Scoring Groundwater Infiltration & Sewage Exfiltration Risk in a Sanitary Sewage Collection System

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CHARLOTTE WATER

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Introduction

Charlotte Water (CLTWater, formerly Charlotte-Mecklenburg Utilities) serves an estimated population of 818,005 in Mecklenburg County, North Carolina. To meet the needs of its customers, CLTWater maintains over 4,189 miles of wastewater mains and 4,209 miles of water distribution lines throughout the county. Each day, it treats 123 million gallons of sewage and pumps an average of 100.5 million gallons of drinking water. Maintaining such extensive collection and distribution systems requires an operating budget of over $308 million, and has led CLTWater to become a very data-intensive organization (Charlotte-Mecklenburg Utilities, 2014).

CLTWater currently operates well above industry standards. As the utility's operations become progressively more proactive, new opportunities to use existing data must be explored. Operational data is managed in a collection of information systems that serve specific functions for individual departments. To fully leverage this frequently isolated data, it must be analyzed in innovative ways to look for relationships that have not yet been realized. Newly-recognized relationships among datasets offer an opportunity to better manage resources and predict future impacts to operations. This project uses several existing CLTWater datasets, as well as datasets maintained by other agencies, in novel ways to develop a scoring model for sewer infrastructure failure risk.

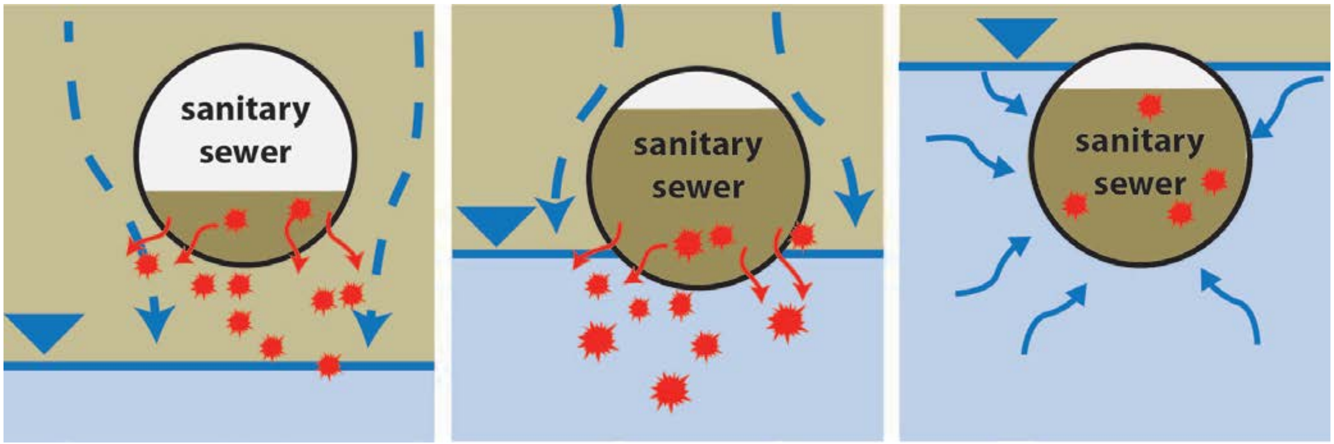
Objective

The objective of this project was to use GIS tools to design a simple scoring system for sanitary sewer pipes. Scores would summarize a pipe's failure risk by incorporating pipe material and the volume of sewage carried by those pipes. Once scores were assigned to the pipes, they would be divided into two separate datasets: those situated above the water table and those below. The pipe's position relative to the water table determines whether the pipe is likely to be at risk for either sewage exfiltration or groundwater infiltration. The score quantifies the risk of exfiltration or infiltration actually occurring.

Background

This project idea was based on a 2013 pilot study that was a collaborative effort between CLTWater and Charlotte-Mecklenburg Storm Water Services (CMSWS). That pilot study sought to find a method to predict the risk of sewage exfiltration into groundwater (Moore, 2013). The need for such a predictive method was shown by groundwater sampling conducted by CMSWS in 2000. That sampling found that high concentrations of fecal coliform bacteria were found in groundwater samples from test wells in areas where sewer pipes were situated above the water table. Damaged pipes were allowing sewage and the bacteria it carried to exfiltrate into the surrounding soils and groundwater (Figure 1a, 1b). Some of this groundwater and bacteria ultimately reach surface waters, potentially harming water resources.

Bacteria concentrations were substantially lower in groundwater samples from test wells in areas where sewer pipes were located in the saturated zone below the water table (Mecklenburg County Department of Environmental Protection, 2000). In this situation, hydrostatic pressure from groundwater kept the sewage from leaking out of the pipe. In areas with damaged pipes, groundwater can infiltrate through the cracks or separated joints (Figure 1c). As a result, CLTWater may be treating groundwater unnecessarily. This groundwater uses capacity in the pipes and in the wastewater treatment facilities, impacting CLTWater's ability to effectively treat sewage.



1a: Pipe located above water table; sewage exfiltrates from damaged pipe.

1b: Pipe located predominantly above water table; sewage exfiltrates from damaged pipe.

1c: Pipe located below water table; groundwater infiltrates damaged pipe.

Figure 1 - Graphic illustrates potential interactions between sewer pipes and groundwater; derived from (http://cfpub.epa.gov/ncer_abstracts/images/fckimages/index.cfm?imgid=6781).

Certainly not all sewer lines above the water table are guaranteed to leak sewage into surrounding soils and groundwater, and not all of those located below it are allowing groundwater to seep in and overwhelm sewer system capacity. A method was needed to predict whether a pipe was subject to a risk of exfiltration or infiltration, and to quantify how much risk it posed.

While the pilot study of 2013 focused on a small study area, this project would involve improved methods and include the entire county. The two output datasets would have different potential uses. Sewer pipes located above the groundwater elevation and scored by risk of sewage exfiltration could be used by CMSWS to support targeted water quality monitoring in high exfiltration risk areas. Sewer pipes located below the groundwater elevation and scored by risk of infiltration could be used by CLTWater when evaluating inflow and infiltration in the collection system. Both datasets would have the potential to be used as a factor when prioritizing sewer line rehabilitation and repair plans.

Methodology and Results

The analysis for this project involved a two critical datasets: a Mecklenburg County groundwater elevation surface; and a coverage of CLTWater's sanitary sewer pipe segments with associated elevations, pipe materials, and sewage volume information. While the sewer pipe segment dataset was readily available, the groundwater elevation surface ultimately had to be modeled from multiple input datasets.

Modeling a Groundwater Elevation Surface

Groundwater elevation, also known as the water table, is a dynamic surface that flows and fluctuates; its elevation and flow rate vary according to the season and the amount of rainfall received (Maine Geological Survey, 2005). The intent of this project is not to model groundwater flow or fluctuations, but to use available data to visualize a groundwater elevation surface. The water table will be treated as a static surface in this analysis.

Accurate, recent, and local groundwater elevation surfaces are not commonly available for most areas; including Mecklenburg County. While regional water table maps do exist in the United States, they are not considered useful on a site-specific scale due to variable local conditions (USGS, Groundwater Frequently Asked Questions, 2012). Research led to only one existing raster – created by USGS in 2001 – that was relevant to this project. This lack of options drove the development of three other potential groundwater elevation rasters. These rasters were created from the analysis of pertinent local datasets that were obtained from other organizations. The three new rasters and the existing USGS raster were evaluated for suitability, leading to the selection of one raster for use in the project analysis.

USGS NC Estimated Depth to Water

The one available raster was the North Carolina Estimated Depth to Water raster, which was created in 2001 by a USGS team. The raster cell values represented the depth (in feet) to groundwater. The cell values were calculated using a regression equation and input values of slope, elevation, and soil thickness. The equation was calibrated with a regression analysis of slope, elevation, soil thickness, and static water level values from monitoring well locations throughout NC (Eimers, Giorgino, & Terziotti, 2001).

Silvia Terziotti, one of the original authors of the 2001 USGS study, provided the Depth to Water raster file for this analysis and occasionally acted as a resource for the project. She cautioned that the raster was derived from slope and elevation data that was not collected with LiDAR, but with less precise, lower resolution methods. Terziotti encouraged exploring other potential data sources or conducting a regression analysis on more recent, higher resolution slope and elevation data (personal communication, October 23, 2014).

The Depth to Water raster values represented the estimated depth (in feet) to groundwater. In order to allow a direct comparison to the elevation values of sewer pipes, the raster was converted to groundwater elevation values. Using the raster calculator in the ArcGIS Spatial Analyst extension, the Depth to Water raster values were subtracted from the ground surface elevation values in the 2012 Mecklenburg County DEM to produce a groundwater elevation raster (Figure 2).

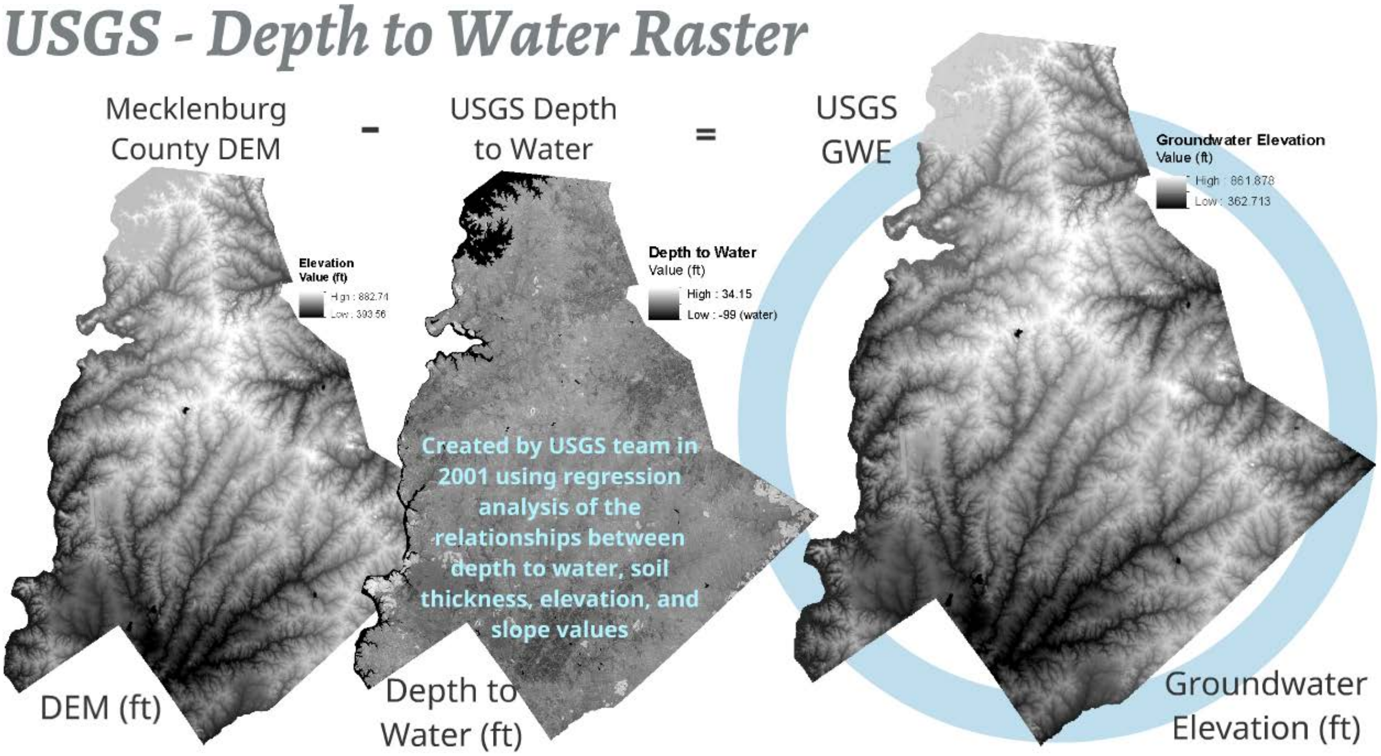


Figure 2 - Groundwater Elevation raster calculated from USGS Depth to Water raster

USGS Depth to Water Methodology with New Input Data

In an effort to create an updated raster using the USGS team's methods, a new raster was created by performing a raster calculation using the regression equation the team developed in 2001. The inputs for the raster calculation were a 2012 Mecklenburg County slope raster, a 2012 Mecklenburg County DEM, and a NC soil thickness raster. As with the Depth to Water raster, the values of the raster calculation output were subtracted from the ground surface elevation values in the 2012 Mecklenburg County DEM to produce a groundwater elevation raster (Figure 3). Terziotti cautioned that the regression equation was only valid for the data that was used to calibrate it, and that it may not be appropriate for newer data sets (personal communication, April 8, 2015).

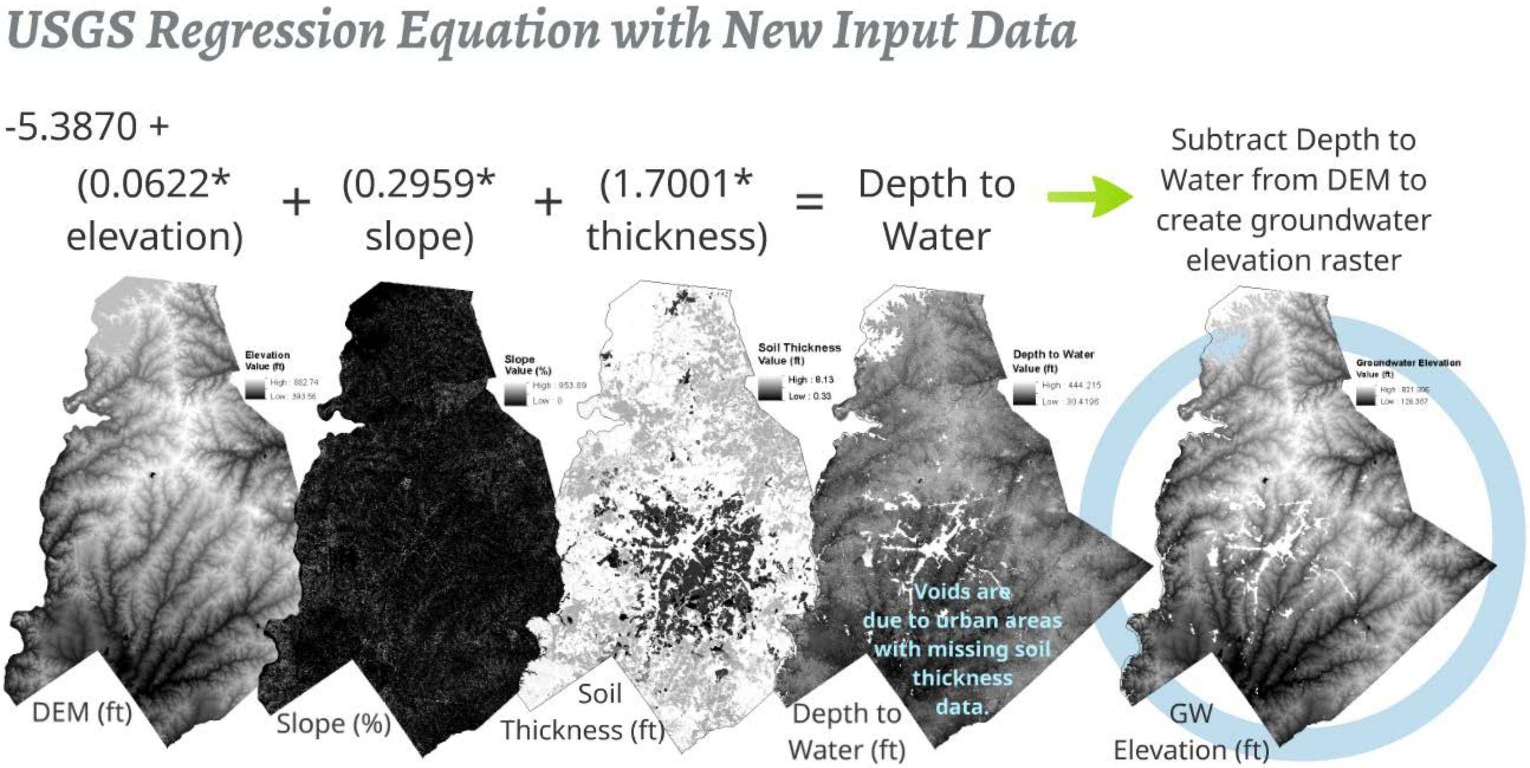


Figure 3 - Raster calculation process used to create groundwater elevation raster from new inputs and regression equation developed by USGS team

Inverse Distance Weighted Interpolation

The USGS regression analysis used for the Depth to Water raster was modeled using slope, elevation, soil thickness, and depth to water values from the Piedmont and Coastal Plain physiographic provinces of NC. The USGS model was not calibrated specifically for the Mecklenburg County landscape. Rather than using a raster that was not a good fit for the area, relevant local datasets were researched to locate potential source data for the development of a localized raster. Two local datasets were identified for use: monitoring well locations with static water level measurements, and minimum stream channel elevations.

USGS and Mecklenburg County Environmental Health provided datasets with a total of 779 monitoring well locations with static water level measurements in Mecklenburg County (Figure 4). Most monitoring wells are placed to monitor the flow of contaminants near the ground surface and through the surficial aquifer. The static water level elevations of monitoring wells generally reflect the water table elevation, or groundwater elevation (Figure 5).

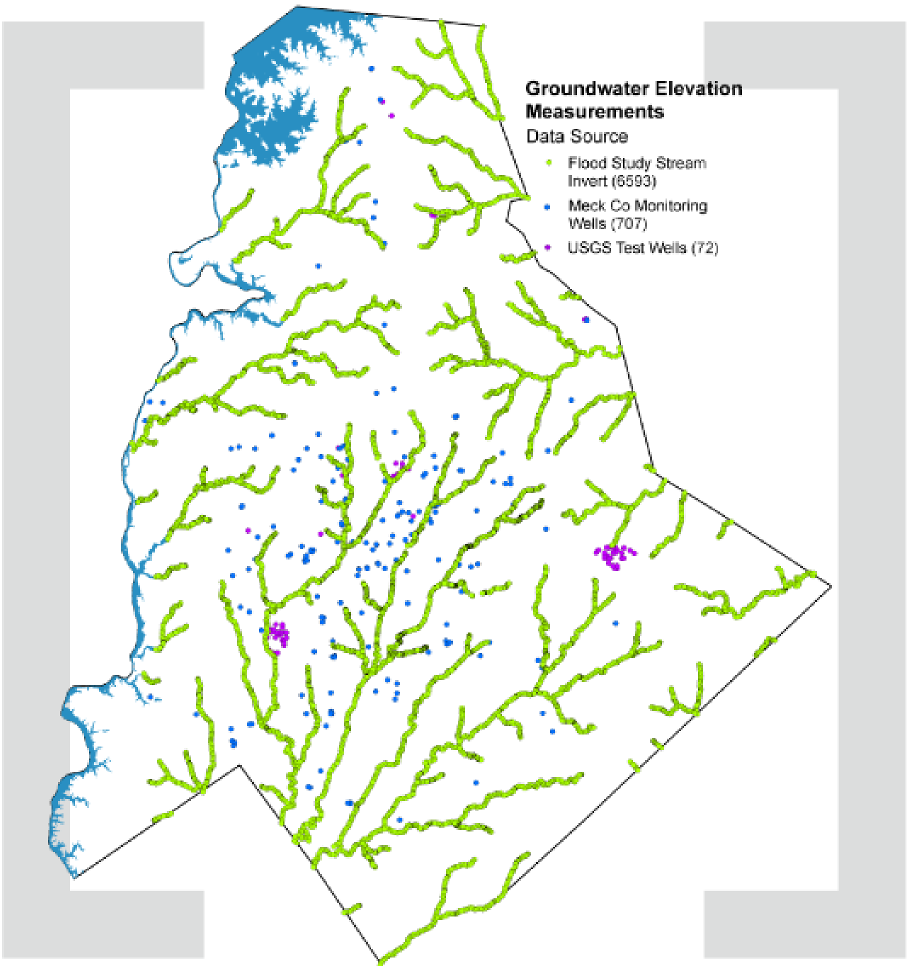
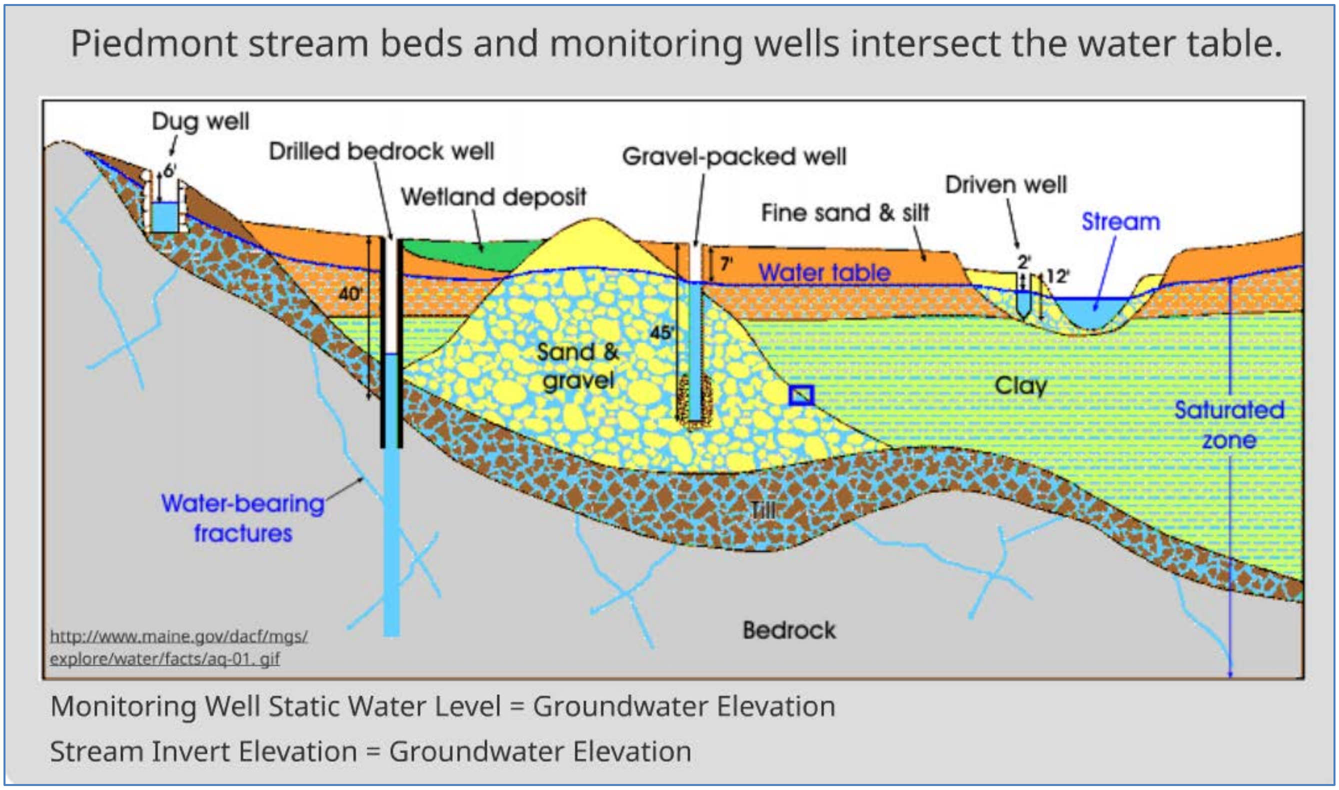


Figure 4 - Monitoring well and flood study data point locations

In groundwater-fed piedmont streams like those in Charlotte, the water table intersects the stream bed; the minimum stream channel elevation is roughly equivalent to the groundwater elevation (Figure 5). Charlotte-Mecklenburg Storm Water Services developed a dataset of 6,593 minimum stream channel elevations (or inverts) for a flood study. 1,046 of the data points were survey grade field measurements, and the remaining 5,547 points were modeled from the survey grade points using the Hydrologic Engineering Centers River Analysis System (HEC-RAS) (Figure 4).



Piedmont stream beds and monitoring wells intersect the water table.

Monitoring Well Static Water Level = Groundwater Elevation

Stream Invert Elevation = Groundwater Elevation

Figure 5 - Relationship between the water table, shallow monitoring wells, and the stream bed.

One of the more straightforward ways to use the monitoring well and minimum stream channel elevation data was to create an interpolated groundwater elevation surface. The Inverse Distance Weighted (IDW) interpolation method was chosen from multiple methods available in the ArcGIS Spatial Analyst extension (Figure 6). Other interpolation methods were considered, but IDW was selected as the most appropriate method for the dataset and analyst expertise (Bannister, 2013).

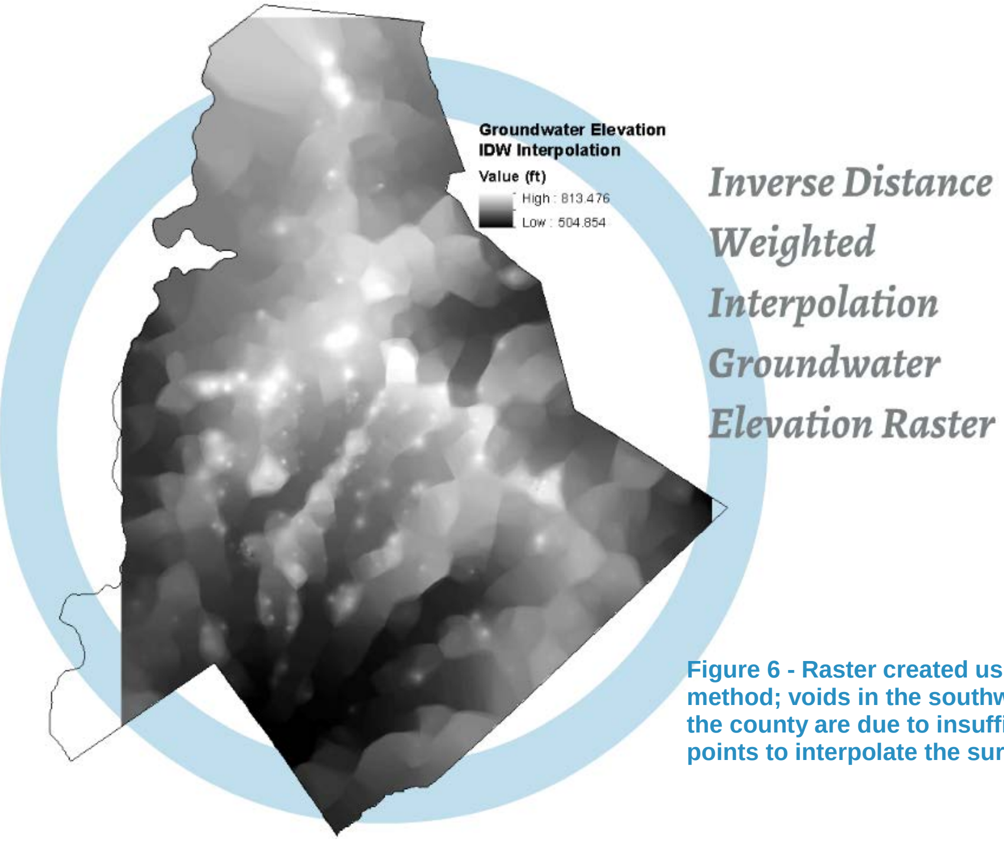


Figure 6 - Raster created using the IDW method; voids in the southwest corner of the county are due to insufficient data points to interpolate the surface

Regression Analysis of Local Datasets

The availability of such an extensive set of Mecklenburg County groundwater elevation data points, a soil thickness raster, and high resolution slope and elevation rasters supported the decision to perform a new regression analysis – modeled after the USGS team's work – in order to determine if there was a relationship between the four data types.

In order to prepare the data for the regression analysis, the ArcGIS Spatial Analyst extension was used to extract the slope and soil thickness values from the respective raster cells at the location of each of the 7,372 groundwater elevation data points. For the minimum channel elevation points, the groundwater elevation was equivalent to the ground surface elevation. For the monitoring well locations, elevations were extracted from the DEM for each well location.

Regression analyses were conducted on multiple combinations of the four datasets. The best fit was a regression equation that incorporated elevation and slope, yet omitted the soil thickness values. Terziotti, who was a member of the USGS team that utilized a regression analysis from statewide data, suggested that soil thickness be removed from the regression analysis; soil data is generally not as accurate for urban areas like Mecklenburg County. There were data voids in the soil thickness raster due to missing data in the urban center of Charlotte and along the major thoroughfares radiating from it.

The selected regression analysis of groundwater elevation, slope, and elevation values had an r^2Adusted value of 0.99. This high value suggested the possibility of autocorrelation between elevation and groundwater elevation. Terziotti mentioned that the possibility of autocorrelation was why the USGS team used depth to water instead of groundwater elevation; however, she thought this analysis was probably an appropriate fit for local use (personal communication, April 27, 2015). The output values from the regression analysis are as follows:

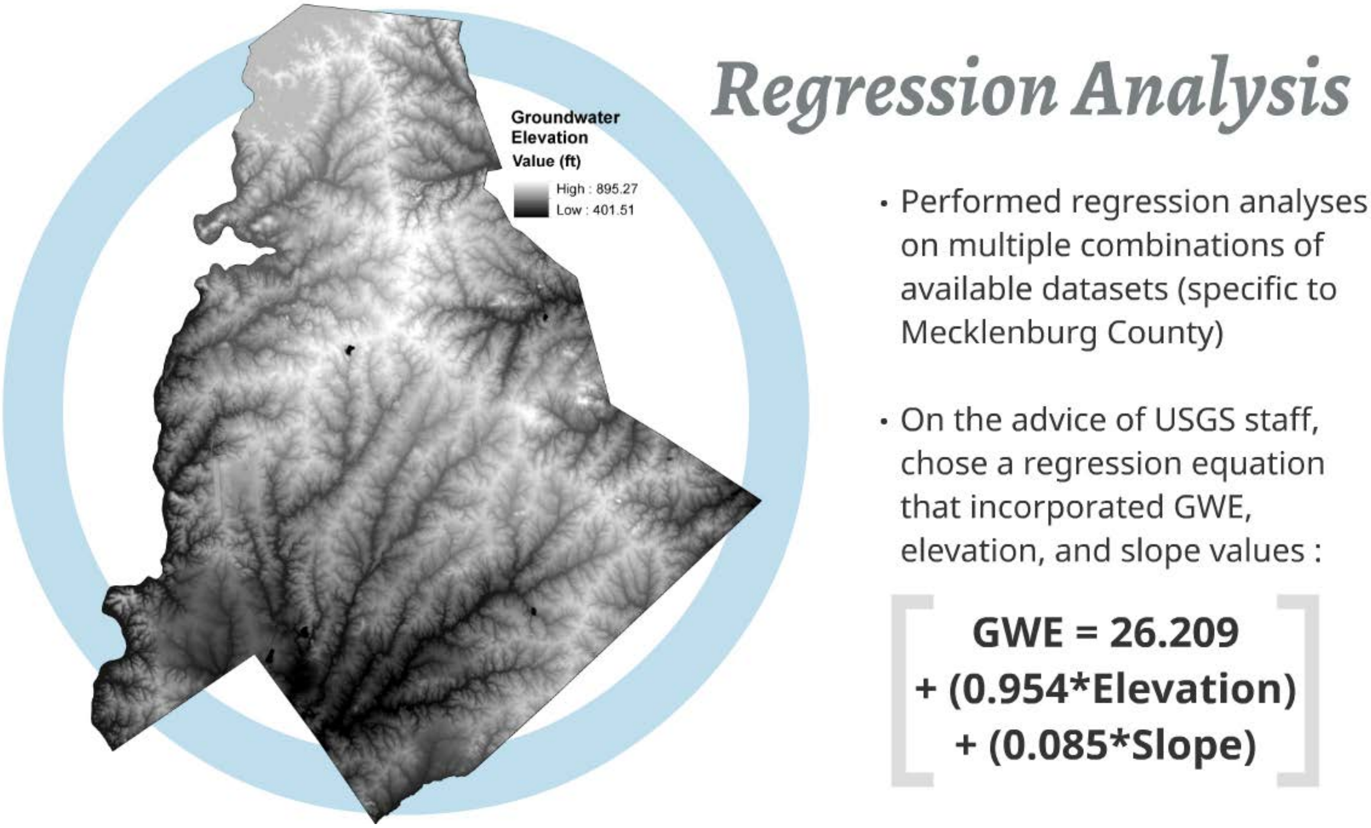
Regression Statistics
Multiple R = 0.994427154
R Square = 0.988885366
Adjusted R Square = 0.988882349
Standard Error = 6.140981728
Observations: 7,372

	Coefficients	**P-value**
Intercept:	26.20873861	5.3406E-245
Elevation:	0.953523058	0
Slope:	0.084975057	9.3357E-71

Resulting Regression Equation:

Groundwater Elevation (feet) = 26.209 + (0.954*Elevation in feet) + (0.085*Percent Slope)

The resulting regression equation was used to construct a raster calculation; the inputs were a 2012 Mecklenburg County slope raster and a 2012 Mecklenburg County DEM. The output raster represented the groundwater elevation surface modeled from the regression analysis (Figure 7).



Regression Analysis

- Performed regression analyses on multiple combinations of available datasets (specific to Mecklenburg County)
- On the advice of USGS staff, chose a regression equation that incorporated GWE, elevation, and slope values :

$$\left[\begin{array}{c} GWE = 26.209 \\ + (0.954 * Elevation) \\ + (0.085 * Slope) \end{array} \right]$$

Figure 7 - Groundwater elevation raster modeled from regression analysis

Testing Groundwater Elevation Surfaces

Raster Test Methodology

Four potential groundwater elevation rasters were now available, and a method was needed for selection of the most accurate model. An innovative method that leveraged existing Closed Circuit Television (CCTV) observational data was used to test each of the four rasters for accuracy.

CLTWater has a large database of observations that were noted during CCTV investigations. These investigations use an in-pipe camera to locate and document pipe breaks, blockages, groundwater infiltration, and other issues within sewer pipes. Each observation is linked to the GIS feature ID of the subject pipe. A dataset of 1,399 documented groundwater infiltration observations dating from 2008 were extracted from a database of CCTV observations. Many of these observations were associated with the same pipe feature ID; the dataset was summarized to eliminate duplicates, resulting in 574 infiltration observations in unique pipes. All of these pipes have invert elevation values (the elevation value of the lowest point of the pipe interior), yet not all of them are considered survey grade measurements. The level of accuracy for pipe invert elevations, and the invert values themselves, are stored in the attribute data of the connected manhole features. 245 survey grade manholes that intersected pipes with documented infiltration observations were extracted from the CLTWater manhole dataset (Figure 8).

Selecting only survey grade manholes and pipes provided a dataset that contained elevation values stored in a vertical datum (NAVD88) that was consistent with the groundwater elevation data. Using only the survey grade features eliminated evaluating pipes that used localized coordinate systems for elevation values. Using pipes that contained localized elevation data could result in an inaccurate comparison of pipe elevations relative to groundwater elevations.

Groundwater had been documented at the invert elevation of each of the 245 survey grade manholes. For those locations, the groundwater elevation was greater than or equal to the invert elevation of the manhole and pipe. On the advice of Dr. Barry Evans, the Penn State advisor to this project, the groundwater elevation values from each of the four potentials rasters were compared to the invert elevations of the 245 selected manholes. The groundwater elevation was known to be greater than or equal to the manhole invert elevations in those locations. The groundwater elevation raster that correctly predicted the most of these documented infiltration locations would be picked for use in the analysis.

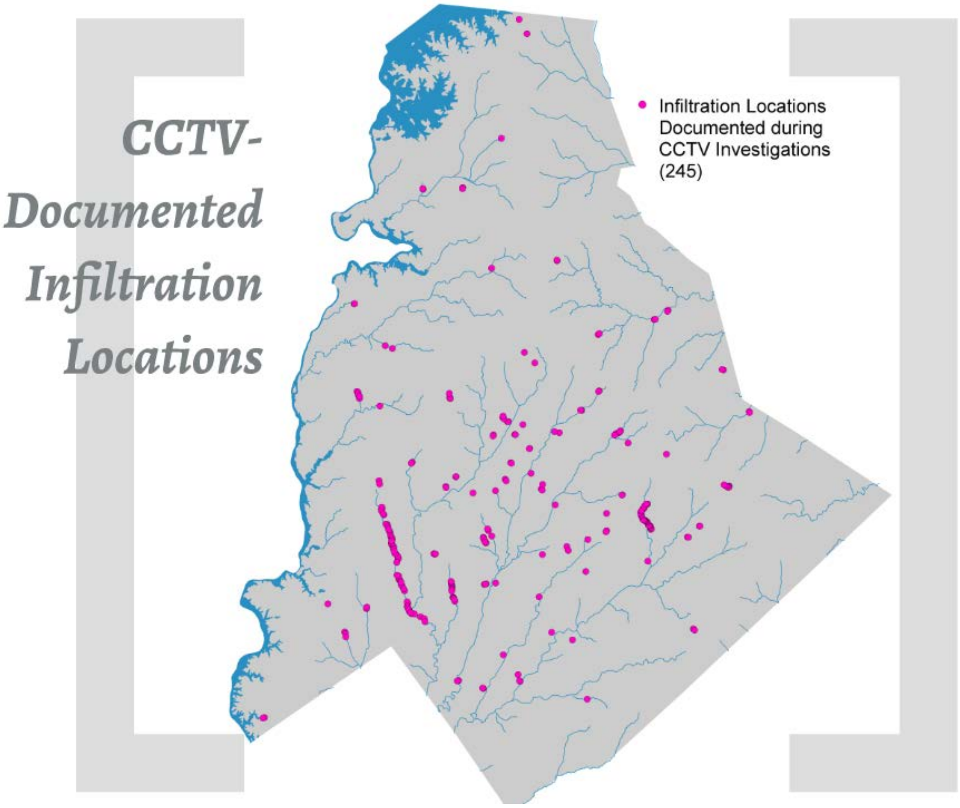


Figure 8 - Survey grade manholes with documented groundwater infiltration; these locations were used to test the accuracy of each potential groundwater elevation raster.

Raster Test Results

For each groundwater elevation raster, the Spatial Analyst extension was used to extract the elevation values from the cells that intersected the locations of the 245 manhole locations. Those cell values were compared to the corresponding manhole invert elevation values; raster values that were greater than or equal to the manhole invert elevation values were counted as a correct prediction. Table 1 lists the raster test results. The Regression Analysis of Local Datasets raster far outperformed the other potential rasters, correctly predicting 89.4% of the infiltration locations.

Raster Name	*# of Correct Predictions*	*% Correct Predictions*
USGS Depth to Water Methodology with New Input Data	0	0%
USGS NC Estimated Depth to Water	14	5.7%
Inverse Distance Weighted Interpolation	115	46.9%
Regression Analysis of Local Datasets	**219**	**89.4%**

Table 1 - Results of groundwater elevation raster tests

There was concern that the Regression Analysis of Local Datasets raster correctly predicted so many of the infiltration locations because it had possibly raised the groundwater elevation to an unrealistically high level – meaning most test points would pass. Limited manual quality assurance checks found that actual conditions were well-represented; therefore this groundwater elevation raster was selected for use in the analysis.

Infrastructure Analysis and Scoring

Determining Pipe Position Relative to Groundwater Elevation

The next step of the process, which is outlined in Figure 9, was to assign groundwater elevation values to the CLTWater infrastructure data for direct comparison to the invert elevations. 19,121 survey grade manholes were extracted from the manhole dataset. The Spatial Analyst extension was used to extract and append the groundwater elevation values from the Regression Analysis of Local Datasets raster to these manholes.

A spatial join was used to extract the pipes that were connected to these survey grade manholes. Typically two manholes were connected to each pipe; the averaged values for those two manhole invert elevations and groundwater elevations were appended to each pipe. For the pipe dataset, a calculated field with the difference between the averaged invert elevation and the averaged groundwater elevation was added.

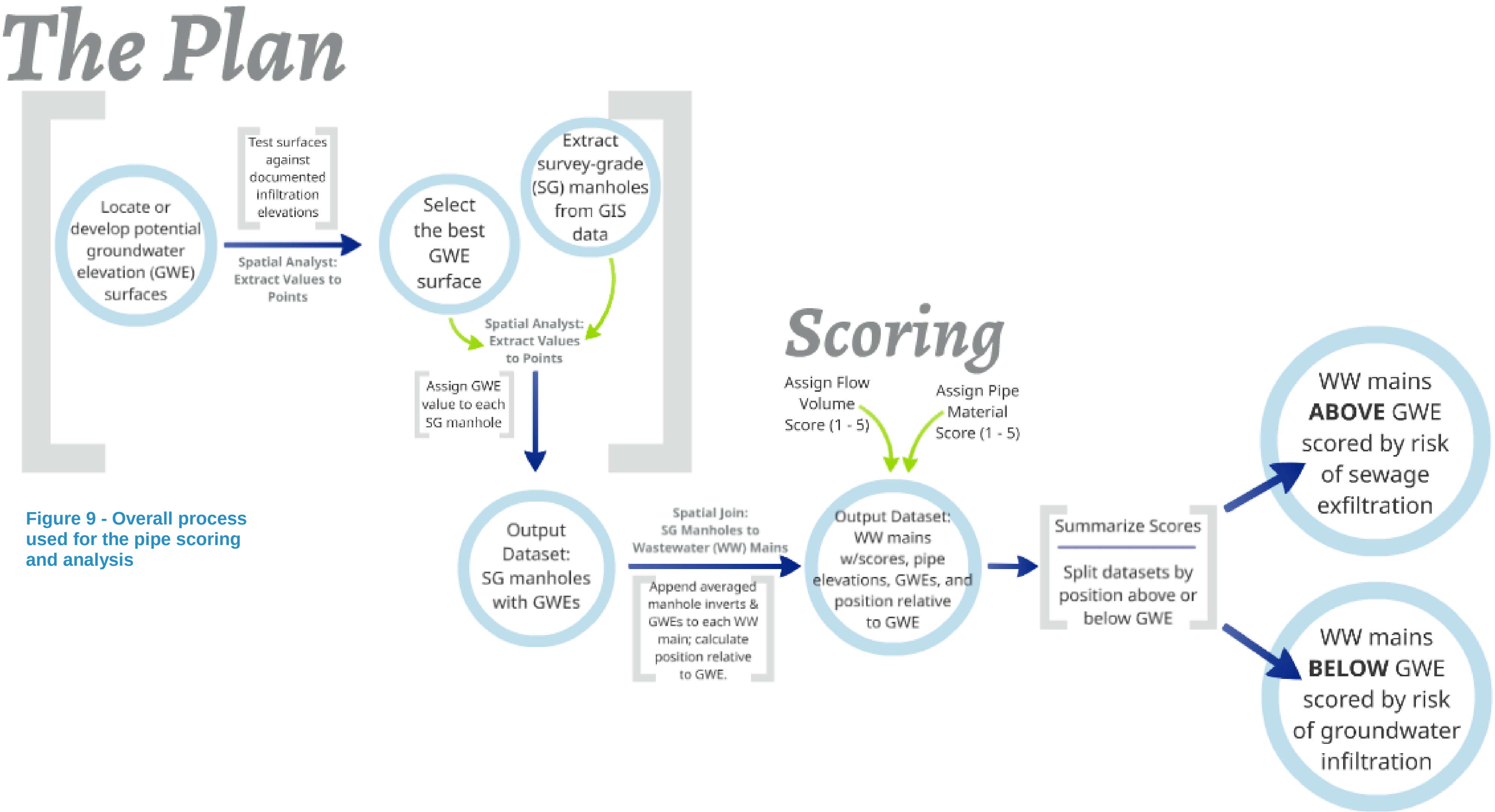
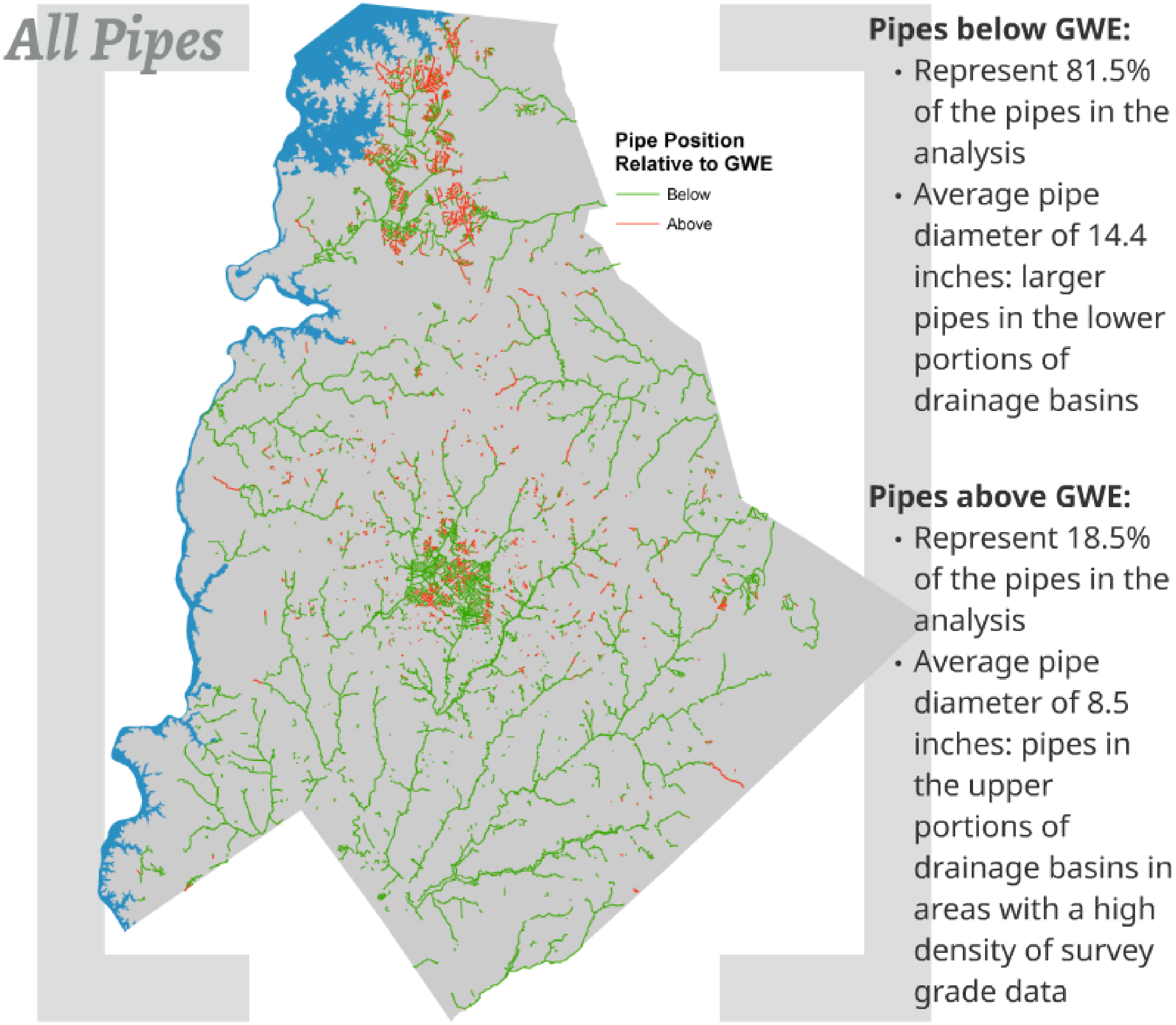


Figure 9 - Overall process used for the pipe scoring and analysis

Negative values indicated the pipe was positioned below the groundwater elevation; positive values were located above. The calculations indicated that 81.5 percent of the pipes were located below the groundwater elevation (Figure 10). This was not surprising, as most of CLTWater's survey grade features are larger diameter lines located along streams where the water table is closer to the land surface. The average pipe diameter of these pipes calculated to be below the water table was 14.4 inches.



Pipes below GWE:
- Represent 81.5% of the pipes in the analysis
- Average pipe diameter of 14.4 inches: larger pipes in the lower portions of drainage basins

Pipes above GWE:
- Represent 18.5% of the pipes in the analysis
- Average pipe diameter of 8.5 inches: pipes in the upper portions of drainage basins in areas with a high density of survey grade data

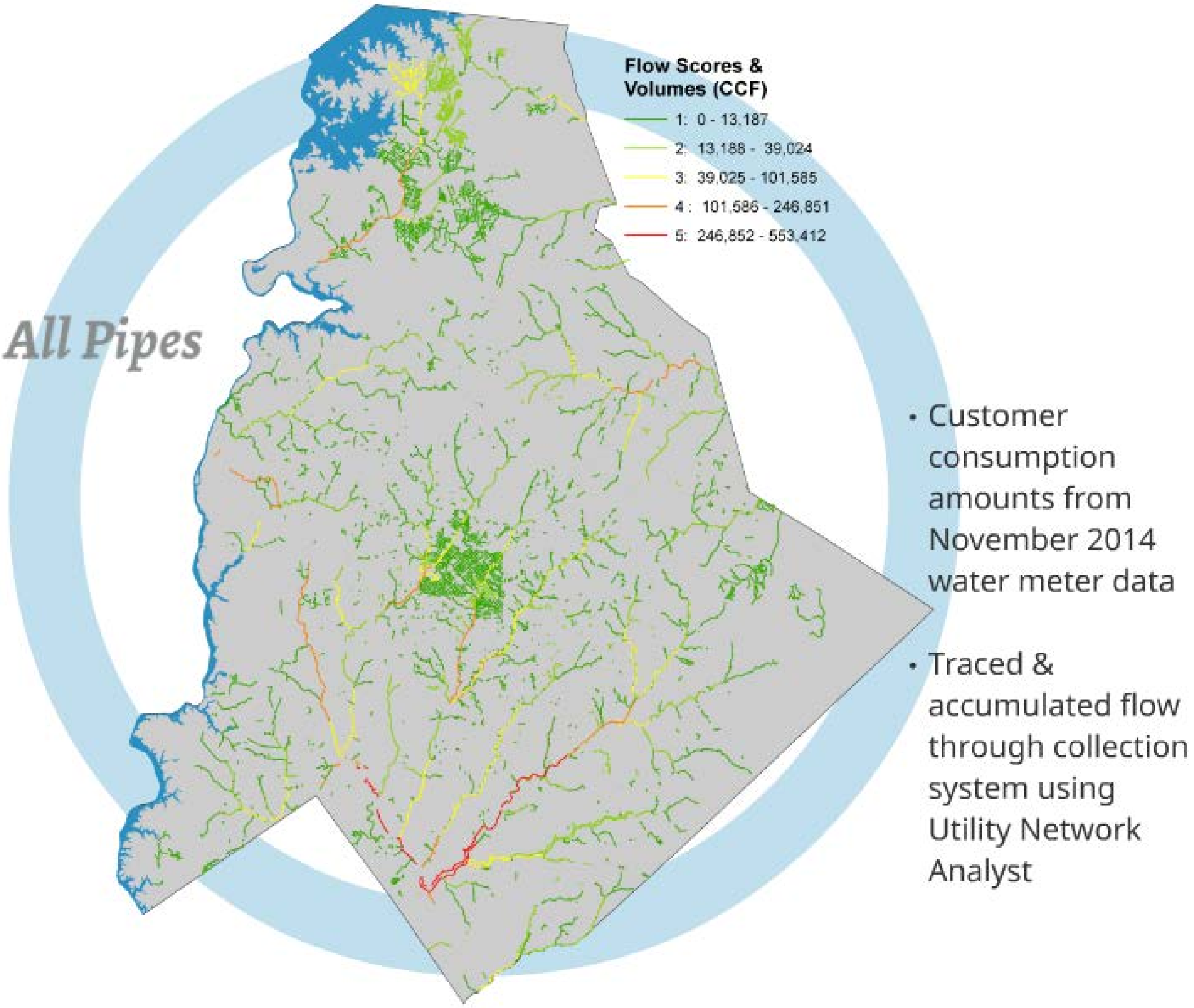
Figure 10 - Pipe positions relative to the groundwater elevation (GWE)

18.5 percent of pipes in the analysis were calculated to be above the groundwater elevation (Figure 10). The average diameter for these pipes was 8.5 inches. These lines were concentrated in areas where CLTWater has a high density of survey grade data, such as the Central Business District and newer portions of the system in the northern area of the county.

Scoring Pipes According to Volume of Sewage

The next portion of the analysis process was to score the pipes according to the volume of sewage they typically carried. While there are flow monitors installed throughout the CLTWater sewer system, they are mainly on large trunk lines and are not representative of the upper portions of drainage basins. As an alternative method, customer consumption data was used to calculate flow. The ArcGIS Infrastructure Editing tool was used to build laterals from cleanouts to the sewer pipes, and then an extract of customer consumption water meter data for November 2014 was joined to those cleanout locations on the premise ID. ArcGIS Utility Network Analyst extension tools were used to trace flow and assign accumulated volumes to the pipes in the analysis. The Natural Breaks method was used to classify the volumes (in CCFs, or cubic hundred feet) assigned to the pipe data, and a score of 1 through 5 was appended to each pipe (Figure 11). Higher accumulated volume scores were observed in the lower portions of the system as pipes approached wastewater treatment facilities.

While consumption data does not necessarily equal actual flow in a wastewater system, it was a good approximation for this analysis. November was chosen as a representative month, as it is not during the “busy season” of summer lawn watering. The consumption numbers for large water consumers that are not returning most of the water back into the system, such as a Coke bottling facility, were thrown out or lowered. Using drinking water consumption data from the CLTWater customer billing system for this analysis was an innovative use of a dataset that had not yet been used in combination with the sewer infrastructure data.



- Customer consumption amounts from November 2014 water meter data
- Traced & accumulated flow through collection system using Utility Network Analyst

Figure 11 - All pipes scored according to volume of sewage carried

Scoring Pipes According to Material

The next step approached was the scoring of pipes according to the material. The CLTWater Engineering staff was consulted about pipe material failure rates, and research of pipe failure studies was conducted (Folkman, 2012). Based on the findings, a score range of 1 through 5 was developed for pipe materials according to risk of failure; 5 represents the highest risk and 1 represents the lowest (Figure 12). Terracotta pipes, which still make up a large part of CLTWater's system, were given the highest risk score of 5. If a pipe had been rehabbed within the last 5 years, then a score of 1 was automatically assigned. If the pipe material was listed as "Unknown" or NULL in the attribute data, then a score of 3 was assigned, effectively rendering the material score as neutral. Less than 3 percent of the pipes in the analysis were missing material information.

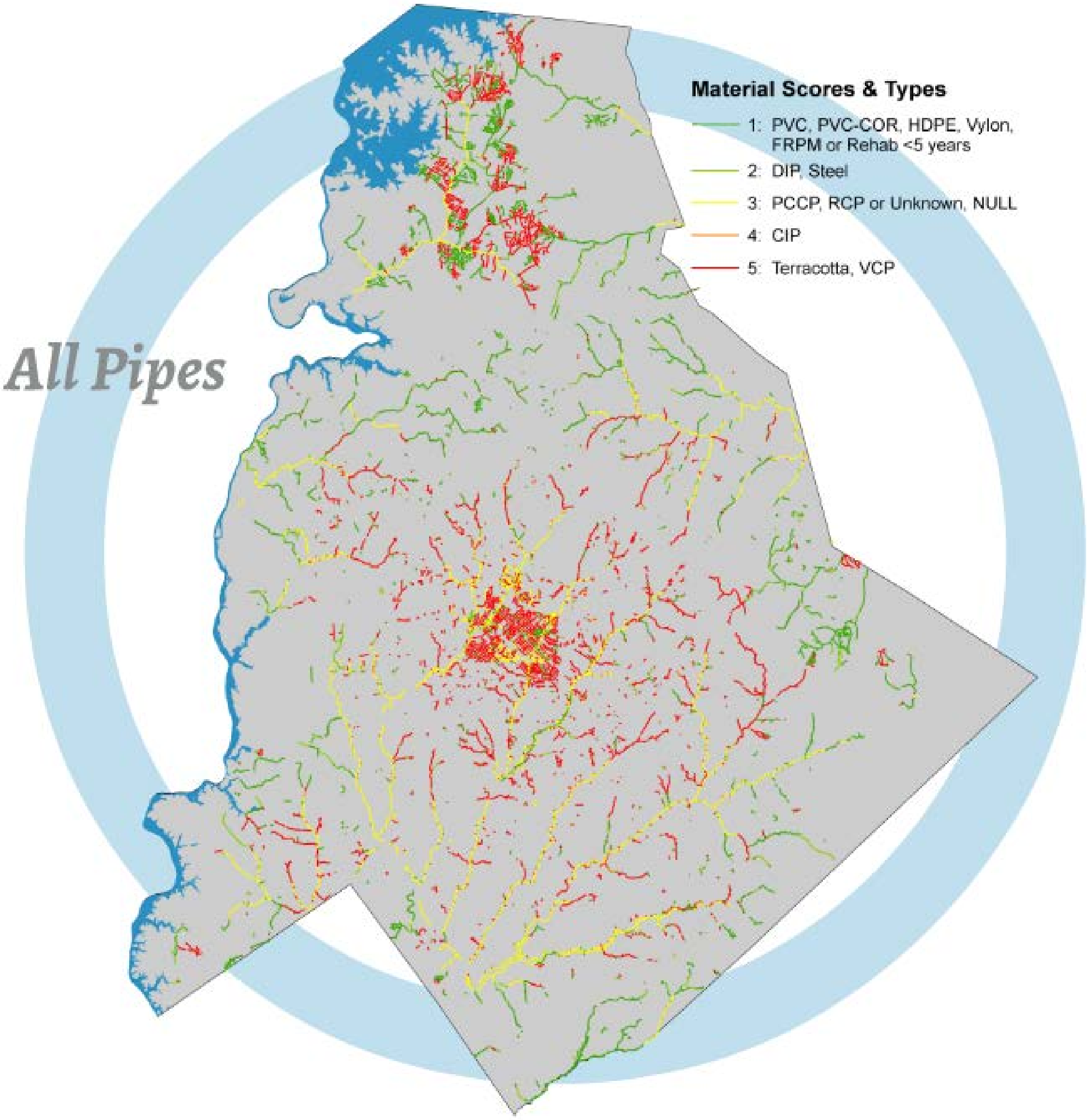
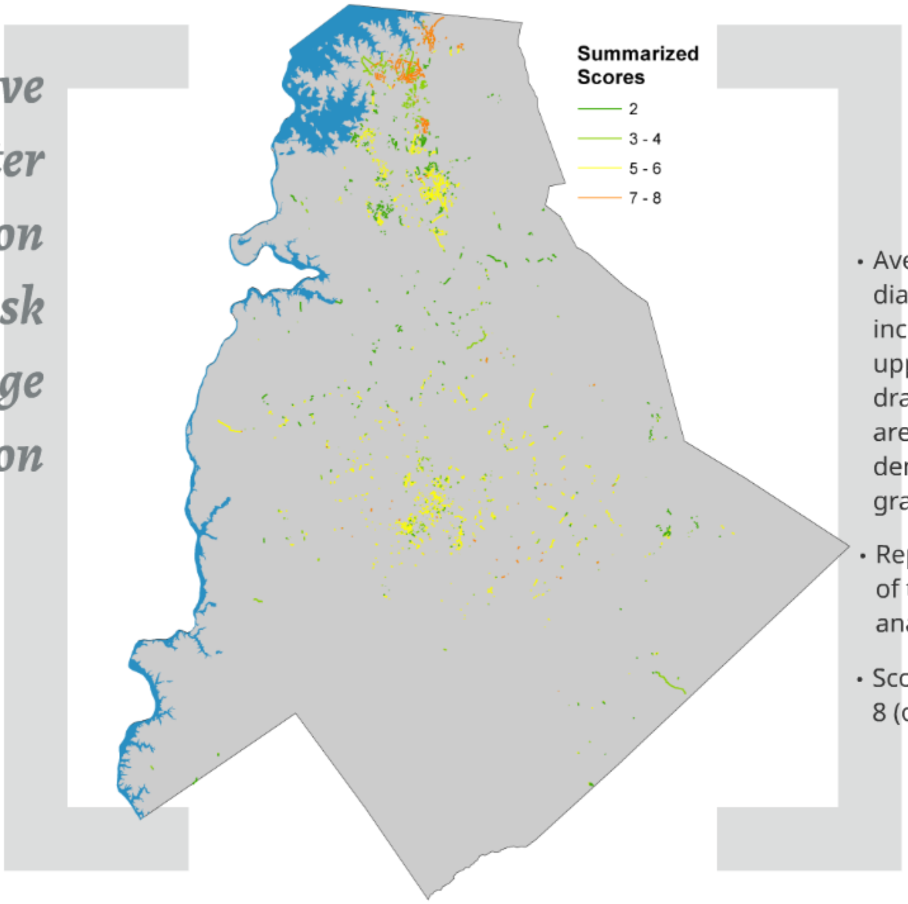


Figure 12 - All pipes scored according to material failure risk

Preparation of Final Output Datasets

The volume and material scores were summarized into a single score for each pipe. The pipe dataset with summarized scores was then split according to the pipe's position relative to the groundwater elevation, resulting in two output datasets: pipes above groundwater elevation scored according to sewage exfiltration risk (Figure 13), and pipes below groundwater elevation scored according to groundwater infiltration risk (Figure 14). For the pipe dataset located above groundwater elevation, the score summary range only reached 8 of a possible 10. This was mainly due to the lack of large volumes of sewage flowing through these pipes, as they are often located in the upper portions of drainage basins.

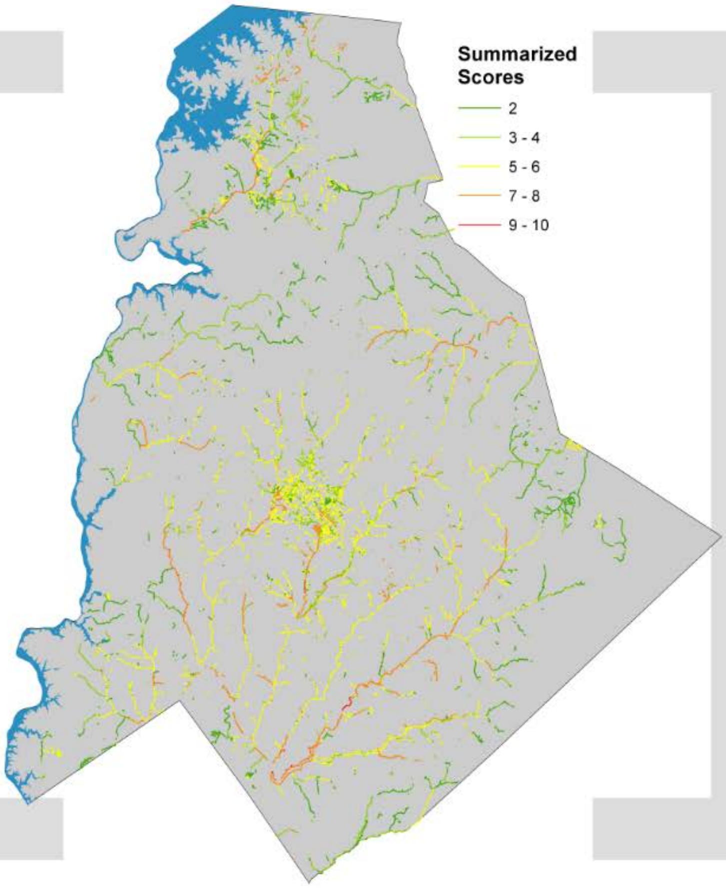
Pipes above Groundwater Elevation Scored by Risk of Sewage Exfiltration



- Average pipe diameter of 8.5 inches: pipes in the upper portions of drainage basins in areas with a high density of survey grade data
- Represents 18.5% of the pipes in the analysis
- Scores only range to 8 (of a possible 10)

Figure 13 - Pipes above groundwater elevation scored according to risk of sewage exfiltration

Pipes below Groundwater Elevation Scored by Risk of Groundwater Infiltration



- Average pipe diameter of 14.4 inches: larger pipes in the lower portions of drainage basins
- Represents 81.5% of the pipes in the analysis

Figure 14 - Pipes below groundwater elevation scored according to risk of groundwater infiltration

Conclusions

Perhaps one of the most useful outputs from this analysis is the groundwater elevation raster. Although "above" and "below" pipe datasets were extracted, due to groundwater elevation fluctuations, there is a transitional area where pipes are submerged only part of the time. The pipe datasets that are currently separated into above and below datasets are not locked down. Pipes can be extracted by varying elevation criteria that reflect weather conditions at the time, but the flow and material scoring will be consistent no matter what the pipe position relative to the groundwater elevation. There are also plans to partner with CMSWS to further refine the statistical methods used to produce the groundwater elevation raster that was chosen for the analysis.

The scored pipes will be a flexible dataset. As more survey grade data of the CLTWater infrastructure is collected, more pipes can be scored and evaluated. The flow data will change over time and will need to be reevaluated as population grows, shrinks, or shifts around the county.

Both the groundwater elevation raster used in the analysis and the scored pipe datasets have been provided to CMSWS, and there are plans to make the data available on the City of Charlotte's Open Data Portal (http://clt.charlotte.opendata.arcgis.com/). The results of this project will also be incorporated into CLTWater's Strategic Operating Plan in 2016, and will be considered for incorporation into the prioritization strategy for pipe rehabilitation planning. This project's innovative use of available datasets has aided progress towards CLTWater's goal of becoming a proactive organization that prevents infrastructure failure through prioritized maintenance.

Prezi URL for accompanying presentation:
http://prezi.com/8lzj6hyt5psy/?utm_campaign=share&utm_medium=copy&rc=ex0share

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