Bringing GIS to a Small Community Water System

by

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To my wife, Krista Reger, and mother, Eithne Scelzi

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List of Abbreviations

AM/FM   Automated Mapping/Facilities Management

CAD   Computer Aided Design

CWS   Community Water System

CWD   Community Water District

Esri   Environmental Systems Research Institute

GIS   Geographic information system

NTNCWS   Non-Transient Non-Community Water System

TNCWS   Transient Non-Community Water System

Abstract

Community Water Systems (CWS) are public or private water systems that supply water to the same population year-round, and they provide drinking water to over 300 million people in the United States each year. While the majority of the population is served by larger CWSs, where populations range from 10,000 to 100,000+, there are three times as many small water systems, where populations are less than 10,000, and these water systems generally have smaller budgets for maintaining or improving their systems. Many of these small CWSs rely on outdated maps or have no maps at all, and may not have the budget for a GIS. The goal of this study is to develop inexpensive geospatial solutions that can be implemented in small rural CWSs.

As a case study, a geographic information system (GIS) was created and implemented at the Descanso Community Water District in San Diego County, California using open source GIS software. The Descanso CWD relied on outdated paper CAD maps and has no spatial data of their infrastructure. Locations of all features found in the water system were collected using high accuracy GPS. The locations of pipes were digitized with the aid of Descanso CWD employees using Esri's ArcMap. The datasets were added in QGIS, an open source GIS software, and displayed over aerial photographs and other background data. A detailed map atlas of the water system and a small-scale wall map were created. Metadata for all data was created in XML format. A system employee was trained on the functions of the GIS software that are necessary to update the data as needed, which will allow the Descanso CWD to operate and maintain their GIS in-house instead of relying on a contractor to perform the work for them. A workflow for implementing a GIS at a small CWS was then created based on the findings of the case study.

Chapter 1 Introduction

The use of geographic information systems (GIS) in the utility industry has become commonplace, as GIS allows not only for the accurate mapping of infrastructure features, but also the ability to add attribute data to those features. When a utility stores their data in spatial format, they can also use GIS software to query and analyze specific attributes of their data. Water utilities in particular utilize GIS for the mapping of system infrastructure to replace existing paper maps or to create maps when none were had before. This project will be a case study in the implementation of a GIS at a small rural community water system using open source GIS software.

1.1 Public Water Systems

As of 2011, there are 152,713 water systems in the United States that serve 318 million people (EPA, 2013). This number includes Transient Non-Community Water Systems (TNCWS), Non-Transient Non-Community Water Systems (NTNCWS), and CWSs (EPA, 2012). TNCWSs provide water in a place such as a gas station or campground where people do not remain for long periods of time. TNCWSs served 12.6 million people in 2011. NTNCWSs regularly supply water to at least 25 of the same people at least six months per year, but not year-round, such as hospitals, schools, or office complexes. In 2011 NTNCWSs served 6.2 million people. Community Water Systems (CWS) supply water to the same population year-round, and in 2011 served 299.2 million people (EPA, 2013). Examples of CWSs are municipalities, community service districts, or mutual water companies. This study will focus on CWSs as they serve the majority of the population of the United States.

Based on the population that each CWS serves, the EPA reclassifies them into five categories. Very Small systems serve 25-500 people, Small systems serve 501-3,300 people,

Medium systems serve 3,301-10,000 people, Large systems serve 10,001-100,000 people, and Very Large systems serve 100,001+ people (EPA, 2012). 15.6% of CWSs are Very Large, Large, or Medium, serving 91% of the population that gets its water from a CWS, and 84.2% are Small or Very Small, serving only 9% of those that get their water from a CWS (EPA, 2013). This statistic means that 4,108 Very Large, Large, or Medium CWSs provide water to 275 million people and 47,248 Small or Very Small CWSs provide water to only 27 million people. This averages to 66,282 people per Very Large, Large, or Medium CWS, and 569 people per Very Small or Small CWS. When it comes to funding infrastructure improvements or technology changes for CWSs it is obvious that the larger systems will have a significantly higher income than the smaller systems. For this reason, this study will focus on the smaller systems. From here on, Very Small and Small CWSs will be referred to as small systems.

1.2 Motivation

Most of the larger systems utilize GIS in their daily activities, while the majority of smaller systems do not. Many of these systems believe GIS to be cost-prohibitive and do not understand what they could achieve with a well-designed GIS. These systems rely on dated as-built maps of their infrastructure that may or may not be accurate, and some systems do not have any maps of their infrastructure at all. In my six years of working for the California Rural Water Association, a non-profit organization that helps small rural water communities, I have personally visited over 400 small systems in the State of California, very few of which utilize GIS. The majority of these systems rely on engineering firms to create and maintain their maps, at a high cost to the system. By creating and maintaining a GIS of their infrastructure, these CWSs will have the ability to create maps on their own.

The utility industry has relied on computer aided design (CAD) systems in the mapping of its water systems. Many large CWDs have found that GIS works not only as a mapping system, but also as a database system. Information about all parts of the water system can be stored in a GIS, such as information on hydrants, valves, or pipe (Goubert, 1992). Customer use data can also be stored in a GIS, which can be analyzed to find trends in usage or even leaks.

The Environmental Systems Research Institute (Esri) is the most well-known GIS software company and provides a very robust program, ArcGIS. ArcGIS is capable of performing any spatial task a water utility may need, but it comes at a high cost. As of this writing, the cost of the most basic single user license is a one-time cost $1,500 (Esri 2016-1), which may make it unattainable for many small water systems.

There are, however, other options for these systems in the form of open source GIS software. Open source refers to software that the developer has made the source code available to anyone and can be modified by anyone, which is made possible under the GNU General Public License, and allows for the developer to release the software for free (IMT 2010). There are numerous options, but the most mature and robust options are GRASS GIS, SAGA GIS, gvSIG, and QGIS (GIS Geography 2016).

1.3 Project Objective

This purpose of this study is to develop inexpensive geospatial solutions that can be implemented in small CWSs. To develop these solutions, a case study will be performed to show that low cost open source GIS is as effective in the creation, manipulation, and presentation of spatial data as proprietary GIS software when implemented at a small CWS. A generalized workflow for implementing a GIS at a small CWS will be created based on this case study. Studies on the implementation of a GIS in a CWS have been conducted before (Rayburn, 2004,

Crawford, 2012, and Fellers, 2013). However, these previous studies were conducted in larger systems with large budgets, not small systems with small budgets.

The systems that I am interested in helping are small systems with modest budgets. A large budget would not be necessary to implement a GIS in one of these CWSs. This can be accomplished by using a low-cost GPS unit or renting a high cost GPS unit, installing open source GIS software, such as QGIS, and teaching a system employee how to manipulate the GIS software themselves. The result of this case study will be a generalized workflow for the implementation of a GIS in other communities that can be used by other GIS professionals in the water industry. This workflow will include all of the basic steps necessary to collect, manipulate, and display spatial data for small water systems.

Each of the above mentioned open source GIS software options has strengths and weaknesses. The U.S. Army Corps of Engineers originally developed GRASS GIS and later released the software as open source. It offers the user to perform image processing analysis, digital terrain manipulation and statistics but falls short in cartographic design. SAGA GIS was originally created for terrain analysis and has particularly helpful tools for working with rasters. However, like GRASS GIS, it is not useful when it comes to cartography. gvSIG is a software package that is as capable as any commercial software and has extensive CAD tools. QGIS, formerly Quantum GIS, has the most user-friendly interface, is capable of data manipulation like all of the other software, but is the best at cartographic design (GIS Geography 2016). Iowa's Department of Natural Resources recommended QGIS to small water systems and provided free trainings on its use (SmallWaterSupply.org 2012). Also, the Institute for Mapping Technology selected QGIS as their preferred software (2010). For these reasons, QGIS was selected as the software to be used in this project.

1.4 Project Area

The Descanso Community Water District (CWD) is a CWS located in Descanso, a small census-designated place in the Cuyamaca Mountains, within the Mountain Empire area of southeastern San Diego County, California. They are located at 32.855174°, -116.616322° at an elevation of 3,450 feet. The service area covers approximately 19 square miles, all land. Figure 1 displays the location of the Descanso CWD. The Descanso CWD provides potable drinking water to a population of 870 residents via 307 residential and 15 commercial service connections. The Descanso CWD does not utilize GIS and currently relies on engineering drawings that are not inaccurate, but do not accurately display updates to the system, which are drawn in by hand by employees. The Descanso CWD hopes to utilize GIS to replace their outdated maps but does not have the expertise to accomplish this in-house or the funds to hire a consultant to perform the work.

1.5 Thesis Organization

This thesis is comprised of five chapters. Chapter Two focuses on the background research necessary to give credence to the project, such as why particular software elements were chosen and how the methodology was determined. Chapter Three describes the steps taken to locate, obtain, and display the data necessary for case study in , particularly the use of GPS to locate field data and QGIS software in map production. Chapter Four provides the generalized workflow for the implementation of a GIS in a small CWS. Chapter Five discusses the positive aspects of the project and where it could be improved. This chapter also describes how this project could be furthered by continued research.
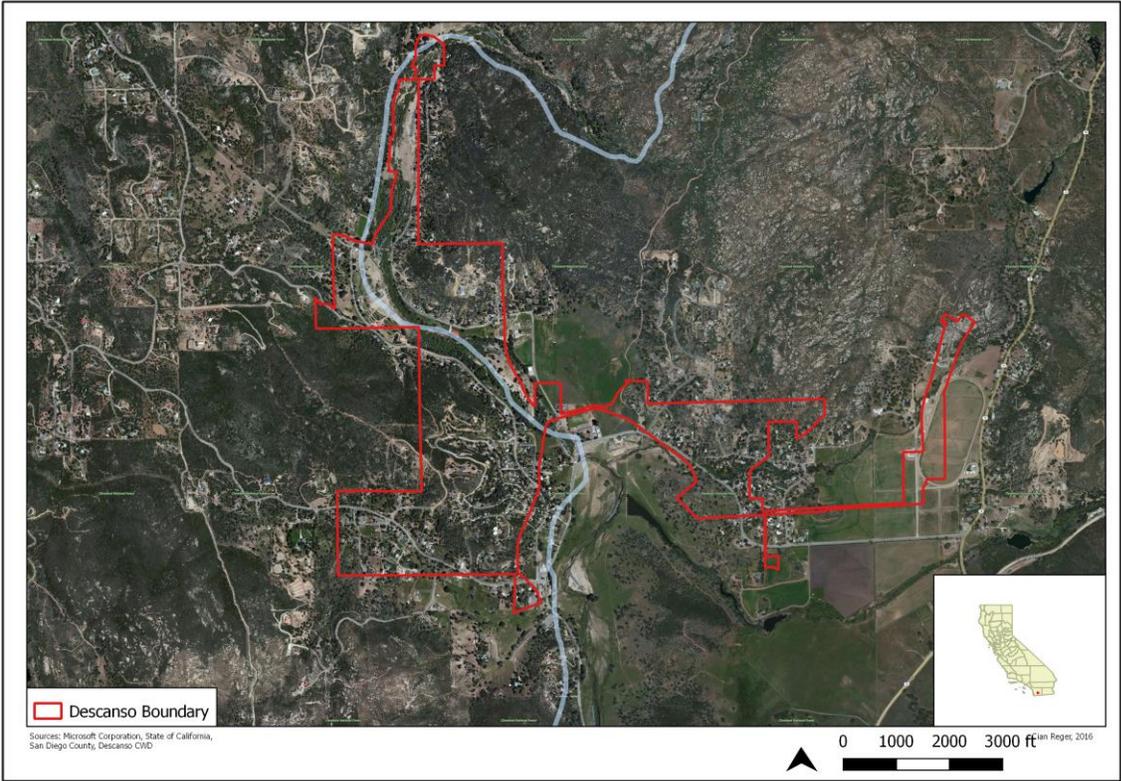
Figure 1 The location of the Descanso Community Water District

Chapter 2 Literature Review

What sets GIS apart from other mapping technologies the ability to relate data to a location. In a water utility, a large majority of the utility's data is tied to location. It is important that a utility know where their infrastructure is located, which a well-designed GIS allows. A GIS also allows for the utility to relate attribute data to these locations. How this data is collected, stored, and manipulated is different for each utility. Data can be created by digitization from existing maps or collected in the field using a GPS receiver. Many different software packages exist to view, manipulate, and display the data, but they all fall into two categories: open source or closed source software. Proprietary GIS software, especially Esri's ArcMap, is most commonly used in GIS implementation projects, and there no records of open source (commonly known as freeware) GIS software being used for the same task. A utility's data can be stored in various formats, but the most common are shapefiles and databases. Storing spatial data in a shapefile was once the industry standard, but relational databases have proven to be a more efficient method. However, shapefiles are what this thesis project is going to use because of their simplicity. Simplicity is necessary for this project as the finished product will be handed over to an employee of the Descanso CWD, who will be trained to use the GIS software. To ensure the employee is capable of maintaining the data, their proficiency in the use of the GIS software will be evaluated.

Literature in the realm of GIS implementation for utilities can be found in various forms, such as peer reviewed journal articles, student theses, technical manuals, and GIS textbooks. Of the four studies of GIS implementation located, only one involves small systems, which is considerably larger than the Descanso Community Water District. Literature pertinent to why and how GIS is used in water utilities, open source GIS options for water utilities, data storage,

and GPS data collection are included in this chapter. This chapter also includes case studies centered on GIS implementation in water utilities.

2.1 GIS in Utilities

In 1999, Cannistra wrote that most utilities throughout the United States are currently employing or planning to implement a GIS. While there are no available statistics to prove it, it is arguable that most large utilities use GIS in one form or another. However, from my own experience in California, this does not hold true for small CWSs, where many rely on paper as-built maps. Digital mapping software has been in use in the utility industry since the late 1970s. The effort to digitize a utility's infrastructure first focused on computer-aided design/drafting (CAD) software (Longley et al. 2005). This system became known as Automated Mapping/Facilities Management (AM/FM), which remains an industry standard. However, the limitations of the system became apparent when users attempted to link graphical features to databases. The result was a push towards GIS, which was made popular in the early 1980's by land and natural resource management users (Coppock and Rhind 1991). By the late 1980's AM/FM users began using GIS because of its ability to spatially relate features to a database, as well as map infrastructure. As GIS technology improved, it became more of an information system rather than a mapping system and is now used in conjunction with AM/FM (Longley et al. 2005). GIS allows utilities to create features with attribute data, enforce a topology, and create printable maps.

Implementing a GIS is no simple task, as numerous steps must be taken to ensure that it is done properly. Huxhold and Levinsohn (1995) identify six properties that ensure success in a GIS implementation: planning, application driven, organization, end-user participation, measurable objectives, and effective documentation. While Tomlinson (2007) further describes

ten stages for implementing GIS in small and large systems, Fellers (2013) noted in his writing that not all ten steps are necessary for a small system, as the size and the nature of the water system dictate which stages are the most necessary for the implementation. The stages that benefit small systems are conducting a technology seminar, describing the information products through a needs assessment, creating a data design, determining system requirements, and planning the implementation.

GIS implementation can be cost prohibitive to small systems. As such, small systems often rely on engineering consulting firms to create maps for them at a high cost. Because of the cost, maps are not updated regularly and can become outdated. In many cases, paper maps are updated by hand by utility personnel (Crawford 2012). Lyon and Clifford (2008) documented this at the Hardin County Water District No. 1 (HCWD 1). HCWD 1 only had two paper maps of the entire system, which did not show any improvements or updates. Because of this, HCWD 1 was out of compliance with the mapping requirements of the Kentucky Division of Water. Many small water systems could benefit from a GIS as it could replace their outdated maps, or in the case of systems with no maps, become their mapping system, as well as create a database for the water systems infrastructure. (Fellers 2013).

2.2 Spatial Data Collection Methods from Previous Studies

To properly determine the best methods of collecting data, previous studies similar to this should be looked at to see how other utilities collected data. Rayburn (2004) implemented a GIS for the City of Lufkin, Texas, which maintains water utilities to both residential and commercial users through nearly 674 miles of water main. Before the implementation, the city already maintained an extensive GIS database of its wastewater facilities, but had no data for the majority of its water infrastructure. The Four Season Subdivision was new construction, so data

on valves and hydrants had been collected for the area. This area was chosen as a pilot project for the city to build its water GIS. Meter location data was collected using a sub-meter accuracy Trimble GPS unit, and water mains were digitized by referencing as-built maps and existing CAD files, and connecting valve locations (Rayburn 2004).

Lyon and Clifford (2008) documented the implementation of a GIS for the Hardin County Water District No. 1 (HCWD 1). HCWD 1 maintains water, wastewater, and stormwater utilities in Hardin County, Kentucky. In order to get back into compliance with the Kentucky Division of Water, HCWD 1 began the process of creating a GIS. In the first phase, HCWD1 utilized sub-meter accuracy GPS units and field staff collected the infrastructure data. Post processing of the data and shapefile creation was completed by a contractor, who then sent the data back to HCWD 1 to use the data to digitize water mains. Later, in HCWD 1 began upgrading its GIS and purchased more accurate sub-foot GPS units, similar to what will be used in this project, to collect any new data (Lyon and Clifford 2008).

Crawford (2012) also documented the implementation of a GIS for the City of Calhoun, Georgia. This utility maintains water, wastewater, and electric utilities and provides water to nearly 20,000 customers through over 800 miles of water main. The City of Calhoun utilized existing data collected by a sub-foot RTK GPS, which included valves and fire hydrants. Meter location data was collected using a sub-meter accuracy GPS unit, which was post processed to ensure a higher accuracy. The valve locations were used as reference points to aid in the migration of water line data from CAD to GIS. For background data in the GIS, the city utilized aerial drawings as well as a hillshade raster (Crawford 2012).

Common field data collection methods exist between all of these GIS implementation projects. High accuracy GPS was used to collect field data, which included the locations of

hydrants and valves. These locations were imported into a GPS and used as reference points to aid in the digitization of water lines. The majority of the attribute data, when it was discussed, was also common among the implementation projects.

2.3 Open Source GIS

Before there can be any talk of what implementing a GIS, the term "open source" must first be discussed. It is important to know the difference between the terms freeware and free, or open source, software because they can sometimes be misused. Freeware is a computer software that is offered for use at no cost, while open source software can be "used, copied, studied, modified, distributed and redistributed in a modified or unmodified form, without any restriction" (Kepoglu 2011). The distinction between open and closed source software must also be made. A software's source code instructs the computer to carry out certain functions, and by altering this code, programmers can modify, fix, or add other functions to the software. Closed source, or proprietary, software code is made unavailable to the consumer as it is considered proprietary. Open source software, however, is made freely available to the consumer and can lead to a collaboration that results in software that is constantly updated, fixed, or improved (ITG 215).

The history of open source GIS extends back to the late 1970s with the advent of GRASS by the U.S. Army Corps of Engineers (McKee 2012). Now there are numerous open source GIS software options available, such as SAGA GIS, gvSIG, and QGIS, which was selected for this thesis project. After an exhaustive search for literature involving the use of open source GIS software in the implementation of a GIS in a utility. There are, however, numerous examples of QGIS being used effectively to create thematic maps of user collected data. Skoglund and Matsuoka (2013) of the Norwegian Polar Institute created the "Quantarctica" database, a

collection of Antarctic geographic datasets, using QGIS. They used QGIS because it was low cost and easy to use, and have examined geographic data at all scales, layered scientific data over base maps, and prepared maps for publication. The most similar example project was performed by Jarrett Totton (2013), a volunteer with the Fundy Hiking Trail Association Inc. (FHTA). Totton used a GPS receiver to map the Fundy Footpath in New Brunswick, Canada, as well as point features, such as campsite locations. He imported the data into QGIS and created thematic maps of the trail system. Although QGIS may not be as popular as its closed source counterparts, these projects highlight its ability to create high quality maps.

The two software types are sometimes perceived very differently; open source is seen as flexibility, and proprietary is seen as usability (Optimus Information 2015). Open source software consumers are often seen as an "open, collaborative community of like-minded professionals who come together to crowd-source ideas and build great things" (Backaitis 2013). There are many pros to open source software, such as the ability to try the software before deciding which will be used, support is generally free, usually in the form of detailed documentation, forums, wikis, newsgroups, email lists, and live chat, and vendor lock-in is avoided. Also, because the source code is open, more people will be looking through it, so there is better chance that more bugs are exposed compared to the code from a proprietary vendor that most likely has a smaller development staff (Optimus Information 2015). However, the main drawback to open source software is usability. Most open source software packages are aimed at skilled end users and may require coding knowledge to use them.

Similarly, there are many pros to proprietary software, such as product stability and a sense of ownership. While open source software support is usually community based, proprietary software support is specifically designed and honed for their product. Since the support is in-

house, training for support is more complete and accessible. Unlike open source software, proprietary software's biggest pro is usability. Proprietary software packages are focused on a smaller group of end users, so they are generally more user friendly. The biggest drawback to proprietary software is that the source code is closed. The end user of this software cannot make any changes or customizations to it to suit the user better (Optimus Information 2015).

2.4 GIS Training and Evaluation Methods from Previous Studies

To ensure a GIS is being maintained properly, a trained GIS professional would be the obvious choice to perform the work. However, this is not a possibility at many small utilities because of budgetary constraints, so an employee may need to be trained to perform the necessary tasks in maintaining the GIS. Michelle Lin (2016) aided in the implementation of a GIS at the Pacific Symphony to locate potential performance locations based on heat maps of their customer base. Lin created step-by-step guides for teams of employees of the Pacific Symphony on how to use Esri's GIS Online and Business Analyst Online. She also held webcasts for specialized training, where she guided the teams step-by-step through exercises. To ensure their comfort with each task, Lin had each team leader perform the exercise alone before the webcast was over. After the training was completed, she provided a questionnaire to each employee to gauge the success of the training. The feedback provided from these questionnaires pushed Lin to expand her training guides as the users felt the software was not intuitive and needed more guidance. In the end, the necessary analysis was performed by only two of the employees, as the others did not have enough time due to other work, or did not feel comfortable performing the work. (Lin 2016). For this thesis project, instead of creating a step-by-step guide, existing QGIS training materials will be utilized by the Descanso CWD employee.

Chapter 3 Case Study: Development of a GIS for the Descanso CWD

A case study must first be completed in order to develop the generalized workflow for the creation of spatial data sets for rural water communities. The first step in any data collection process is to determine what the end user wants and how they will use the data. After that a desktop evaluation of the water system must be completed, to determine what features will be collected, through the examination of existing maps and discussion with the CWD employees. Field data can then be collected and imported into a GIS, so then the rest of the data can be digitized. After all of the datasets are complete maps can be created.

3.1 User Needs Assessment

A meeting was held with the Lead Operator of the Descanso CWD, Julie Seevers, and the Lead Field Tech, Travis Creamer, in June 2016 to determine what the CWS wanted out of the GIS. Many options for how the GIS could be prepared and used were presented to them. Being a small system, they decided that using a GIS to create their maps and provide a database aspect was all that was needed since they did not have the expertise or funding to continually update it. This led to the idea that one of the Descanso CWD employees learn to use the GIS software. Julie decided to move forward with the idea and Travis Creamer volunteered to learn how to use the software. During this meeting the existing map of the system looked over and which features would be surveyed were selected, including sources, storage tanks, valves, hydrants, meters, and other minor features, such as air vacs and blow offs. It was also decided that an atlas and a wall map of the system would be created. The staff of the Descanso CWD expressed excitement for the project at the conclusion of the meeting and were looking forward to beginning the project.

3.2 Source Data Evaluation

In designing the methods for this case study, it was important to determine what data would be collected in the field and what would be created at the desktop. This information will be used to identify the best survey route as well as what attribute data is available for each feature. A desktop investigation performed first to identify what infrastructure records the Descanso CWD has. The previous operators had created a set of CAD maps in April 2008 which displayed the locations of residential meters, valves, hydrants, water sources, storage tanks, and other minor features, such as blow off valves and air vac devices. Based on these maps and input from the Descanso CWD employees, a list was created that contained features, and their associated attribute data, which were to be included in the GIS. Table 1 displays the features and attribute data to be collected during the field data collection.

Table 1 Features and data to be collected in the field

Feature	Attribute Data
Water Sources	Source ID GPS Location GPS Date Source Type Depth (if applicable)
Water Storage Facilities	ID GPS Location GPS Date Capacity Construction Material Date Constructed Condition
Valves	ID GPS Location GPS Date Size Manufacturer Type Valve Position

	Date Installed
	Notes
Fire Hydrants	ID
	GPS Location
	GPS Date
	Color
	Manufacturer
	Type
	Size
	Date Installed
	Notes
Water Meters	ID
	GPS Location
	GPS Date
	Construction Material
	Manufacturer
	Type
	Size
	Date Installed
	Notes
Water Lines	Type
	Material
	Size
	Date Installed
Other Features	Type
	GPS Location
	GPS Date
	Color
	Manufacturer
	Size
	Date Installed
	Notes

During the examination of Descanso CWDs existing maps, it was observed that several point features were considered "Lost" by the previous survey. Figure 2 displays an example of a lost feature in the existing maps. The CWDs employees were aware of the issue and had located several lost features and when the possibility arose, they would spend time attempting to locate them. It was determined that during the survey, attempts would be made to locate lost features. It was also noted that CWD employees had drawn in changes made to the system on their own

maps. All of these changes would be included in the GIS. The existing maps also labeled each

meter with its serial number, which were no longer consistent as many of the meters had been

changed. The CWD determined that the meters were to be labeled with the customer number

instead, which would allow for easier identification and cross-referencing.
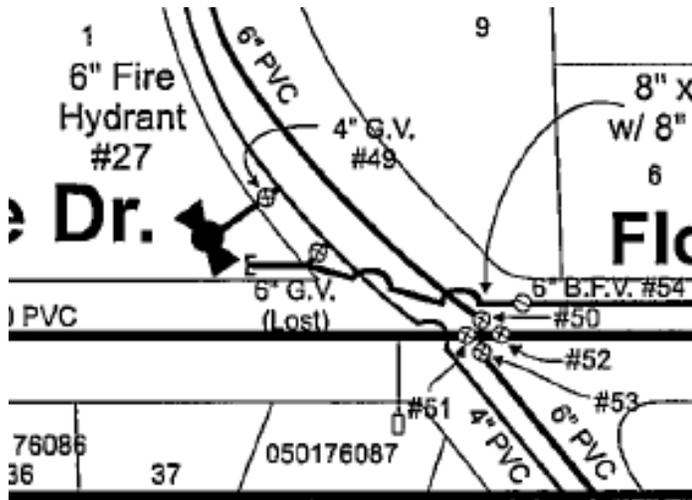
Figure 2 Example of a lost feature in the Descanso CWDs existing maps

3.3 Data Collection and Preparation

When preparing for the data collection portion of this project is was perceived that the majority

would be from field collection, and that the only data that would be digitized were water lines

and any features unable to be surveyed. For this project, a Trimble Geo 7 series GPS unit, on

loan from the University of Southern California, was used to collect field data. To ensure that the

field data collection went smoothly, a data dictionary was created using Trimble's GPS

Pathfinder Office. Field data was collected over three days, and after each day of collection, was

post processed in GPS Pathfinder Office.

3.3.1. Data Dictionary Creation

Using the information from Table 1 as a guide, a data dictionary was created using Trimble's GPS Pathfinder Office. The included features were water sources, storage facilities, valves, fire hydrants, residential meters, and other features. The attributes listed in Table 1 for each feature were included. When creating the attributes, it was possible to make custom menus in the software to make data collection faster. Figure 3 displays an example of the features and attribute data selected for the data dictionary. For valve features, a list of valve types (gate, butterfly, globe, etc.) was created with gate valves being the default, as they were the most prominent type in the system. Another menu was created for valve diameter, which was based on the sizes noted in the existing maps. The same custom menus were created for fire hydrant type and size, as well as meter size. In hindsight, it would have been useful to create these menus for both hydrant and meter manufacturers as there were only a few for each. The date and time of collection, as well as the GPS coordinates, were automatically filled in for each point. Also, the data collection time for each point was set to 30 seconds. After the data dictionary was complete it was loaded into the GPS unit and tested in a local neighborhood to ensure all of the menus were sufficient.

3.3.2. Field Data Collection

Field data collection commenced at 7:00 AM on Monday, August 29, 2016. A tailgate meeting was held with the Descanso CWD field staff that would be working with me over the next few days to determine the best route. It was decided that their meter reading route would be followed. Not only did it allow for the fastest path through the community, it also allowed for the easier determination of which meter belonged to which address, as customer ID numbers

were arranged in their database according to their meter reading schedule. This database was printed out, along with a set of the existing maps, to help identify the appropriate features.
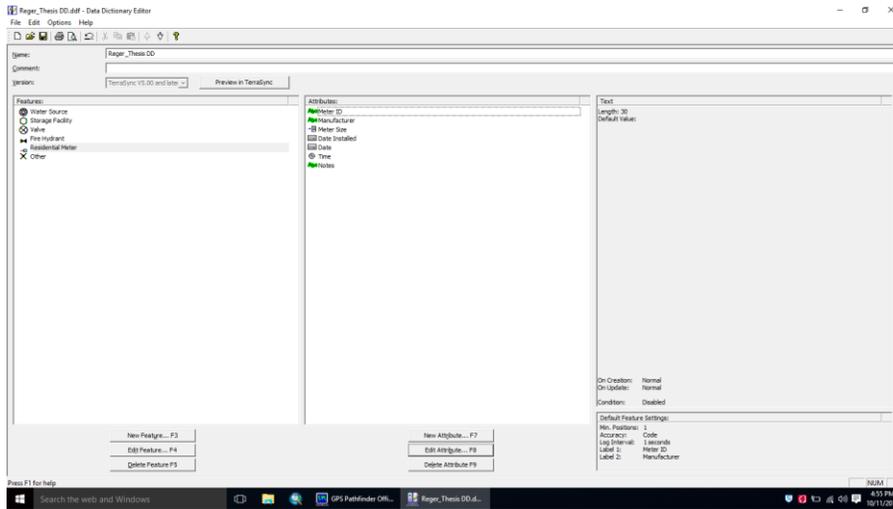
Figure 3 An example of the features and attribute data in the data dictionary

The GPS was mounted to a pole using a bracket to ensure a consistent position during data capture, and data collection started in the northeast section of the community along Highway 79. Figure 4 displays the boundary of the Descanso CWD. Feature points were captured as they were located, and as much attribute data as possible was collected into for point. Data was collected only after the GPS was within 20 cm accuracy, and if a feature was obscured by vegetative cover, the offset method was used to capture the point. If a buried feature could not be located with a metal detector, it was noted on the paper map to be digitized and labeled "Lost" so it could be located in the future. Data collection continued along Viejas Boulevard, including the Well 6 site, to Manzanita Lane. Day one ended after all of the points on Manzanita Lane., Guatay Road and Oak Lane were collected.

At the end of each day, and when all data collection was complete, data was downloaded from the GPS unit to GPS Pathfinder Office. The National Geodetic Survey Continuously Operating Reference Station (CORS) at Monument Peak was selected for post processing as it

was the nearest station at 16 kilometers away. Although it was some distance away, it maintained

an Integrity Index of 92.38. This station provided 100% coverage of the data, and corrected 88%

of the 15,878 collected points to 50 cm or less. After post processing, the data was exported to

shapefile and ready to be imported into a GIS. In total, 576 individual feature locations were

collected; 2 wells, 2 storage tanks, 189 valves, 309 meters, 70 fire hydrants, and 4 other features.
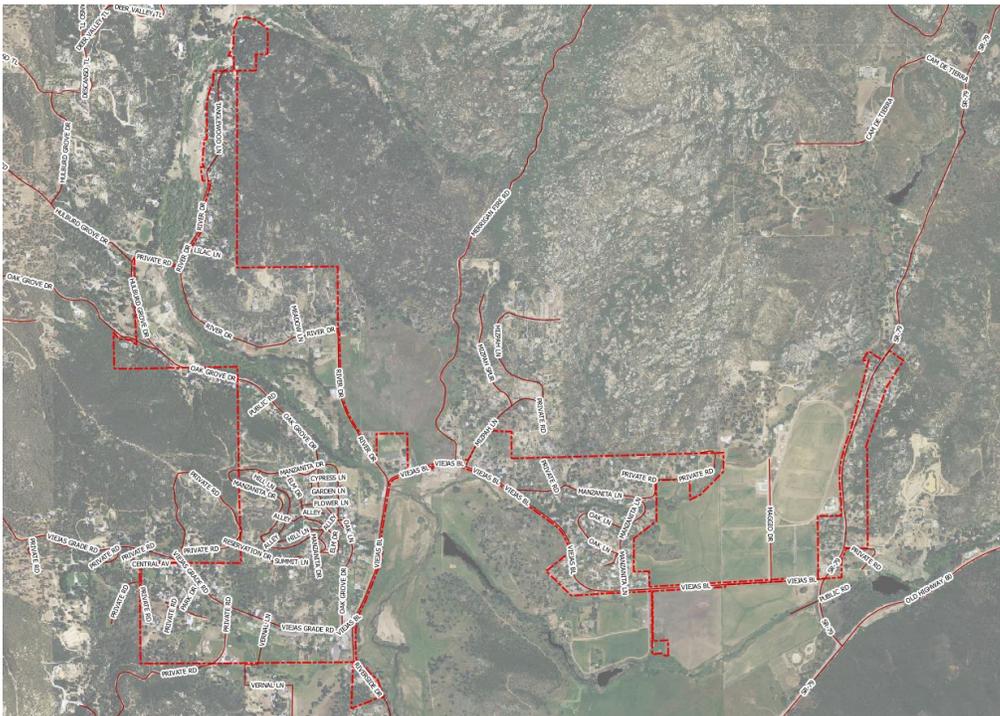
Figure 4 Boundary map of the Descanso Community Water District

3.4 Creation of a Water System GIS for the Descanso CWD

Before any data manipulation was attempted, a data storage method needed to be determined.

After the creation of a database in QGIS was attempted and abandoned, shapefiles were chosen

to be the data storage method. The corrected field data was imported into QGIS so water lines

and other features could be digitized. However, it was discovered that QGIS does not have a

snap to point capability, so Esri's ArcMap 10.4 was used for all digitizing of data, as this

software allowed for snapping to points. After all digitizing was completed a quality control check was performed on all of the data to ensure that no points or lines were missed.

3.4.1. Use of Shapefiles Versus Geodatabase

      In QGIS there are two primary methods of storing spatial data, Esri shapefiles and databases, and for this thesis project, data will be stored in shapefiles. A shapefile is a storage format created by Esri that stores the shape, location, and attribute data of a feature. This format requires multiple file types to store all of the data. It is important to note that a database file for a shapefile cannot exceed 2 gigabytes, so large datasets may not be saved in one shapefile (Esri 2016-2). QGIS utilizes a database plugin, an individual feature that can be added after the initial software installation, that connects a user's relational database to the GIS software, creating a spatial database. Multiple rasters and vector features, including their shape, location, and attribute data, can be stored within the database. Database options for QGIS are PostgreSQL, PostGIS, and spatialite databases (QGIS 2013). All of these database software function similarly, but require the user to be knowledgeable in the creation and management of relational databases, as well as how to query these databases. Although a spatial database is a more efficient method of storing spatial data, shapefiles are not inefficient and are a simpler method of storing data. While most studies of implementation of GIS in utilities involve storing data in databases (Rayburn, 2004; Lyon and Clifford 2008, Vega 2009, Crawford 2012, and Fellers 2013), these were large entities with budgets available for in-house technicians or contractors. An attempt was made to create a PostGIS database for the storage of this project's data, but the implementation required an extensive background in database management, so it was abandoned. A novice, such as the Descanso CWD employee, would not be able to complete this task. So, for this project

shapefiles were used as the data storage method. The employee from Descanso CWD that was trained to maintain the GIS was not a GIS or database professional, so simplicity is paramount.

3.4.2. Background Data

Background data was collected before any data manipulation commenced. There are many potential sources for background imagery, either through QGIS or from online repositories. In QGIS, Open Street Map, Google imagery, and Bing imagery are available through the "OpenLayers" plugin. However, the Bing and Google imagery could not be printed due to copyright restrictions and the Open Street Map imagery was not an aerial. The State of California hosts the USDA National Agriculture Imagery Program (NAIP) data, which provides one meter resolution aerial imagery (Farm Services Administration 2016). Each county image is broken up into quadrangles, which can be downloaded individually. The appropriate quadrangles from 2014 were identified and downloaded, imported into QGIS, and merged into one raster file (CalAtlas 2016 - 1).

Other datasets were also sourced to provide further background information, such as the Descanso CWD service boundary, parcel information, and road locations. The service boundary was sourced from the CalAtlas geoportal (CalAtlas 2016 - 2), and the parcel and road datasets were obtained from the SanGIS/SANDAG GIS Data Warehouse and imported into QGIS (SANDAG, 2016)

3.4.3. Digitizing Data

It was intended that QGIS version 2.16 would be used to perform all of the GIS work for this project. It was selected because it is user-friendly, has a well-made and easy to follow tutorial, and is free. This software was thought to have the ability to create and modify all of the necessary vector features and attributes that were created during this project as well as produce

print quality maps. However, one of QGISs flaws became apparent when digitization began, which is that points cannot be snapped to in an editing session. So, the digitization of water lines had to be performed in Esri ArcMap 10.4. Snapping lines to points was a necessary function for this project to have the possibility to create a geometric network in the future.

To ensure all of the data would display correctly, all of the shapefiles were projected to the NAD83 California State Plane Zone VI projected coordinate system, and the data frame was set to the same projected coordinate system. The 2014 NAIP aerial image and parcel map were added to the data frame as visual aids for digitizing the water lines. The parcel map was generally congruent with the areas of the aerial it overlaid, except for hilly areas, where the two datasets did not line up. It is unclear as to why this distortion occurs, but the field data points aligned with the aerial. As a result, the aerial was used more frequently as a basis for the location of digitized lines.

The data associated with water lines can be difficult to obtain because records can be lost or, in the case of the Descanso CWD, destroyed by moisture. Depending on the age of the water system, many different types of pipe of different materials may be in the system, as was the case of the Descanso CWD. This information was collected from the existing maps and water system operator knowledge. This methodology was used by Rayburn (2004) Lyon and Clifford (2008), Clifford (2012), and Fellers (2013). The expert knowledge of Descanso CWD field staff proved to be invaluable in identifying the locations of water lines in the GIS. In general, the employees were in agreement with the locations drawn on the existing maps. However, they did point out various incorrect locations. The correct locations were drawn on the hardcopy maps and included incorrect sizing or construction material, and areas where new pipe had been installed.

There are three types of water distribution systems: looped, grid, and branched. Looped and grid systems are the optimal layouts as they provide better water flow for fire protection and minimize dead-end lines. Branched systems are not optimal as they result in dead-ends on every line, which can result in bacteriological, taster, and odor problems. Frequent flushing of these dead-ends is required to minimize these problems, which results in extra work for system employees and wasted water. The Descanso CWD is a combination of a looped and branched system, where the large mains are looped and the laterals running to service connections are branched.

In ArcMap, an editing session was started and the digitization of water lines began in the northeast section of the water system, which followed the same route as the field data collection. Lines were drawn in similar locations to those found on the existing maps and in some locations, where the water system employees noted the location to be. The most common suggestion from Descanso CWD employees was that most water lines were located in the dirt shoulder. As lines were draws they were snapped to any valves or other features, such as air vacs or blow offs, that were encountered. Figure 5 displays an example of digitizing water lines in ArcMap.
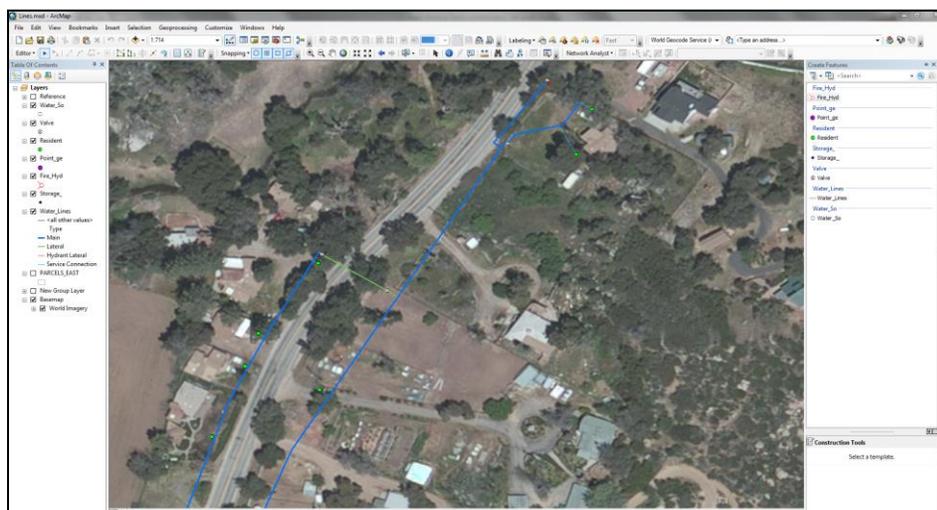
Figure 5 Example of digitizing water lines in ArcMap

The attributes for water line features follow those in Table 1. Water line segments were digitized by size, type, and construction material. After a line segment was digitized the size was input as well as the type and construction material. The 'Type' attribute was broken down into 5 different water line types: main, high line, lateral, hydrant lateral, and service connection. Main lines are the larger lines (6" – 8") that run down the main streets in the water system and provide the bulk water flow. A high line is a temporary main that runs above ground and provides water flow during construction. Laterals are smaller lines (2" – 4") than the mains that serve as arteries to the service connections. Hydrant laterals are water lines, usually the same size as the fire hydrant, that connect fire hydrants and their control valves to mains or laterals. Service connections are small water lines (1/2" – 1") that connect mains, laterals, or hydrant laterals to residential water meters. Water lines were also classified by construction material, such as iron, steel, asbestos concrete, and PVC. In total, 477 water line segments were digitized; 54 mains, 1 high line, 51 laterals, 63 hydrant laterals, and 308 service connections.

Other features also had to be digitized, such as lost valves. Any features that were noted as "lost" during the field survey digitized in ArcMap. These features were snapped to the digitized water lines in the location that was identified from the existing maps. Attribute data was entered for each point as it was created. Figure 6 displays an example of the attribute table and attribute data entered in the GIS.

On Friday, September 2nd, a large leak occurred in the area behind Descanso's Town Hall. A 2" steel line collapsed and the building lost service. The line ran to a meter at the back of the building, but the exact location was unknown, so the line was cut above the collapsed section and capped. A new service connection was run from the high line in the street in front of the

Town Hall to a new water meter at the curb. The exact location of the service connection and

meter were unknown, but were digitized based off of modified drawings of the existing maps.

Figure 6 An example of attribute data entered into GIS

Metadata was also created for each dataset using the QGIS metadata assistant. The

information in the metadata included a title, description, keywords, storage type, geometry,

number of features, extent, and reference system. Figure 7 displays an example of the

information entered into the QGIS metadata assistant.

Figure 7 Example of the information entered in the QGIS metadata assistant

3.5 Map Output

After the features and associated attribute data were collected and post processed, a data storage method was selected, and water lines had been digitized, maps were created. Two types of maps were created for the Descanso CWD using the background, collected, and digitized data described above. A large scale atlas comprised of twenty-three 11" x 17" pages was created to allow the field staff to easily identify individual system components. A single page 3' x 5' map was also created to be hung on the CWD's office wall. This is a common practice in water systems as it allows for daily planning of work activities and is an excellent quick reference map.

3.5.1. Styles and Labeling of Features

Before any maps could be created with the data, the style and label for each feature type was selected. Point feature styles were selected from the choices of simple shapes in QGISs style manager menu. Each feature was given a specific icon with a unique color, which can be seen in Figure 8. Line features were displayed by category, main, high line, lateral, hydrant lateral, and service connection. The lines were displayed with different thicknesses based on the category. Main, high line, lateral, and hydrant lateral were displayed with thicker lines, and service connections were displayed with thinner lines. Figure 8 displays the style elements selected for each feature. Some of the background features were also displayed. The boundary of the Descanso CWD was displayed using a dot and dash red line, and the parcel features were displayed using a dark gray line. The street lines cluttered the map, so they were displayed with no color to allow for the streets to still be labeled.
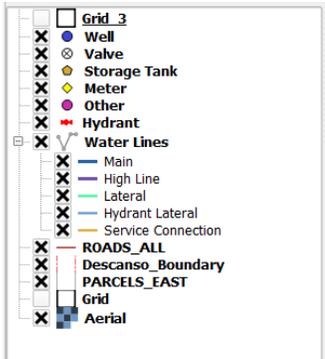
Figure 8 Style elements for each feature

The Descanso CWD requested that each feature be labeled for easy identification in the field. Because some features were spaced so tightly together, small fonts had to be used to ensure their placement. The point features were displayed using a six-point font and were placed around the point with a 1.5 millimeter offset. The line feature labels were also displayed using a six-point font, but were placed on the line. To make each label more easily identifiable over the aerial imagery, all of the labels were created using a white halo.

The text used for the labels was derived from the attribute data. Some of the feature labels only required information from one column of attribute data, while others required several. The well features were labeled using the 'Source _ID' data, the storage tank features were labeled using the 'Facility_ID'' data, the meter features were labeled using the 'Meter_ID'' data, the other features were labeled using the 'Comment'' data, and the road features were labeled using 'RD20FULL' data. The valve features were labeled using the expression "Valve_ID || '\n' || "Valve_Diam" || "Valve_Type"'' so the identification number, diameter, and type would all be displayed. Hydrants were labeled using the expression "Hydrant_ID || '\n' || "Hydrant_Size" || "Hydrant_Type"'' to the identification number, size, and type would all be displayed. The water line features were labeled using the expression "Size || Material" so size and construction material would be displayed. The parcel features were labeled using the conditional expression

"if(ADDRNO > 0, ADDRNO, " ")" so that parcels with no address numbers, which have a '0'

entered in the attribute table, would not be displayed.

3.5.2. Atlas

The purpose of an atlas is to break up a large area into smaller, more detailed maps. This

is a multi-step process in QGIS. A grid that overlays the area of interest must first be made. This

grid will be used to generate the detail maps, one map for every feature in the grid. The grid was

created in the QGIS map view by selecting the 'Vector Grid' function under 'Vector > Research

Tools'. The grid extent was based on the 'Boundary' shapefile and all of the defaults were

accepted. The output was a 28 square grid, however, five of the points contained no features, so

they were deleted. Figure 9 displays the grid used for the creation of the atlas. These boxes were

then numbered sequentially in the data attribute table.
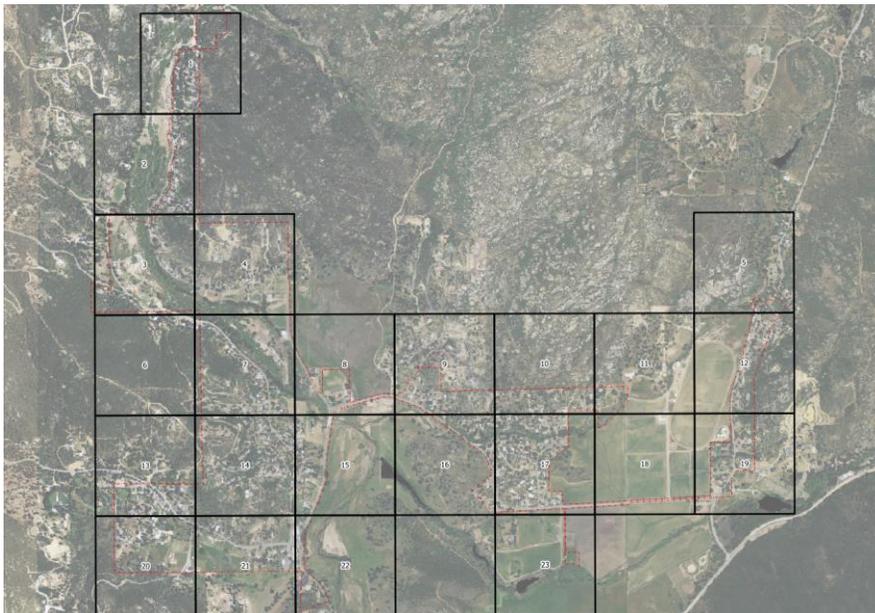
Figure 9 Final grid used for atlas creation

In QGIS, creating a printable map is done in a 'Print Composer' window. A new

composer was created and given a name, in this case 'Atlas'. The page size was determined

before any components were added to the composer. The Descanso CWD wanted the maps printed on 11" x 17" paper to be large enough to read in the field. Paper size was selected in the 'Composition' tab and the orientation was set to landscape. The first component added to the composer was the map. The 'Grids for Atlas' plug-in allows for the creation of grid layers that can cover the extent of the coverage layer (Chaussat 2015), and by selecting the 'Snap to Grid' setting in 'View' the map was snapped to a point in the upper left corner and sized to fit the page. The map only took up two-thirds of the page to allow space for the other map components. In order for the atlas to be created, 'Controlled by Atlas' was checked in the 'Item Properties' tab, and the margins around each feature was set to 10%. This created a 10% overlap between each map page. Under the 'Atlas Generation' tab, the grid created before was selected as the 'Coverage Layer' and it was set as a 'Hidden Coverage Layer'. The 'Page Name' was set to the 'Page' column of the grid's attribute table, which allowed for each atlas page to have a corresponding page number. Figure 10 displays the selected settings in the 'Atlas Generation' tab.
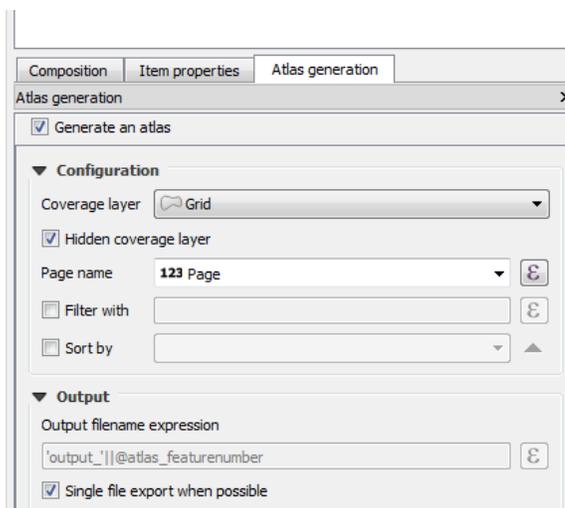
Figure 10 Selected settings on the 'Atlas Generation' tab

Before the atlas was created, all of the required map components were placed on the map canvas. This included a title, legend, scale bar, north arrow, source data and author text, page number, neat line, and inset map. The inset map was created to act as a reference to what atlas page was being viewed. In the 'Item Properties' tab, under 'Overviews', a new overview was created and the defaults were accepted. This created a colored box in the inset map that would correspond to the atlas page being viewed. Figure 11 displays the inset map containing the grid with the overview box.

After the map components were placed in their optimal locations, the 'Preview Atlas' button was selected to ensure that all of the grid placement was appropriate and the overview box moved to the correct corresponding grid. The final step was to export the atlas, which could be saved as individual images, or a single .pdf file. The Descanso CWD requested a .pdf file, so that method was selected, which resulted in twenty-three atlas pages in one .pdf file.
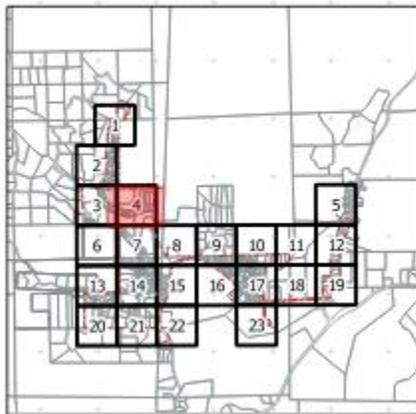
Figure 11 The inset map with grid and overview box

The atlas was presented to the staff of the Descanso CWD who looked it over to see if any changes were necessary. They decided that only names, no lines, were needed for the street layer as it crowded the map. The change was made in the map window, and the main map was

updated in the print composer by selecting 'Update Preview' in the 'Item Properties' tab. The atlas was then exported again as a final product and sent to the Descanso CWD.

3.5.3. Wall Map

The Descanso CWD also requested one 3'x 5' small scale map be created to hang on its office wall to use as a reference map. This map was created in QGIS using methods similar to those used to create the atlas. A new print composer was created and labeled 'Atlas'. The page size was set to 3'x 5' in landscape orientation. A new map window was added to the composer window and set to fit the entire window using the snap to grid function. The layers included in the map were the system boundary, streets, water sources, storage facilities, valves, hydrants, meters, water lines, and other features.

The necessary map components were added to the composer window, including a title, legend, scale bar, north arrow, source data and author text, and neat line. Each component was optimally located so as not to obscure the data. The map was exported as a .pdf file, as requested by the Descanso CWD, and presented to the employees for approval. The map was approved, so no changes were required.

3.6 Employee GIS Training

One of the goals of this project was to have a Descanso CWD employee learn how to use the QGIS software to update and/or create new datasets for the CWS in house. Travis Creamer volunteered to complete chapters one through six of the QGIS Training Manual (QGIS 2016). Table 2 displays the chapter topics covered in the training manual.

Table 2 Chapters and topics of the QGIS Training Manual

Chapter	Topic
One	Course Introduction
Two	The Interface
Three	Creating a Basic Map
Four	Classifying Vector Data
Five	Creating Maps
Six	Creating Vector Data

3.7 Time Accounting

A result of this case study was to create a generalized workflow for the implementation of a GIS in other communities that can be used by other GIS professionals in the water industry. In order to determine how long future projects may take, the time needed to complete this project was documented. This will allow for the extrapolation of time to determine how long similar projects would take for larger or smaller systems. The user needs assessment took three hours, and examining the existing maps and creating the data dictionary took six hours. Field data collection spanned three days. Each field day was comprised of nine hours surveying and one hour validating the data. Importing, correcting, and exporting the data took two hours. Sourcing and preparing the background data took four hours. Data digitization took 3 days, with each day lasting eight hours, and map making took four hours. Final edits to the maps took 2 hours. In all, this case study took 75 hours to complete.

This accounting of time will be used to gauge the length of time needed for future GIS implementations at small CWDs. However, this case study was a best-case scenario. The Descanso CWD had existing maps that were relatively accurate and new compared to other CWSs. Also, the field staff of the Descanso CWD were extremely knowledgeable about their system layout and features. Other potential project systems may not have any existing maps or a good working knowledge of the system, and may take longer to complete.

Chapter 4 Generalized Workflow for Creating a Community Water System GIS

Many community water systems (CWSs) rely on outdated maps of their infrastructure or have no maps at all. These systems would benefit the greatest from low cost GIS solutions, however they may not know the steps necessary to complete this themselves. The purpose of this workflow is to provide a framework for creating a GIS for these systems. This workflow describes the steps necessary to implement a low-cost GIS: user needs assessment, source data evaluation, field data collection, implementing a GIS, and map production. The intended audience for this workflow is water professionals working in or for small CWSs that may or may not have a background in GIS.

4.1 User Needs Assessment

To determine what data will be collected and how it will be displayed, a discussion must be had with all of the parties of the CWS involved in the GIS. Shamsi (2005) identified eight steps to this user needs assessment: identify stakeholders, talk to stakeholders, inventory resources, establish need priorities, create system design, create pilot test, prepare an implementation plan, and conduct the final presentation. Depending on the size of the system, not all of these steps may be necessary. For most small water systems, the most important steps would be to talk to the stakeholders to establish need priorities, inventory resources, and create a system design.

During the user needs assessment meeting, many questions will need to be answered in order to design an appropriate GIS. Every aspect of the project must be determined before it begins to ensure a smooth implementation. First, who will perform all of the work must be determined, whether it is will be in-house or outsourced. Next, any existing maps or spatial data

needs to be located and examined to determine the depth of the project. Examining the maps, or if a CWS has no maps, speaking to an employee who knows the system well, will help determine what features and attribute data will be collected and imported into the GIS. Field data collection methods, including the accuracy of the GPS, will be determined. GIS software choice, and who will perform the work is of vast importance. The choice between proprietary and open source GIS software can be a difficult one as it severely impacts the budget of the project. This choice also impacts how the data is stored. After these decisions have been made, what data will need to be digitized can be determined, as well as what types of maps the CWS wants.

4.2 Source Data Evaluation

In order to accurately locate and identify the underground features in a CWS, any existing maps and the expert knowledge of field staff need to be evaluated. Four possible scenarios exist when it comes to evaluating a CWSs existing data. A CWS may have no existing maps or spatial data, and may rely solely on the memory of the system employees to locate the various underground features. The second scenario is that a CWS has old paper maps that do not reflect all of the underground features currently in the system. The third scenario is that a CWS has newer maps but no spatial data. The final scenario is that a CWS has paper maps and spatial data that need to be updated.

The most difficult scenario for both field data collection and data digitizing will be when a system has no existing maps. Field data collection planning will have to rely on discussions with the CWS field staff to dictate the locations of the underground features. The field staff will also have to accompany the surveyor to aid in the location and identification of the features. Aid from system employees will also be needed in the identification of the attribute data of each

feature. A suggestion would be to have the CWS field staff draw a map identifying the locations of the underground features and include any attribute data they may want to include.

Data collection and digitization will also be difficult when a system has maps that are old and do not reflect updates to the system. Field data collection planning will rely on a combination of locating features on the existing maps as well as having field staff identify and updates to the system on the maps. Attribute data should be identified by field staff and included on the maps, which will allow for the GIS specialist to digitize data independently. If this step is omitted, then data digitization will most likely need to involve the aid of CWS field staff.

Both field data collection and digitization will be less difficult when a CWS has maps that reflect updates to the system, as was the case with the Descanso CWD. Field data collection planning could solely be completed by examining the existing maps, but including the CWS staff in the identification of features is still recommended. GIS digitization could also be completed without the help of CWS staff, but including them is recommended.

The final, and not necessarily best case, scenario is when a CWS has both updated maps as well as spatial data for the features in their system. The metadata of spatial data needs to be looked through first to identify when it was created and at what accuracy, as the steps necessary to complete the project are dependent on them. If the accuracy is sufficient for the CWS, then surveying digitizing only the updated parts of the system could be a solution. If the accuracy is not sufficient, then a full system survey, followed by digitizing all of the water lines, may be necessary. If no metadata is included with the spatial data, then it would not be recommended to use the data.

4.3 Field Data Collection

The majority of data needed for a GIS implementation will be collected in the field, so a GPS unit will be used to collect the data. For projects with a modest budget, higher accuracy GPS units can be used to collect data, although sub-centimeter accuracies are not necessary in water asset management due to the lack of emphasis on exact elevation (Rayburn, 2004). A low accuracy recreational unit can be used to collect GPS locations to keep costs low, but the best accuracy that can be achieved with these units is nine feet. This will most likely not be sufficient for water system data collection.

A high accuracy GPS unit could be purchased; however, these units can be very expensive. A Trimble Geo Series GPS unit could be rented for $540 per week from Duncan Parnell (2016) to keep the budget low while maintaining high accuracy. This unit has a 10 cm accuracy that will allow for accurate locations at about the same cost as a high-end Garmin handheld unit that only achieves 9 ft. accuracy. Although 10 cm accuracy is not necessary for all aspects of the survey, in certain locations of a water system, like T intersections where valves are clustered, a high accuracy GPS allows for high resolution data.

A high accuracy unit is also recommended because they can record both spatial and attribute data at the same time. This is done through the use of data dictionaries, which are created using special software included with the GPS unit. Trimble's GPS Pathfinder Office allows a user to create data dictionaries that contain features and attribute data. When imported into the GPS unit, the user can select which type of feature point is being collected as well as any attribute data for each point.

Before data collection begins, talk through the process with the CWSs field staff, as they know the system best. If possible, follow the staff's meter reading route, as this is usually the

fastest route through the system. If this is not possible, use mapping software (Google Maps, Bing Maps, etc.) to plan out the field data collection route.

What GPS type is selected will determine how data is collected. If a recreational GPS unit is used, a field notebook should be used to record the data, including latitude, longitude, and any attribute data associated with each point. If a high-end unit is selected, then the data will be stored in the unit and exported later. When collecting data with a recreational unit, ensure the WAAS option is selected, and allow the GPS to sit in a stationary location to obtain the most accurate reading. If a high-end unit is being used, a location collection timer can be set so that locations can be collected every second for a specified amount of time. In water applications, 30 seconds is sufficient. If possible, mount the GPS unit to a pole to help maintain an accurate position, and remember to position the unit over the feature when collecting data. How features are collected should also be determined before commencing field data collection. Regardless of what type of GPS unit is being used, it is recommended that feature locations be recorded as they are encountered to optimize the data collection time.

After each day of data collection, it is a good practice to import the data from the high-end GPS units to a computer. This is to ensure that the day's data has been saved if there is any failure of the GPS unit's memory. Depending on the manufacturer, the data may be able to be post-processed to improve its accuracy. Trimble's GPS Pathfinder Office allows the user to post-process the data using known local reference stations. Once post processed, the data must be converted to a file type that is usable in a GIS, such as a shapefile or geodatabase.

4.4 Design and Implementation of a Water System GIS

Choosing the GIS software that will be used for digitizing data and creating maps should be the priority for this part of the project. The requirements set by the CWD during the user

needs assessment will dictate what software will be used. The field collected data can be imported into the GIS and water lines, and any data not able to be collected during the survey, can be digitized. The appropriate attribute data should be entered while data is being digitized. All of the data should then be put through a quality assurance process to ensure the validity of the data.

4.4.1. Selecting GIS Software

The task of selecting a GIS software package to use for the implementation is not a simple one. Several factors need to be taken into account during the selection process, including cost, usability, technical support, and the intended use. There are several choices for each type of software, such as QGIS, GRASS GIS, and gvSIG for open source software, and Esri and MapInfo for proprietary software.

The most obvious, but not necessarily most important, factor is the cost of the software. Open source software is free to the end user, and proprietary software must be purchased. As of this writing, Esri's ArcGIS for Desktop costs $1,500 for the basic software. However, if a CWS is a 501c3 non-profit company, Esri has a program that offers the software free of charge, and only charges an administration fee to the company. In many cases, companies that have chosen to adopt an open source software package do so because they believe it is superior to the proprietary options. To these companies, cost is a secondary factor (Optimus Information 2015).

Generally, the intended user of open source software is someone with a strong computer background that has a knowledge of code writing (Optimus Information 2015). This may limit the number of CWSs that would use open source as they may not have a full-time technology professional on staff. Proprietary software companies, such as Esri or MapInfo, create software

for users of all levels that do not require knowledge of coding, although it may help. Usability may play a limiting role in the selection of open source GIS software for some CWSs.

The availability of technical support may also play a limiting role in using open source software in a CWS. These software producers are seen as more of a community than a company. So, technical support is usually provided through user forums, blogs, and wikis (Backaitis 2013). A user may get the help they need, but most likely in a longer timeframe. Proprietary software companies generally have a much more robust technical support capability, as their customers have to pay a fee for the product (Optimus Information 2015). An excellent example of this is Esri's technical support network. Consumers have the ability to call a technical support line or chat via text during normal business hours, or for an extra fee, twenty-four hours a day, seven days a week, all year round.

What may be the most important factor in determining which software type to choose is what ultimate goal the CWS wants to achieve. If the CWS is only interested in creating a basic GIS database and design maps for printing, then open source software may be sufficient. However, if CWS intends wants to create a robust database for utility network flow analysis or incorporate their GIS into an asset management program they would need to choose a proprietary software package.

4.4.2. Digitizing Data

Any data that was not collected in the field but is required to be in the GIS needs to be digitized using GIS software. Which particular data this includes will be decided in the needs assessment. There are various methods of data digitization, but for small systems heads-up digitizing and freehand drawing seem to be sufficient.

Heads-up digitizing is commonly known as rubber sheeting. This method of digitizing relies on a scanned image of the area being digitized. This image is lined up over the area of interest, the method of which varies by software, and the features are traced in an edit session and saved to the GIS. Freehand drawing is as exactly as it sounds: features are drawn in a GIS software using a map as a visual reference or from memory. This method benefits greatly from an accurate and up to date background image and help from the water system.

When digitizing data, it is important to create data that can be used for other purposes than map making. When drawing lines or locating point features, it is important to snap, or connect, the features being digitized to existing features. For example, when digitizing water lines, a node of that drawn feature should be connected, or snapped, to in-line valves or hydrants. Similarly, any digitized valves or hydrants should be snapped to water lines in their correct location. This creates a continuous water system, which would allow the data to be used to create a GIS utility network in the future.

One of the greatest benefits of using a GIS is the ability to store attribute data with spatial features. Any type of spatial data storage method, whether it is a shapefile or geodatabase, allows the user to store attribute data. Some of this data was collected during the field data collection. During digitization, this data should also be collected and entered when a new feature is created. It is recommended that the attribute table for the data being digitized be open during an editing session so that the attribute data can be entered when the feature is created. This limits any possible error that may occur from entering the data at a later point.

After all of the data is entered, it is good practice to perform some type of quality assurance or quality control check of the data. If the dataset size is small, all of the data could be checked. If the dataset is large, then checking a random sample may be sufficient. This check is

done to ensure that the entered data is correct and free from errors. A simple quality control check for hydrants is to compare the number of hydrant entries in that dataset's attribute table to the number of entries of hydrant laterals in that dataset's attribute table. The same can be done for meters and service connections. If a further check is required, then a topology can be run. How a topology is carried out varies by GIS software, but the basics are the same. A set of rules are created for individual data types, such as all points must be snapped to a line. These rules are tested on each feature in the GIS, and errors are tabulated, which the user can go through individually and correct.

It is also good practice to include metadata for each dataset. Metadata provides future users all of the basic information about a dataset, such as when the data was created, who created the data, how the data was created, what format the data is in, and what the data is. There are standards by which to create metadata, such as the Content Standard for Digital Geospatial Metadata (CSDGM) or the International Standards Organization (ISO) geographic metadata standard (19115). Which standard to select should be determined during the needs assessment. How this data is entered is dependent upon the GIS software, as each has their own methods.

4.5 Design of Map Output Products

To create a print quality map, several key map elements must be considered and implemented appropriately. These map elements include the frame and neat line, mapped area, inset map, title and subtitle, legend, data source, authorship, scale, and north arrow. There is an art to making all of these elements work together in a map, and it takes practice in order to do so. Typography must also be implemented properly to ensure a quality map. This includes selecting the proper typeface, type size, word spacing, and word orientation. After these elements are determined, maps can be created to the CWSs specifications.

4.5.1. Map Elements

The first map element added is the mapped area, which will be sized as large as possible without cramping the other map elements. Thematic symbols, such as water lines, valves, and hydrants should be centered in the mapped area, and base data should be easily identifiable, but not have as much visual weight as the thematic symbols. This can be accomplished by adjusting the transparency of the symbol or using lighter colors in the symbolism.

If an inset, a smaller map that represents a smaller scale view of the project area, is required, it should be added so as not to cover any of the necessary thematic symbols. An inset is a useful method to display a city in a state, a neighborhood in a city, or, in the case of an atlas, which section of the atlas a page represents.

The title should succinctly identify the theme of the map, and if needed, the subtitle should identify the geographic region and date. Neither of these elements should cover any of the thematic symbols, but should be placed to catch the reader's eye. The placement of the legend follows the same map element guidelines. The legend contains definitions of the thematic symbols used in the map, and may contain base data at the user's discretion. The legend's placement and size should make it easily visible, but no so much that it draws the reader's eye from the map.

The data source displays where the thematic data were obtained. It should be formatted in a similar format to a bibliographic reference, but, as often is the case, it can be much more concise. This data can often be combined into the same text box as the authorship information, which includes the name of the author and the date that the map was created.

Two elements that are also usually found together are the scale bar and north arrow. The scale bar represents a ruler that can be used to measure distances on a map and the north arrow indicates to the reader which direction is north on the page. In every GIS software, there are

many choices for both elements. Regardless of the selected style, both elements should be sized appropriately and placed out of the way so as not to attract undue attention.

The final map element added is the frame line as it establishes the available space for map elements. The frame line's size is determined by the size of the intended printed page as well as any other map elements' placement on the page.

4.5.2. Typography

The differentiation of individual features on a map is done through the use of labels. The type size selected for the labels mapped area should be large enough to be easily read, but not so large as to crowd the map. It is recommended to not select a type size smaller than five point as the labels may become unreadable. Labels should also be placed so as not to overprint other features or labels. If possible, symbols should be placed on the left and labeled on the right. If an aerial image or dark colored background is used, a halo, an extended outline of the letters, should be employed to make the label more visible. Depending on the GIS software, label placement can be dictated by rule-based location settings, or even be placed manually, such as through annotation feature sets in ArcMap.

The title will have the largest type on the map, followed by the subtitle. To increase readability, word and letter spacing can be increased. The legend heading should be smaller than the subtitle and the definitions should be smaller than the heading. The data source and authorship type should be of the smallest readable type possible so as not to draw attention from the thematic symbols.

This was a very general walkthrough of the necessary elements of map creation. For a more in-depth discussion of each element, it is recommended to read the chapter on map

elements and typography from *Thematic Cartography and Visualization* by Slocum, McMaster,

Kessler, and Howard (2014).

4.5.3. Map Creation

After all of the map elements are placed properly and the appropriate typeface and sizes

are set, maps can be created. The types of maps will be decided during the user needs assessment

by the CWS. The most commonly found map in the field is an atlas that displays small sections

of the water system in a large scale. These are useful to the field staff because they allow for the

easy identification of individual system features. Atlases can be created in both open source and

proprietary GIS software with relative ease. QGIS uses a feature embedded into its print

composer window to prepare and create atlases. While it is not an intuitive process, it can be

performed by reading through a tutorial found on QGISs website, which will be discussed further

below.

A myriad of other types of maps can also be created, including boundary maps,

watershed maps, and wall maps. All of these maps can be created using the same data and

methods described above. The final step is to export the maps to a file type that can be printed,

such as .pdf, .png, or.jpg. Saving in one of these file types will allow for easy dissemination of

the maps to the printer or other users.

4.6 Training Requirements

As previously stated, the intended audience of this workflow is water professionals

working in or for small CWSs that may or may not have a background in GIS. This section of the

workflow benefits those who have never used GIS software before or those who have, but may

have let their skills lapse. The goal is to minimize cost by training an employee of the CWS to

use the selected GIS software. This is so the CWS has someone in-house to implement and maintain the GIS. How the employee will be trained depends on which GIS software is selected.

As stated above, there are definite differences between open source and proprietary GIS software, and this includes training. An example of open source training options is the training manual created by QGIS that is available on their website. Like the software, the training manual is free, and is comprised of eighteen learning modules. These modules walk a new user through the basics of GIS all the way through spatial analysis. If the CWS selects QGIS as its GIS software, it is recommended that the student work through at least the sixth module, 'Creating Vector Data'.

In the past, Esri includes a very robust basic training manual with the purchase of their software. While this manual is no longer included, it is available from several schools online for free. This training manual relates to older versions of Esri products but can still teach the student the basic tools needed to create and edit data in a GIS. Esri now hosts their own training academy online in both free and fee based training modules. These modules are either self-taught or instructor led web courses.

Chapter 5 Discussion

The purpose of this thesis project was to develop inexpensive geospatial solutions that could be implemented in small rural CWSs. This was to be accomplished by performing a case study in a small rural water, where a GIS would be implemented using open source GIS software. After completing this case study, a generalized workflow for implementing a GIS in a small CWS would be created. The Descanso CWD proved to be an excellent case study for this project, and the project can be considered a success. Spatially accurate data was collected and created, and multiple maps were created, including an atlas and a large wall map. Based on the methods used in the case study, a comprehensive workflow for the creation of similar implementation projects was produced. However, the case study did have its issues. The project was not completed using open source GIS software as intended because lines could not be snapped to point features in QGIS, which led to the use of ArcMap to complete the data digitization process. A key area for improvement was the training of a Descanso CWD employee in the use of GIS software, where things did not go as planned, but were still successful.

Many future possibilities can come of this thesis project, not only for the Descanso CWD, but for new projects as well. For the Descanso CWD, all of the future work could be completed using ArcMap. The data could be migrated to a geodatabase, and a network can be created, thus expanding the role of GIS in the water system. The GIS could also be combined with other types of software, including asset management, maintenance scheduling, or water quality sample scheduling. If the CWS chooses to, the data can also be hosted online through several different avenues.

The workflow for the implementation of a GIS can be used for any CWS that wants to go through this process. These CWSs will see several benefits from using the workflow for GIS

implementation, such as cost savings, the beginnings of an asset management system, and the ability to update their infrastructure maps themselves when changes are made to the system.

5.1 Successes

The areas of success of this thesis project are the field data collection and map creation portions of the Descanso CWD case study, and the creation of the GIS implementation workflow. The field data collection process was conducted quickly and with almost no issues. This success was due in large part to the information provided by the field staff of the Descanso CWD in the form of existing maps and their intimate knowledge of their water system. This made it possible to plan a route based on the existing locations of features, and being able to identify any potential problem areas for data collection. The use of a high accuracy GPS with the capability of importing a data dictionary also added to the efficiency of the data collection. In all, over 15,000 points were collected as 30 points were collected at each feature location to achieve the highest accuracy. 88% of these points were within a 50 cm accuracy, which was deemed highly acceptable by the Descanso CWD.

The map creation process also went smoothly, due in large part to QGISs online training manual. The manual provided very clear step by step instructions on creating an atlas in the print composer. While not a completely intuitive process due to the need of selecting multiple options in separate tabs, the process was similar to creating an atlas in ArcMap using data driven pages. The tutorial provided tips on creating the inset map with a moving page indicator and unique text for each page of the atlas. The Descanso CWD was happy with the outcome and will be printing out multiple sets of the atlas for their field staff. The feature that impressed them the most was the aerial imagery background, as their previous maps were set on a white background.

The most rewarding process of this project was the creation of the workflow for implementing a GIS in a small water system (Chapter 4). This workflow was generated from a combination of personal experience, experience of others in the water industry, examples from previous studies, and knowledge from text books. This workflow is geared toward individuals in the water industry, who may or may not have GIS experience, that would like to implement a GIS in a small CWS. The workflow takes the user through a step by step process in creating a basic GIS using either open source or proprietary GIS software. The final output of the workflow is multiple datasets of features in the water system, a large scale atlas, and a small scale map of the CWS.

5.2 Failures

A key tenet of this thesis project was to complete all of the GIS work in QGIS, an open source GIS software. As stated above, there was an issue with snapping new line segments to point features in an editing session in QGIS. As of QGIS version 2.16, which was released on July 22, 2016, there is no provision for performing this snapping method. Because of this, the water lines for the case study on the Descanso CWD were digitized using ArcMap, which allows for the snapping lines to point features. Although this could have been performed in QGIS, the created data would have been subpar, as the lines would never truly intersect with the points. A way of remedying this would be to contact the developers at QGIS to see if there is a possibility of including this snapping method in a future release of the software. This would enable GIS users to complete a similar project to this completely in QGIS.

5.3 Areas for Improvement

One of the goals of this thesis project was to leave the GIS in the capable hands of an employee at the Descanso CWD, so they could perform any future updates in-house. While the

Descanso CWD had no in-house GIS specialist, Travis Creamer volunteered to learn the basic processes necessary to maintain their GIS using QGIS. Travis was tasked with working through the first six modules of the QGIS online training manual. While he is working on the training manual, the process has been slow-going. This is mostly due to the Descanso CWD being a small water district, and only three people work for the CWD, so spare time to spend working on training is not common. Travis spends most of his time in the field reading meters, fixing leaks, and doing his daily rounds. However, he is committed in his desire to learn how to use the QGIS software, and I will continue working with him on any problems he encounters after this thesis has been finalized.

There are a few ways in which the training process can be improved for future projects, such as requiring the employee to work on the training on their own time or during their lunch break. The best choice, however, would be to select an employee that does not spend most of their time in the field. Although office staff are similarly busy to field staff, they have the advantage of being in front of a computer for the majority of their day, and would have more opportunities to work through the training manual.

5.4 Future Possibilities

As the Descanso CWD continues to grow, so will its GIS. The direction in which this growth continues, however, is based upon which type of GIS software is used, open source or proprietary. Proprietary software, such as ArcMap, is very powerful, but that does not mean open source software is not. In its current state, the Descanso CWDs GIS consists of several shapefiles, which contain minimal amounts of attribute data. If they wanted to, the CWD could continue using QGIS and create and import their data to a database, such as PostgreSQL, PostGIS, and spatialite databases. This allows for the storage of all of their data in one location

and increases the amount of attribute data storage capability. The CWD could also begin entering attribute data into the feature datasets where it is missing, include new types of attribute data, and update existing attribute data when new features are installed. The CWD could also make their data and maps available online via the QGIS web client. This, however, requires the CWD host its own website, which requires more resources, and use QGIS Server, which would require extensive further training.

Another option for the Descanso CWD would be to purchase a license for Esri's ArcMap, which can perform all of the tasks mentioned above in a more user friendly and timely manner. The creation of a geodatabase in ArcMap can be completed in a few mouse-clicks, while you need an extensive background in database management to create one for QGIS. In ArcMap, a user can create either a personal or file geodatabase depending on their needs. The personal geodatabase is the original file format for Esri geodatabases, and allows the user to store up to two gigabytes of data in various formats (Esri 2016 – 3). A file geodatabase takes this concept one step further and allows the user to store up to one terabyte of data in a file system, unlike the personal geodatabase, which uses Access to store its data.

With all of the data stored in a geodatabase, the Descanso CWD, or any other CWS implementing a GIS, will have a host of spatial tools available to them. A very specific example would be if a CWS uses SEMS Technologies software to manage their water quality sampling data. The SEMS Integrated Add-on for ArcMap allows a CWS to spatially relate their water quality data that is entered through the SEMS software (SEMS 2014). CWSs will also be able to maintain an asset management system through their geodatabase. There are numerous software options available that integrate with ArcMap that allows the user to keep the asset data in sync between the two systems, and have a spatial view of their assets and work orders.

Similar to QGIS, ArcMap gives its users the option to host their data online. However, users with an ArcMap license or an ArcGIS Online subscription can host their data on an Esri server. If a user's data is stored as shapefiles or feature classes, the data is best added as a layer file that can be created in ArcMap. Data stored as delimited text files, such as .txt or .xls files, can be imported directly into an online map. This data can then be used to create maps that can either be publicly or privately shared. Alternatively, a finished map can be created in ArcMap and saved as a map document, .mxd, file. This file can then be uploaded to ArcGIS Online, along with the map data, and shared to other users.

The most powerful group of tools in ArcMap for CWSs are the geometric network tools. These tools can be used to model and analyze water flows moving through a CWSs water system. A geometric network is created from existing data, which all has to be saved to the same feature dataset. A network is built using the Build Geometric Network wizard which promotes feature classes from points and lines to edges and junctions. Connectivity is then set for the network through the creation of rules. These rules dictate what type of features can be connected to one another and how the features interact. The process of creating the network works best with data that is considered clean, meaning all of the data was snapped during its creation. If the data was not snapped during its creation, it can be during the network creation process. This is done by setting rules for snapping. Several different analyses can be run once the network is created, including: calculating the shortest path between two points, finding all (dis)connected network features, finding network loops or circuits, determining flow direction when sources and sinks are set, tracing network features up- or downstream from a point, calculating the shortest path upstream from on point to another, and finding all network features upstream from many points and determine with features are common to them all (Esri 2016 – 4). The analyses would allow a

CWS to determine several flow related issues, such as flow directions in their system and how to bypass certain parts of the system during emergencies.

If a new CWS decides to begin a GIS implementation project they can use the workflow created for this thesis project. The most important aspect of the workflow is its ability to be used for GIS implementation projects of any size. Since it provides a simple framework and does not apply specifics, it can be adapted to projects both large and small. The one exception would be that the user needs assessment process may need to be expanded for larger entities as they tend to be more complex systems than smaller CWSs.

By utilizing this workflow, CWSs will see several benefits over having a consultant do the work for them. The most obvious benefit would be cost savings. Rates for creating a GIS by a consultant can range from $50 to $200 per hour. By completing the work in-house, a CWS can potentially save thousands of dollars. This would be dependent on the project, however. The more information the CWS can provide during the source data evaluation, the faster the project can be completed. The cost savings would be even more if a CWS utilized open source GIS software, such as QGIS, in the creating and implementation of their GIS. By creating a GIS in-house, a CWS would also benefit from being able to update their infrastructure maps when they make improvements or additions. Because they control their own data, they could print out a new set of maps whenever they wanted to. Also, because they could control their own data, they could use it as a basic asset management system. By adding the installation dates for the pieces of their infrastructure the CWS could keep track of each asset to calculate when its replacement should be.

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