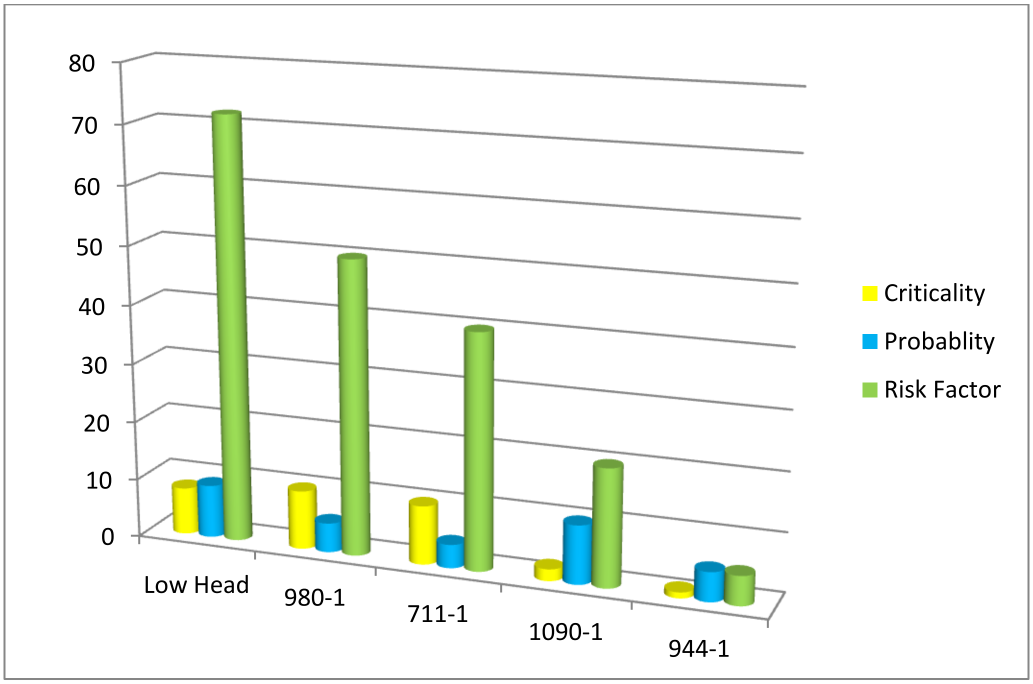


Figure 11 – Chart displaying results for pumps that scored in each risk factor category.
Source: Alexander Schultz (2012)

The results for pump 1 of the Low Head pump station are displayed below in Table 18. Probability had a slightly higher influence on risk factor than criticality. The Low Head pump station contained the pumps with the highest risk factor scores. The area that the pump serves is Otay Mesa which is comprised of industrial users and does not contain any single family residential housing. The primary type of customers being served are business parks and correctional facilities.

On the criticality indicator, this pump scored high because it serves a municipality, lacks redundancy and has high consumption users. Since the pump was centrifugal, the pump also received a high score for time to restore service. The area served intersects the City of San Diego boundary and received the maximum score for this parameter. The redundancy lost score was high because the Low Head pump station only has three pumps and two backup pumps. The pump also scored high for high consumption users because of the industrial users and the prison.

The low scoring parameters were number of schools, presence of a hospital, customers served by pump station, pump station redundancy and reservoir redundancy. Since the land use for this area is mainly commercial and industrial there are no schools or hospitals in this area. The pumps for this station do not directly serve any reservoirs and only pump water to the 870-1 pump station.

The probability for this pump scored high because this pump is just past its expected lifetime. The Water Systems Supervisor said that this pump station is to be demolished within the next 5 years (Vaclavek, 2012).

Table 18 – Risk factor results for Pump 1 of the Low Head pumps.

Description	Score
Restore Service	10
Schools Served by Pump Station	0
Presence of a Hospital	0
Customers Served by Pump Station	1
Hydrants Served by Pump Station	8
Multiple Fire Stations	5
Number of High Consumption Users	7
Serves a Major Municipality	10
Redundancy Lost	8
Pump Station Redundancy	2.5
Reservoir Redundancy	10
Criticality	61.5
Probability	3.06
Criticality after Scaling	8
Probability after Scaling	9
Risk Factor	72

The scores for pump 1 of the 980-1 pump station are displayed in table 19. The pumps for the 980-1 pump station scored in the high to moderate category. After criticality and probability were both scaled, criticality had a stronger influence on the risk factor score than probability. The pumps for the 980-1 pump station are located in the city of Chula Vista. The customers served by the 980-1 pump zone are single family residential.

One parameter that scored high for criticality is redundancy because the 980-1 has three pump stations and received a redundancy score of 8, Other high scoring items for criticality include number of schools, number of hydrants, customers served by pump station, number of high consumption users, serves a major municipality, and reservoir redundancy.

The parameters that score low for criticality were presence of a hospital, number of meters, number of hydrants, has multiple fire stations, number of high consumption users, is in a municipality, pump station redundancy and reservoir redundancy. There are no hospitals within the 980-1 pump zone. The pumps for pump station 980-1 do not directly provide water to any pump stations.

Table 19 – Risk factor results for 980-1 pumps.

Description	Score
Restore Service	5
Number of Schools	10
Presence of a Hospital	0
Customers Served by Pump Station	8
Number of Hydrants	10
Multiple Fire Stations	5
Number of High Consumption Users	10
Serves a Major Municipality	10
Redundancy Lost	8
Pump Station Redundancy	0
Reservoir Redundancy	10
Criticality	76
Probability	1.6
Criticality after Scaling	10
Probability after Scaling	5
Risk Factor	50

The results for pump 1 of the 711 pump station are displayed in Table 20. The pumps for the 711 pump station scored in the moderate category. After the scores for criticality and probability are both scaled, relatively high numbers on criticality drive the overall moderate to high score for the 711 pump station pumps. The area served by the 711 pumps is in central Chula Vista. The types of customers served by the pumps for the 711 were mainly single family residential.

The criticality parameters that scored high for these pumps were number of schools, presence of a hospital, customers served by pump station, number of hydrants, number of high consumers, service to a municipality and reservoir redundancy. The pump zone that the 711 pumps serve has a high concentration of customers so it scores highest for customers served by pump station, schools, and hydrants. A hospital is also located with the pump zone that the 711 pumps serve. The pump zone is also located in the City of Chula Vista, so it scored 10 for presence of a municipality. Also there are many high consumption users because of business parks and condominium complexes in the pump zone.

The pumps scored low for reservoir redundancy, because the 711 pumps directly serve many reservoirs. The other parameters that scored lower were time to restore service, multiple fire stations, redundancy lost and pump station redundancy. The pumps that make up the 711 are vertical turbine so they do not take as long to replace. Pump station redundancy lost scores low because the 711 has five pumps. The 711 pumps only directly serve one pump station so they only received a score of 3.

The probability for the 711 pumps is just over their expected lifetime, but still scored moderate compared to other pumps.

Table 20 – Risk factor results for Pump 1 of the 711-1 pumps.

Description	Score
Restore Service	5
Number of Schools	8
Presence of a Hospital	10
Customers Served by Pump Station	10
Number of Hydrants	10
Multiple Fire Stations	5
Number of High Consumption Users	7
Serves a Major Municipality	10
Redundancy Lost	4
Pump Station Redundancy	2.5
Reservoir Redundancy	0
Criticality	71.5
Probability	1.33
Criticality after Scaling	10
Probability after Scaling	4
Risk Factor	40

The scores for pump 1 of the 1090 pump station are displayed in Table 21. The pumps for this pump station scored in the low to moderate category. Probability of failure is a major driver of the score due to the older age of the pumps. This pump station is located in the unincorporated part of San Diego County and the customers served are mainly single family home residential.

The parameters that scored high for criticality were time to restore service and redundancy lost. The pumps for the 1090-1 are Centrifugal and received a score of 10 for time to restore service. Since there are only two pumps in the 1090-1 pump station it scored a 10 for redundancy.

The parameters that scored low were number of schools, presence of a hospital, customers served by pump station, number of hydrants, has multiple fire stations, number of high consumers, is in a municipality and pump station redundancy. The pressure zone for that the pumps for the 1090-1 serve is small and does not have any schools, hospitals, high consumption users or fire stations. Also there are few hydrants and customers served due to the small size of the pressure zone. The pump station redundancy score for 1090-1 was 0 because the pumps do not serve water to any pump stations. The pumps in the 1090-1 are old and scored high for probability of failure.

Table 21 – Risk factor results for 1090-1 pumps.

Description	Score
Restore Service	10
Number of Schools	0
Presence of a Hospital	0
Customers Served by Pump Station	1
Number of Hydrants	1
Multiple Fire Stations	0
Number of High Consumption Users	1
Serves a Major Municipality	0
Redundancy Lost	10
Pump Station Redundancy	0
Reservoir Redundancy	3.3
Criticality	26.3
Probability	3.3
Criticality after Scaling	2
Probability after Scaling	10
Risk Factor	20

The scores for pump 1 of the 944-1 are displayed below in Table 22. The pumps for the 944-1 pump station scored in the low category. After both criticality and probability were scaled, neither parameter had influence over the other. The pumps for the 944-1 pump station are located in unincorporated part of San Diego County. The pump zone for that the 944-1 serves is comprised of single family residential.

The parameters that scored high for criticality were pump station redundancy and pump redundancy lost. The pumps for the 944-1 pump stations serves many pump stations. The pumps received the highest score for pump station redundancy. The pump station for the 944-1 has four pumps and received a score of 6 for redundancy lost.

Table 22 – Risk factor results for 944-1 pumps.

Description	Score
Restore Service	5
Number of Schools	0
Presence of a Hospital	0
Customers Served by Pump Station	1
Number of Hydrants	0
Multiple Fire Stations	0
Number of High Consumption Users	0
Serves a Major Municipality	0
Redundancy Lost	6
Pump Station Redundancy	10
Reservoir Redundancy	0
Criticality	22
Probability	1.53
Criticality after Scaling	1
Probability after Scaling	5
Risk Factor	5

The parameters that scored low for criticality were number of schools, presence of a hospital, customers served by pump station, number of hydrants, number of fire stations, and is in a municipality. The pressure zone that the pumps for the 944-1 serve is very small and does not serve any schools, hospitals, hydrants, fire stations. The pressure zone for these pumps is located in unincorporated part of San Diego County. The pumps for the 944-1 are vertical turbine so the score for time to restore service is a 5.

4.2 - Expert Confirmation of Model Results

Figure 10 was printed and then presented to Water System Supervisor. Expert confirmation determined if the results made sense and if any of the pumps would need immediate attention based on results. After analyzing the map and discussing the results it was determined that the map looked good representing pumps with a few exceptions (Vaclavek, 2012). The exceptions were largely driven by the position of the pump in the district’s network. Some of the district's pump stations need to be considered more pertinent than others because they directly pump water to other pump stations. If the pump stations that provide water to others were to fail then the pump stations that rely on other pump stations for water would be greatly affected.

The model identified pumps that need to be replaced in the near future. This is valuable to the district, because it will be prepared to allocate funds for future replacement and repairs. Also if two pumps from different pump stations are due to be repaired at a certain date and the district only has a limited amount of funds available, the district can decide which pump is more critical to be repaired or replaced.

The scores that were found to inadequately represent the pumps position in the overall network were those in the 944-1, Cottonwood, and the Rancho Jamul pump stations. The 944-1 had a low risk factor score, but according to Water Systems Supervisor should have scored much higher. It should have scored higher because the pumps for the 944-1 pump station directly provide water to four other pump stations. If the pumps in this pump station were to fail it would leave the other pump stations without water, possibly leaving thousands of people without water.

The pumps for the Cottonwood pump station scored higher than it should have. The station does not serve that many people. If pump failure were to occur the consequence of failure would not be that great due to the low population that the Cottonwood pumps serve. The high scoring result is that the pumps are old. The Water Systems Supervisor said that the pumps had been replaced in 2011 so the model would have to be updated with the new data. Since this was the case regarding the pumps for the Cottonwood pump station the score will be lower after running the model again.

The pumps for the Rancho Jamul pump station scored lower than the Water Systems Supervisor expected. The Water Systems Supervisor expected a higher score because the pumps are starting to age and will probably be replaced within the next 10 years. In this model, the low criticality score made the overall score lower.

4.3 - Sensitivity Analysis

A sensitivity analysis was conducted to better understand the model and scoring system following feedback in the expert confirmation process. To try and increase the accuracy of the pump's risk factor score, the classification of the data was changed from equal interval to natural breaks (Jenks). This method is designed to set values into natural classes. The natural breaks (Jenks) method minimizes the average deviation from class means, while maximizing the deviation of the means from other groups.

After the model was rerun using natural breaks (Jenks) classification, the results had changed for some of the pumps. The pumps for the 944-1 had no change and still scored in the low risk factor. The score is still not scoring in the high risk factor category where it needs to be given its position in the pump network. The only change is in the criticality that moves from 1 to 2 after scaling. The raw criticality score (i.e., before scaling) remained the same but because natural breaks (Jenks) groups the scores differently when scaling the scores.

The scoring for the 1090-1 pumps increased from low scoring to low-moderate scoring using natural breaks (Jenks). Another sensitivity analysis is to weight a few parameters to see if scores can be improved. The scores for pumps in the 944-1 pump station are the least accurate. The reason for this is that the pump zone that the pumps provide water for is small, so most of the spatial parameter scores were very low or 0. The scores that the pumps for the 944-1 scored high in was pump station redundancy and reservoir redundancy. Since these are the only 2 parameters for which the 944-1 pumps had high scores, they will be increased to help increase the risk factor score and improve the results. Pump station redundancy and reservoir redundancy will be increased by multiplying each score by 10. The goal of this will be to increase the risk factor score for the pumps of the 944-1 pump station but not increase or decrease the other pump risk factor scores. In this weighting process the natural breaks (Jenks) scaling is retained to classify the results, since it solved one of the problems noted earlier with the score.

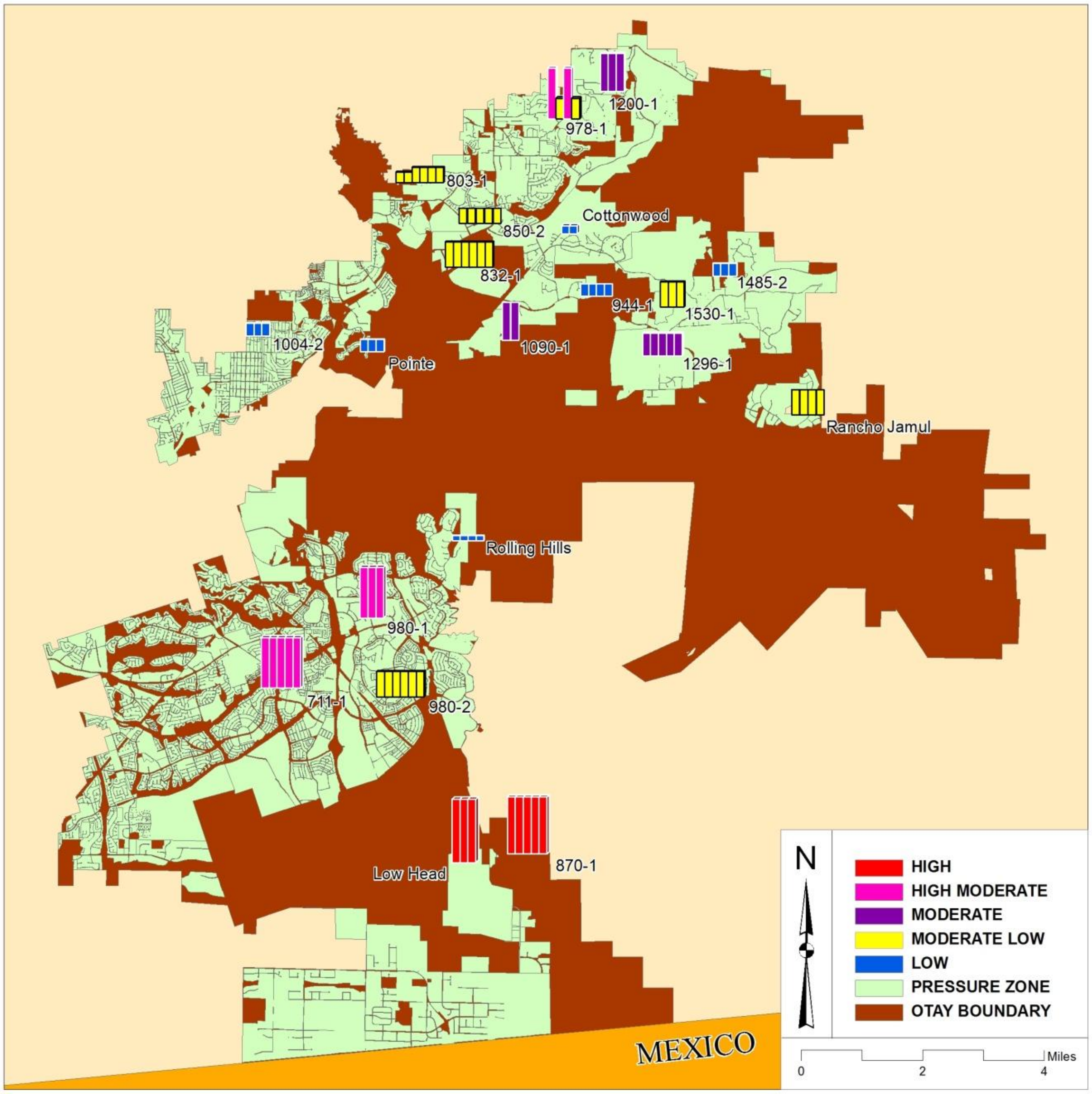


Figure 12 – Results for risk factor using natural breaks (Jenks) classification. Source: Alexander Schultz (2012)

Table 23 – Scoring range for Risk Factor using natural breaks (Jenks).

Data Range	Score
4 - 10	LOW
10 - 18	LOW TO MODERATE
18 - 30	MODERATE
30 - 50	MODERATE TO HIGH
50 - 90	HIGH

Table 24 – Risk factor results for 944-1 pumps equal interval and natural breaks (Jenks).

Description	Equal Interval	Natural Breaks (Jenks)
Restore Service	5	5
Number of Schools	0	0
Has a Hospital	0	0
Customers Served by Pump Station	1	1
Number of Hydrants	0	0
Multiple Fire Stations	0	0
Number of High Consumption Users	0	0
Is In a Municipality	0	0
Redundancy Lost	6	6
Pump Station Redundancy	10	10
Reservoir Redundancy	0	0
Criticality	22	22
Probability	1.53	1.53
Criticality after Scaling	1	2
Probability after Scaling	5	5
Risk Factor	5	10

Increasing the pump station redundancy and the reservoir redundancy by multiplying by 10 had both a positive and a negative impact on the risk factor scores. The positive impacts were the pumps for the 711-1 returned to moderate to high risk factor. This is good because the 711-1 pumps are seen as critical by OWD staff because of the high population that is served. The negative impacts were that the risk factor score for the 944-1 did not change; they still remained at moderate to high risk factor. This was not good because the 944-1 pumps are seen as critical by OWD staff because of the pump stations they directly provide water to. Also the risk factor scores for the pumps of the Cottonwood pump station increased from moderate to moderate to high scores.

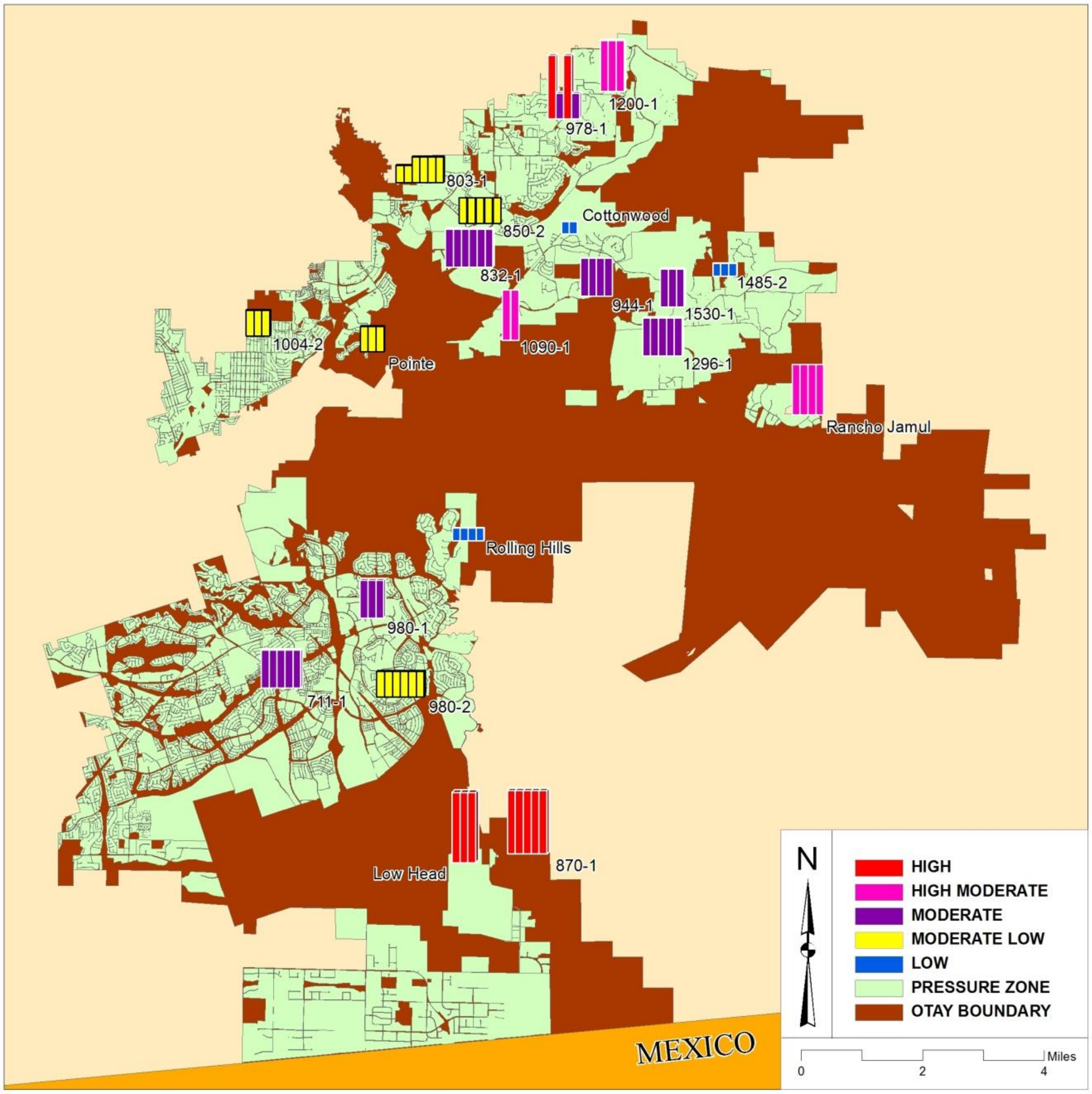


Figure 13 – Results for Risk Factor using natural breaks (Jenks) and weighting redundancy x 10.

Table 25 – Scoring for risk factor range for redundancy x 10.

Data Range	Score
8 - 16	LOW
16 - 32	LOW TO MODERATE
32 - 50	MODERATE
50 - 80	MODERATE TO HIGH
80 - 100	HIGH

Table 26 – Risk factor results for 944-1 pumps increasing x 10.

Description	Score
Restore Service	5
Number of Schools	0
Has a Hospital	0
Customers Served by Pump Station	1
Number of Hydrants	0
Multiple Fire Stations	0
Number of High Consumption Users	0
Is In a Municipality	0
Redundancy Lost	6
Pump Station Redundancy	100
Reservoir Redundancy	100
Criticality	212
Probability	1.53
Criticality after Scaling	10
Probability after Scaling	5
Risk Factor	50

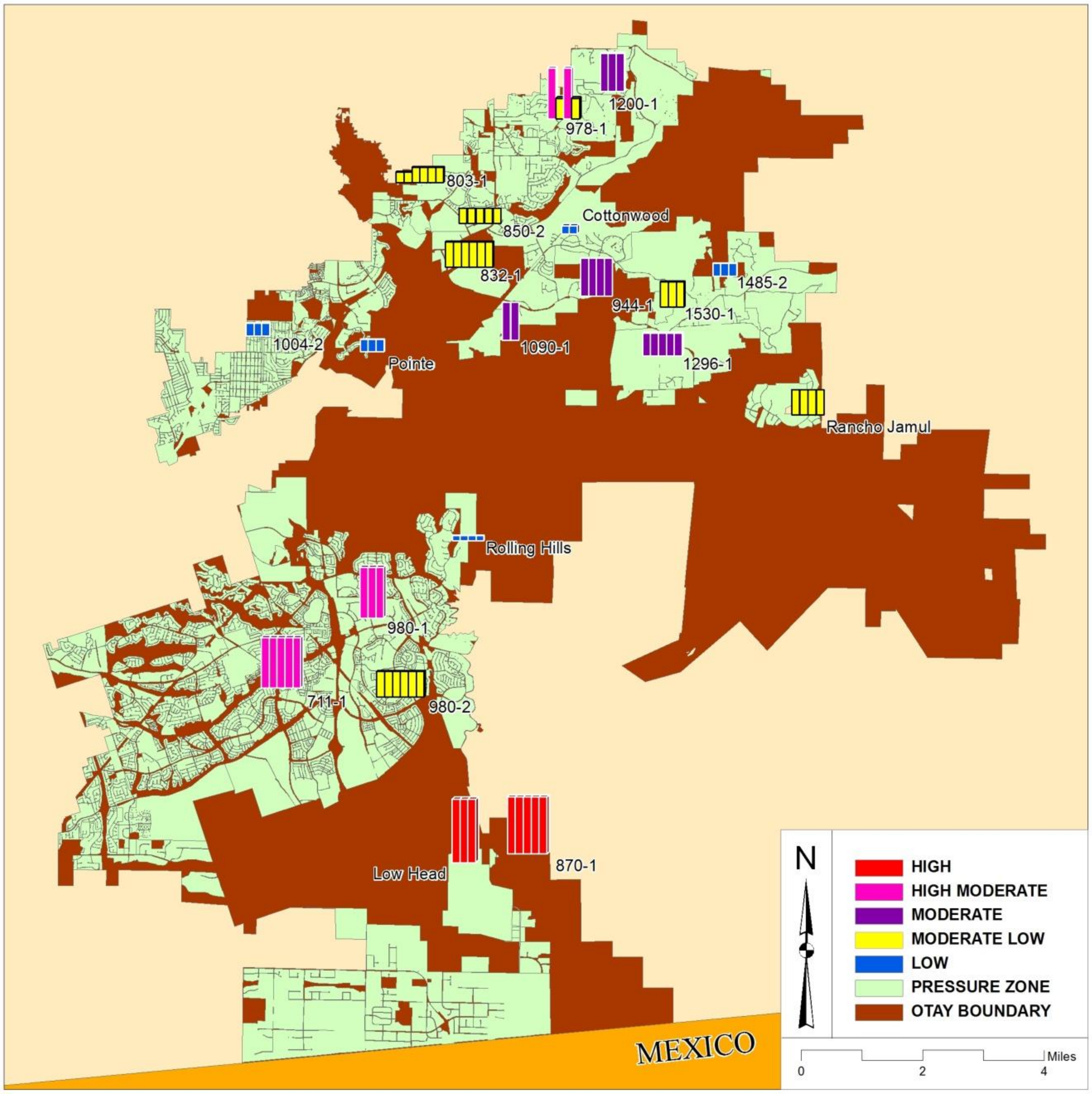


Figure 14 – Risk factor scoring results after populating 944-1 pumps' spatial parameters with mean score.

Table 27 – Scoring for risk factor for pumps with mean criticality.

Data Range	Score
4 - 9	LOW
9 - 18	LOW TO MODERATE
18 - 30	MODERATE
30 - 50	MODERATE TO HIGH
50 - 90	HIGH

Table 28 – Risk factor results for 944-1 pumps with mean criticality.

Description	Score
Restore Service	5
Number of Schools	3
Has a Hospital	1
Customers Served by Pump Station	5
Number of Hydrants	6
Multiple Fire Stations	3
Number of High Consumption Users	5
Is In a Municipality	3
Redundancy Lost	6
Pump Station Redundancy	3
Reservoir Redundancy	5
Criticality	45
Probability	1.53
Criticality after Scaling	5
Probability after Scaling	5
Risk Factor	25

To increase the risk factor score for the 944-1 pumps, the mean scores for all spatial parameters were then added to the spatial parameters of the 944-1 pumps. Populating the 944-1 pumps' spatial scores with the mean from the other pumps still did not increase the risk factor score to place into a higher scoring category. The overall criticality score increased but not enough to move it out of a moderate risk factor.

Since the mean did not help increase the overall risk factor score the next step will be to populate each of the 944-1 pumps spatial parameters with the maximum possible score. This should increase the overall criticality for the 944-1 pumps to the maximum possible score. No matter what was done to increase the 944-1 pumps scoring, the results were still not high enough to put it in the highest scoring range.

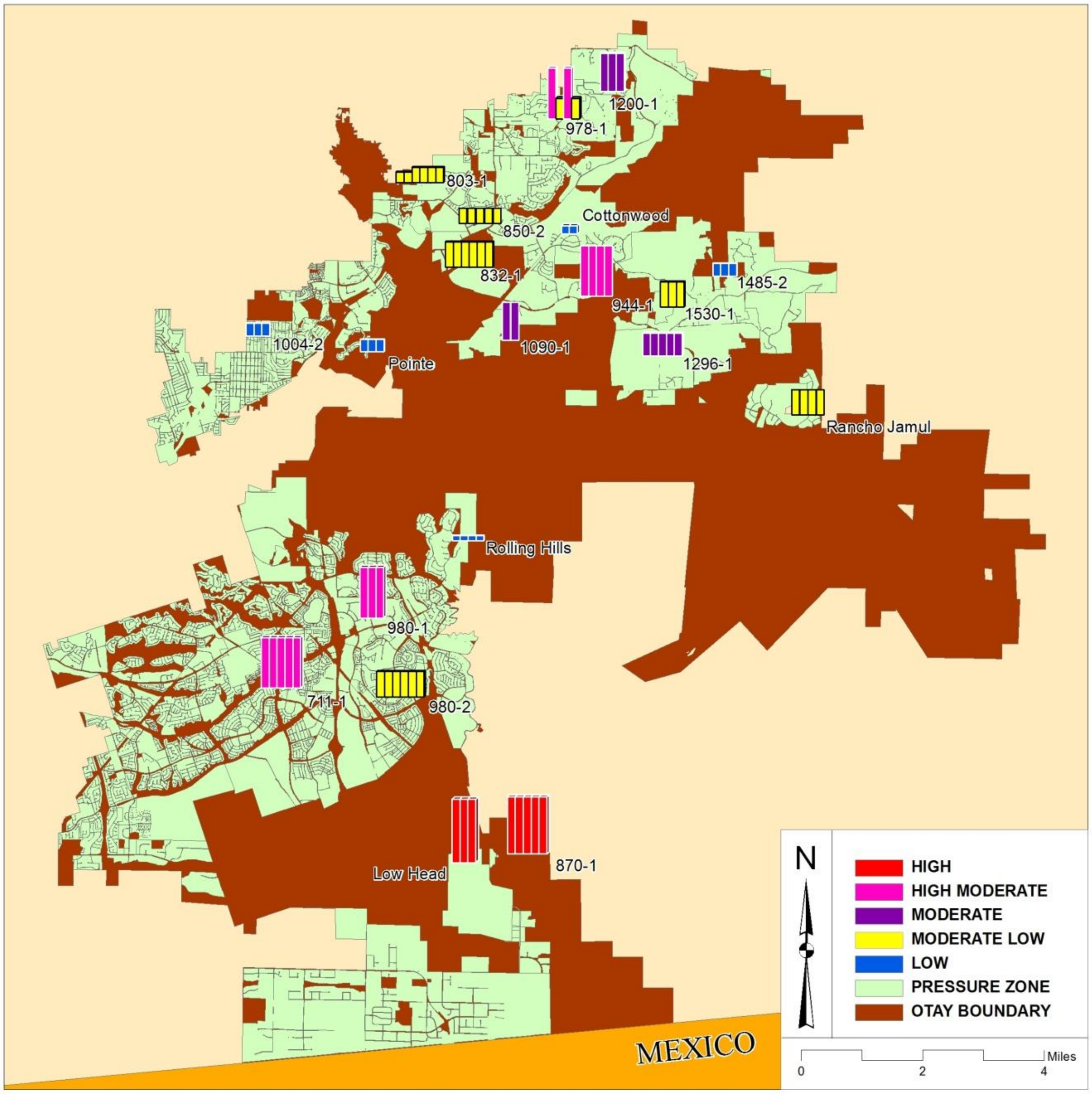


Figure 15 – Risk factor scoring results after populating 944-1 pumps' spatial parameters with maximum score.

Table 29 – Scoring range for risk factor with maximum criticality.

Data Range	Score
4 - 9	LOW
9 - 18	LOW TO MODERATE
18 – 30	MODERATE
30 - 50	MODERATE TO HIGH
50 - 90	HIGH

Table 30 – Risk factor results for 944-1 pumps with maximum criticality.

Description	Score
Restore Service	10
Number of Schools	10
Has a Hospital	10
Customers Served by Pump Station	10
Number of Hydrants	10
Multiple Fire Stations	10
Number of High Consumption Users	10
Is In a Municipality	10
Redundancy Lost	10
Pump Station Redundancy	10
Reservoir Redundancy	10
Criticality	110
Probability	1.53
Criticality after Scaling	10
Probability after Scaling	5
Risk Factor	50

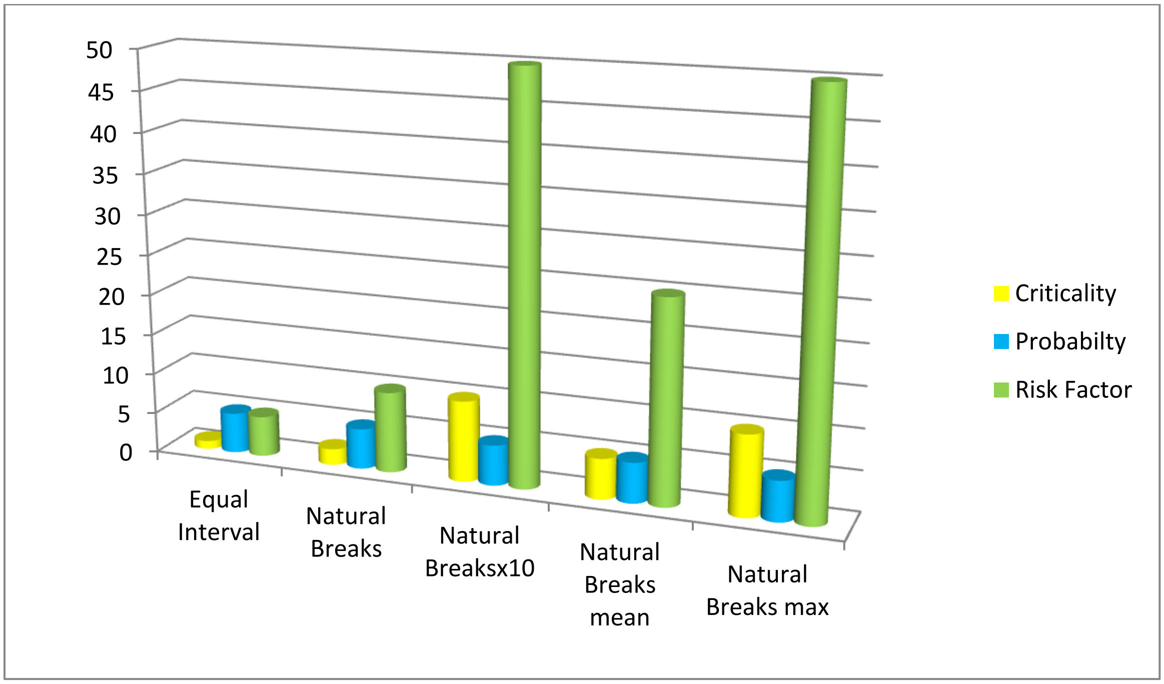


Figure 16 – Chart displaying different scoring results for 944-1 pumps Source: Alexander Schultz (2012)

CHAPTER 5 – CONCLUSIONS

Implementing an asset management system using GIS can be a very powerful tool for managing and predicting risk factors for both vertical and horizontal assets. As was discussed previously, asset management can be very beneficial and cost efficient for water utilities. Further work is required to refine the model presented in this study. However, the model generated in this study brings some immediate benefits to the OWD and also demonstrates the value of integrating GIS with asset management for other utilities.

5.1 - Model Refinements

One important parameter used for determining probability that was not included was condition. Probability only had one parameter of age. After trying three different strategies to boost the overall risk factor score of the 944-1 pumps, none of them was able to increase the risk factor score enough to place it into the high risk factor category. Possibly if a condition assessment was included it could have increased the pump's probability score and raised its own risk factor score or possibly lowered it depending on the condition.

Other possible strategies would be increasing the number of parameters used to calculate the model results. Since the pump zone for the 944-1 pumps is not very large, non-spatial parameters would most likely be used. These non-spatial parameters could include the size of the reservoir for which the pumps provide water and the 944-1 distributes water to other pump stations. The more pumps a pump station has, the larger amount of water it uses to distribute to other customers. Each pump that directly provides water to another pump station could inherit a weighted proportion of all the spatial and non-spatial criticality and probability risk factors scoring from the pumps for which it provides water. The weighted proportions could be based on the allocation of the water provided to other pumps vs. directly to customers. This would be similar to feeder streams and tributaries flowing into a major river with a network diagram that would resemble a trunk and branches of a tree. The greater the number and size of the tributaries the greater flow of water is discharged into the river, increasing the rivers size. The metaphor is instructive because river systems are quite complex and dynamic as a tributaries discharge is not always constant. For example they may experience seasonal fluctuations (Snavely, 2006).

Such complexity can be found in the OWD network of pump stations because demand for water across the network is not constant. Water demand can also change during different times of the day and during different seasons. A dynamic algorithm might be required to calculate parameters for allocation. Also having an application that can calculate and monitor this procedure would also assist in determining this parameter's output. Since I did not have the data for peak and off peak demand or the application to calculate and monitor it, I did not use this parameter. It also involved the complexity of calculating the demand needed by 944-1 pumps to supply the other pumps and how much water each reservoir can store and distribute if pump failure were to occur.

5.2 - Benefits to Otay Water District

One of the benefits that this model brings for the OWD in the way of proactive maintenance is that the district can plan and prepare for when an asset is projected to fail. Also the district will be prepared for the cost of repairing or replacing the asset when life expectancy is coming to an end. Proactive maintenance can also be planned to prolong an asset's life expectancy and save the district future replacement costs. The new information that this brings to the Water Operations department is pumps that might not have been seen as critical, may now have to be inspected for condition assessment to determine if pumps are possibly close to failure. An example of this is the pumps for the 870-1 pump station were inspected and found to be aging and in need of replacement. The CIP that was going to be used for future replacement of the pump station was scheduled to be in 5 years. After the pump station was found to be aging and outdated, the Water

Systems Supervisor is trying to have the Capital Improvement Project (CIP) moved up to 3 years instead of 5. Another example is the pumps for the 980-1 pump station that scored as Moderate to High. After being inspected, it was found that the pumps were starting to show age and would need to be replaced fairly soon. Since the 980-1 pump station is strictly now being used as a backup for the 980-2, replacing these pumps is currently not urgent.

The new insights that the model brings to the district is a better understanding of spatial influences on a given pump's criticality. The consequence of failure is defined as the impact on service to customers. The model creates a better understanding of how some pumps take precedence above others in the way of repairs or replacement and suggests which pumps are priorities to investigate for mechanical condition and to perform repairs to prolong life expectancy.

The study highlights the importance of spatial aspects for asset management of vertical assets. The environment surrounding the asset has an important influence on the overall asset risk score. Infrastructure asset data are typically identified, associated with, or referenced by their geographic locations and spatial relationships. As a result, GIS and spatial data analysis can play to support asset management processes (Halfawy and Figueroa, 2006).

The spatial location of a pump can not only influence its risk factor score but also other pumps' risk factor scores. The 944-1 pump's risk factor score is influenced by the parameters in its pump zone. Since there are very few meters, hydrants, and high consumption parcels, the criticality score for the 944-1 pumps is very low.

5.3 - Otay Accomplishments Present and Future

What OWD has accomplished so far in its implementation of asset management is creating a GIS geodatabase that can store not only horizontal assets but also vertical assets. Vertical assets and their attributes that in the past were not present in GIS can now be accessed. Also the asset management data entry form was created so operations crew members who are out in the field taking asset inventory can populate the database in the field. Currently at this time data are still being acquired and a condition assessment for each vertical asset still has yet to be completed.

OWD is also in the process of implementing Azteca's City Works for its CMMS. The main reason for using City Works is its geo-centric platform. Unlike other CMMS products, its platform sits on top of the GIS database and does not require a separate database for data storage. Having a separate GIS and CMMS to constantly keep in sync with each other can be frustrating and tedious because each database is being populated by different sources. With this process of keeping both databases in sync eliminated, the district can now save time and money. City Works will be used to keep track of maintenance, create work orders and maintain an inventory of assets.

The case study that was conducted in the previous chapters to find the risk factor of assets required a model to be created in ArcGIS ModelBuilder. This process was successful in finding the risk factor for pumps, but is not an ideal long term solution for determining risk factor for all assets. Different models would have to be created for each asset, because not all assets would have the same parameters for determining risk factor. Each model would need to be maintained in sync between GIS and the CMMS. To solve this problem, OWD will implement a new application that will automate the risk factor scoring system. This application will integrate with GIS and City Works. It will predict when an asset will fail and determine what the repair or replacement costs will be. This application will calculate each asset's risk factor with its own customized interface which will let the user add parameters they want to use to determine an asset's risk factor. Also the application will send out alerts when an asset in nearing the end of its lifecycle or when it will need future maintenance. Once in the system the asset will constantly be monitored during its lifecycle, unlike a model in ModelBuilder where the model would constantly be rerun in order to generate new results. OWDs ultimate goal is to have a fully automated asset management system.

5.4 - Value of Integrating GIS with Asset Management in Utilities

Other utilities that provide electricity or gas may also benefit from the database and scoring model that includes not only horizontal assets but also vertical assets, like the one described here. Although some are reported in literature as using GIS to find risk factor for only their horizontal assets, very few discuss using a geodatabase to store vertical feature class tables. Since power stations like pump stations are only being represented by a point in GIS, the vertical assets are excluded. For example, there are a large number of pipelines in power stations, most of which are underground or overhead and constitute complex networks. Using GIS, users can collect the information on the geographical distribution of pipelines or overhead transmission systems and corresponding service areas (Shahidehpour, 2005). When speaking about GIS in an energy utility very few discuss storing a vertical asset table in the geodatabase model. This would be very beneficial because then utilities would also be able the access their vertical asset data within GIS, which could then be edited or used in geoprocessing functions to help determine risk factor.

Other energy utilities do not use GIS to track their assets. Progress Energy’s Lee Plant in Goldsboro, NC could have benefited by using GIS model to tracks their vertical pump’s asset risk factor. Instead they use reactive rather than a proactive approach. As the pumps aged their maintenance became more frequent and more expensive. Several years ago their reliability had deteriorated to the point of compromising the overall plant operations (Anonymous, 2007). Had they had an asset management system in place the pumps could have been monitored and proactive maintenance or replacement could have been done to reduce costs.

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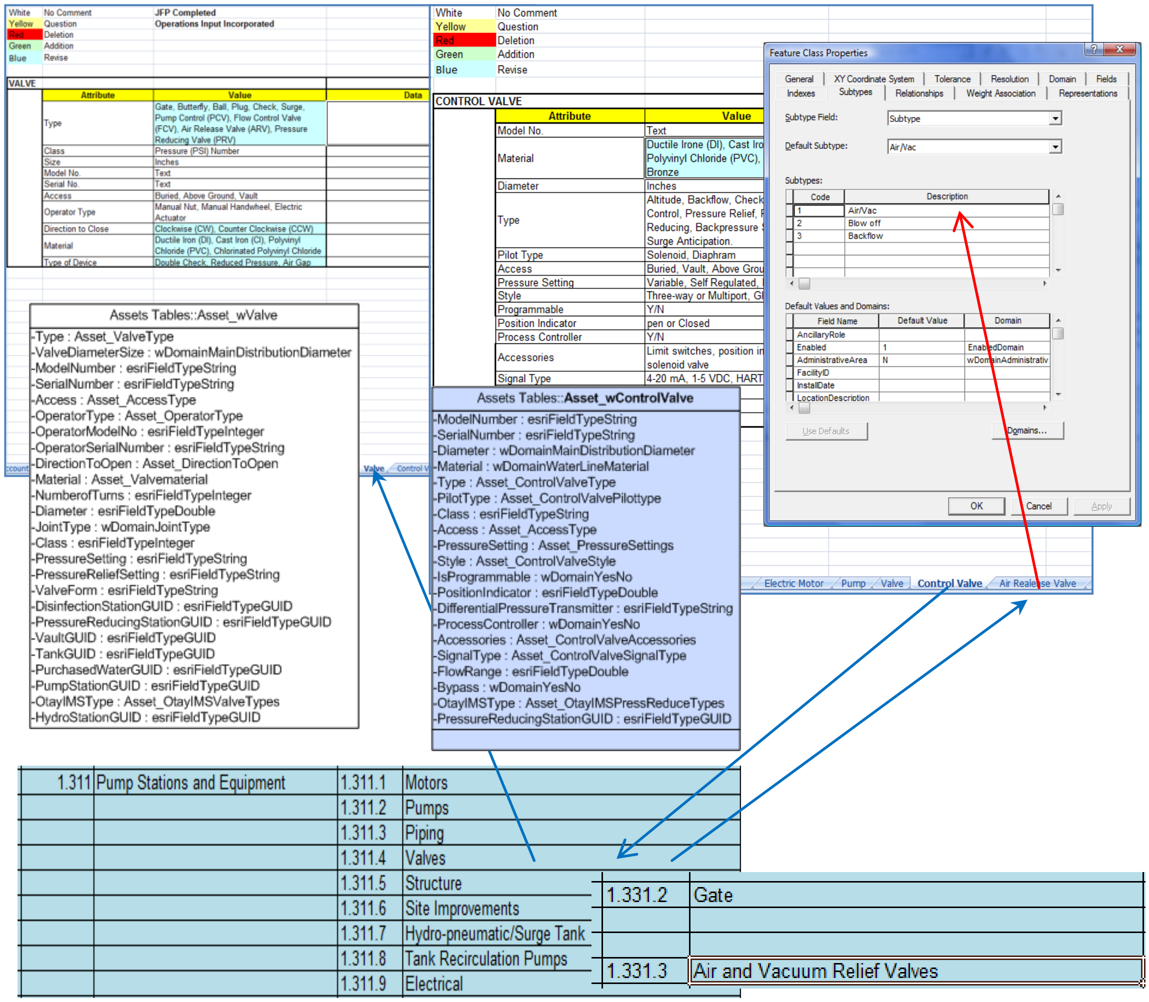
APPENDIX A: Table displaying results using equal interval classification.

Description	Type	Time to restore service	Redundancy Lost	Pump Station Redundancy	Reservoir Redundancy	Schools	Hospitals	Customers Served	Hydrants Served	Fire Stations	High consumption users	Is in a municipality	Criticality	Probability	Risk Factor
944-1-1	Vertical turbine	5	6	10	0	0	0	1	0	0	0	0	1	5	50
944-1-2	Vertical turbine	5	6	10	0	0	0	1	0	0	0	0	1	5	50
944-1-3	Vertical turbine	5	6	10	0	0	0	1	0	0	0	0	1	5	50
944-1-4	Vertical turbine	5	6	10	0	0	0	1	0	0	0	0	1	5	50
1296-1-1	Vertical turbine	5	4	7.5	0	4	0	1	2	10	2	0	3	4	12
1296-1-2	Vertical turbine	5	4	7.5	0	4	0	1	2	10	2	0	3	4	12
1296-1-3	Vertical turbine	5	4	7.5	0	4	0	1	2	10	2	0	3	4	12
1296-1-4	Vertical turbine	5	4	7.5	0	4	0	1	2	10	2	0	3	4	12
1296-1-5	Vertical turbine	5	4	7.5	0	4	0	1	2	10	2	0	3	4	12
978-1-1	Vertical turbine	5	6	0	3.3	0	0	1	2	5	2	0	1	10	10
978-1-2	Vertical turbine	5	6	0	3.3	0	0	1	2	5	2	0	1	4	4
978-1-3	Vertical turbine	5	6	0	3.3	0	0	1	2	5	2	0	1	10	10
978-1-4	Vertical turbine	5	6	0	3.3	0	0	1	2	5	2	0	1	4	4
980-1-1	Vertical turbine	5	8	0	10	10	0	8	10	5	10	10	10	5	50
980-1-2	Vertical turbine	5	8	0	10	10	0	8	10	5	10	10	10	5	50
980-1-3	Vertical turbine	5	8	0	10	10	0	8	10	5	10	10	10	5	50
711-1-1	Vertical turbine	5	4	2.5	0	8	10	10	10	5	7	10	10	4	40
711-1-2	Vertical turbine	5	4	2.5	0	8	10	10	10	5	7	10	10	4	40
711-1-3	Vertical turbine	5	4	2.5	0	8	10	10	10	5	7	10	10	4	40
711-1-4	Vertical turbine	5	4	2.5	0	8	10	10	10	5	7	10	10	4	40
711-1-5	Vertical turbine	5	4	2.5	0	8	10	10	10	5	7	10	10	4	40
Rancho Jamul-1	Vertical turbine	5	6	0	6.6	0	0	1	1	0	0	0	1	7	7
Rancho Jamul-2	Vertical turbine	5	6	0	6.6	0	0	1	1	0	0	0	1	7	7
Rancho Jamul-3	Vertical turbine	5	6	0	6.6	0	0	1	1	0	0	0	1	7	7

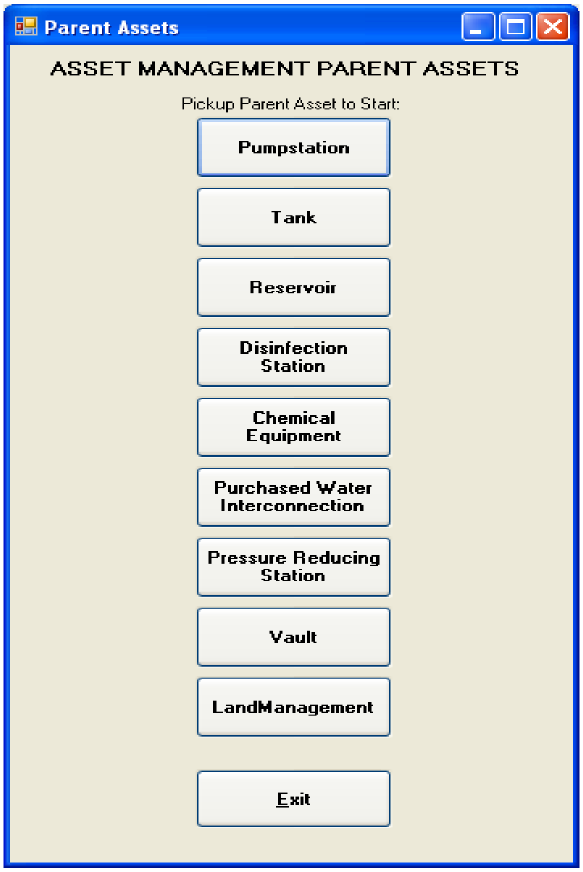
Rancho Jamul-4	Vertical turbine	5	6	0	6.6	0	0	1	1	0	0	0	1	7	7
850-2-1	Vertical turbine	5	4	2.5	0	2	0	4	5	10	4	0	3	3	9
850-2-2	Vertical turbine	5	4	2.5	0	2	0	4	5	10	4	0	3	3	9
850-2-3	Vertical turbine	5	4	2.5	0	2	0	4	5	10	4	0	3	3	9
850-2-4	Vertical turbine	5	4	2.5	0	2	0	4	5	10	4	0	3	3	9
850-2-5	Vertical turbine	5	4	2.5	0	2	0	4	5	10	4	0	3	3	9
803-1-1	Vertical turbine	5	2	7.5	0	4	0	3	4	5	3	0	3	2	6
803-1-2	Vertical turbine	5	2	7.5	0	4	0	3	4	5	3	0	3	2	6
803-1-3	Vertical turbine	5	2	7.5	0	4	0	3	4	5	3	0	3	3	9
803-1-4	Vertical turbine	5	2	7.5	0	4	0	3	4	5	3	0	3	3	9
803-1-5	Vertical turbine	5	2	7.5	0	4	0	3	4	5	3	0	3	3	9
803-1-6	Vertical turbine	5	2	7.5	0	4	0	3	4	5	3	0	3	3	9
832-1-1	Vertical turbine	5	8	5	3.3	1	0	1	1	0	1	0	2	4	8
832-1-2	Vertical turbine	5	8	5	3.3	1	0	1	1	0	1	0	2	4	8
832-1-3	Vertical turbine	5	8	5	3.3	1	0	1	1	0	1	0	2	4	8
832-1-4	Vertical turbine	5	8	5	3.3	1	0	1	1	0	1	0	2	4	8
832-1-5	Vertical turbine	5	8	5	3.3	1	0	1	1	0	1	0	2	4	8
832-1-6	Vertical turbine	5	8	5	3.3	1	0	1	1	0	1	0	2	4	8
Pointe-1	Vertical turbine	5	8	0	10	0	0	1	1	0	0	0	1	2	2
Pointe-2	Vertical turbine	5	8	0	10	0	0	1	1	0	0	0	1	2	2
Pointe-3	Vertical turbine	5	8	0	10	0	0	1	1	0	0	0	1	2	2
Low Head-1	Centrifugal	10	8	2.5	10	0	0	1	8	5	7	10	8	9	72
Low Head-2	Centrifugal	10	8	2.5	10	0	0	1	8	5	7	10	8	9	72
Low Head-3	Centrifugal	10	8	2.5	10	0	0	1	8	5	7	10	8	9	72
Rolling Hills-1	Vertical turbine	5	6	0	10	0	0	1	1	0	0	10	3	1	3
Rolling Hills-2	Vertical turbine	5	6	0	10	0	0	1	1	0	0	10	3	1	3
Rolling Hills-3	Vertical turbine	5	6	0	10	0	0	1	1	0	0	10	3	1	3
Rolling Hills-4	Vertical turbine	5	6	0	10	0	0	1	1	0	0	10	3	1	3
980-2-1	Vertical turbine	5	2	0	0	10	0	8	10	5	10	10	8	2	16
980-2-2	Vertical turbine	5	2	0	0	10	0	8	10	5	10	10	8	2	16

980-2-3	Vertical turbine	5	2	0	0	10	0	8	10	5	10	10	8	2	16
980-2-4	Vertical turbine	5	2	0	0	10	0	8	10	5	10	10	8	2	16
980-2-5	Vertical turbine	5	2	0	0	10	0	8	10	5	10	10	8	2	16
980-2-6	Vertical turbine	5	2	0	0	10	0	8	10	5	10	10	8	2	16
870-1-1	Vertical turbine	5	4	7.5	10	0	0	1	8	5	7	10	7	10	70
870-1-2	Vertical turbine	5	4	7.5	10	0	0	1	8	5	7	10	7	10	70
870-1-3	Vertical turbine	5	4	7.5	10	0	0	1	8	5	7	10	7	10	70
870-1-4	Vertical turbine	5	4	7.5	10	0	0	1	8	5	7	10	7	10	70
870-1-5	Vertical turbine	5	4	7.5	10	0	0	1	8	5	7	10	7	10	70
Cottonwood-2	Centrifugal	10	10	0	10	4	0	3	4	5	3	0	6	6	36
Cottonwood-1	Centrifugal	10	10	0	10	4	0	3	4	5	3	0	6	6	36
1090-1-1	Centrifugal	10	10	0	3.3	0	0	1	1	0	1	0	2	10	20
1090-1-2	Centrifugal	10	10	0	3.3	0	0	1	1	0	1	0	2	10	20
1530-1-1	Centrifugal	10	8	0	10	0	0	1	1	0	0	0	2	4	8
1530-1-2	Centrifugal	10	8	0	10	0	0	1	1	0	0	0	2	4	8
1530-1-3	Centrifugal	10	8	0	10	0	0	1	1	0	0	0	2	4	8
1200-1-1	Vertical turbine	5	8	0	6.6	0	0	1	1	0	1	0	1	7	7
1200-1-2	Vertical turbine	5	8	0	6.6	0	0	1	1	0	1	0	1	7	7
1200-1-3	Vertical turbine	5	8	0	6.6	0	0	1	1	0	1	0	1	7	7
1004-1-1	Vertical turbine	5	8	2.5	10	0	0	1	1	0	0	0	2	2	4
1004-1-2	Vertical turbine	5	8	2.5	10	0	0	1	1	0	0	0	2	2	4
1004-1-3	Vertical turbine	5	8	2.5	10	0	0	1	1	0	0	0	2	2	4
1485-1-1	Vertical turbine	5	8	0	3.3	1	0	1	1	0	1	0	1	1	1
1485-1-2	Vertical turbine	5	8	0	3.3	1	0	1	1	0	1	0	1	1	1
1485-1-3	Vertical turbine	5	8	0	3.3	1	0	1	1	0	1	0	1	1	1

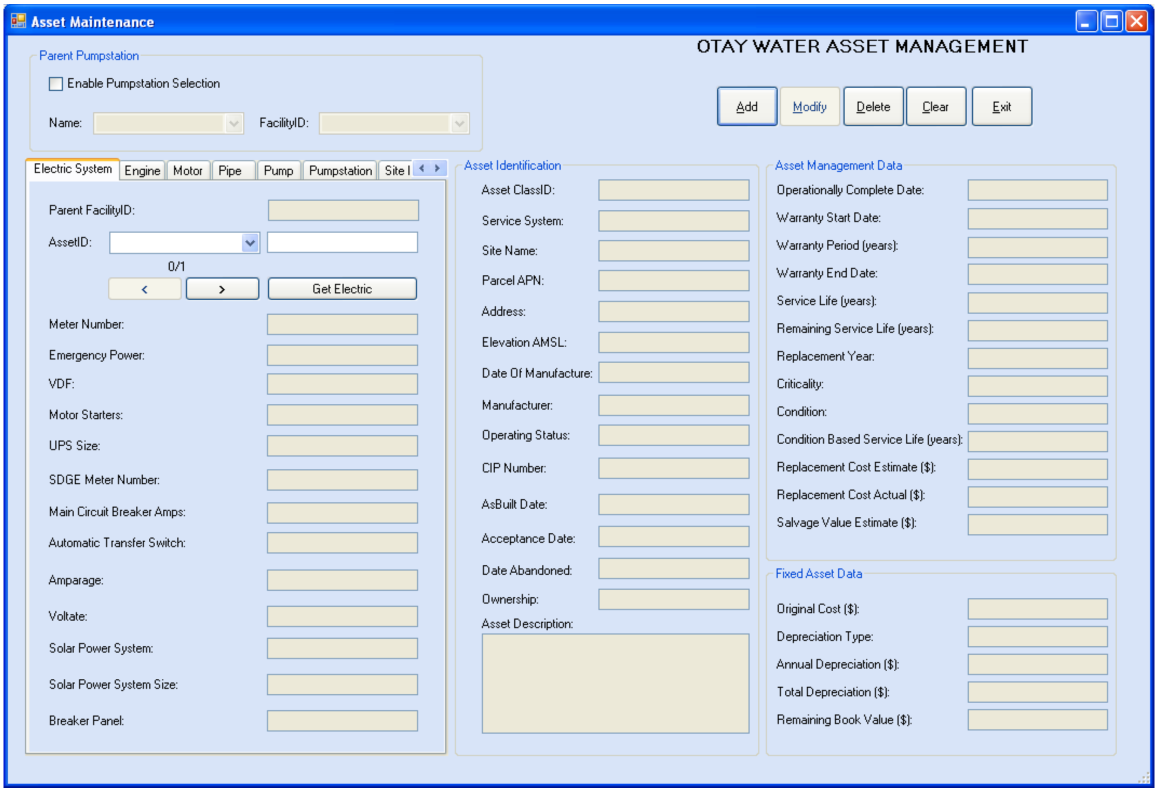
APPENDIX B: Integration of the spreadsheet into data model.



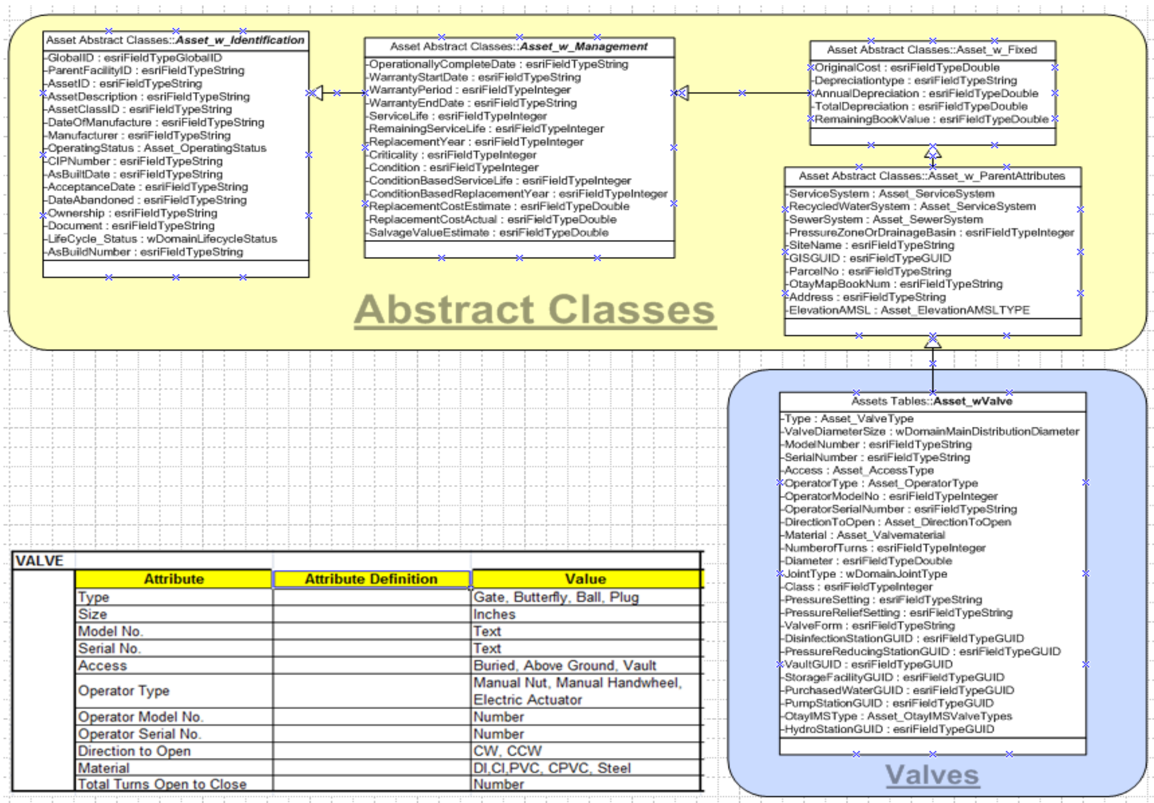
APPENDIX C: Asset Data Entry Form showing examples of parent assets.



APPENDIX D: Example of Asset Data Entry Form for pump station.



APPENDIX E: Feature class relating to abstract class.



Attribute	Attribute Definition	Value
Type		Gate, Butterfly, Ball, Plug
Size		Inches
Model No.		Text
Serial No.		Text
Access		Buried, Above Ground, Vault
Operator Type		Manual Nut, Manual Handwheel, Electric Actuator
Operator Model No.		Number
Operator Serial No.		Number
Direction to Open		CW, CCW
Material		DI,CI,PVC, CPVC, Steel
Total Turns Open to Close		Number

APPENDIX F: Diagram of model used to determine risk factor.