Water Resources Research Institute
of The University of North Carolina

Report No. 399

AN ENVIRONMENTAL WATER QUALITY DATA VISUALIZATION SYSTEM FOR PRIVATE GROUND WATER SUPPLIES

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February 2002

UNC-WRRI-399

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The research on which this report is based was financed by the United States Department of the Interior, Geological Survey, through the N.C. Water Resources Research Institute. Contents of the publication do not necessarily reflect the views and policies of the United States Department of the Interior, nor does mention of trade names of commercial products constitute their endorsement by the United States Government.

WRRI Project No. 50301
February 2002

ACKNOWLEDGMENTS

Many individuals aided in the completion of this project. Gratitude is extended to the personnel at the Division of Environmental Health at the North Carolina Department of Environment and Natural Resources, especially Malcolm Blalock for consultation on data development and analysis. We also thank Glenn Cats from Woodlot Forestry at North Carolina State University for his help with the Avenue programming. We extend our appreciation to the personnel and staff at the Center for Earth Observation at North Carolina State University, especially Beth Eastman for her assistance with editing the report.

Several graduate students aided in the completion of this project; we especially thank Okan Pala, Daniel VanBrunt and Debbie Savage, all from North Carolina State University, for their help. We also thank the staff at the North Carolina State University Libraries for their assistance with data acquisition. Finally, we thank the staff at Water Resources Research Institute for administration of the project.

ABSTRACT

The main purpose of this project was to contribute to the development of a comprehensive water quality database for North Carolina. The project involved three components: building a geospatial database of contaminated private wells in eastern North Carolina; enhancing the geospatial database by assembling data relevant for environmental water quality assessment of private wells; and developing analytical procedures to answer questions concerning the water quality of private wells.

The geospatial database of private wells was built by merging water quality test results data for total coliform, fecal/E.coli, nitrate, and nitrite, and well inspection data for 2,490 private wells. To enhance the geospatial database, about 20 geospatial data layers relevant for environmental water quality assessment of private wells were acquired from various state agencies and were converted to a standard format to facilitate easy and immediate use. We also developed an Internet Map Server application to provide public access to this database through the Internet.

In demonstrating the analytical procedures to answer questions concerning water quality and private wells we focused on spatial relationships between contaminated private wells and swine operations. These procedures included three proximity assessment analyses: proximity of private wells to nearest swine operation; proximity of private wells to swine operations; and proximity of a swine operation to private wells. The results of proximity assessments revealed that there is not a consistent connection between contaminated wells and their proximity to swine operations. On the other hand, the results indicated that swine operations might play a role in contamination of private wells. To further clarify this relationship, future studies should examine the construction characteristics of both contaminated wells and swine operations that are within two miles of each other.

(Key words: Private ground water supplies, water quality, North Carolina)

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SUMMARY AND CONCLUSIONS

SUMMARY

The main purpose of this project was to contribute to the development of a comprehensive water quality database for North Carolina. The project involved building a geospatial database and developing a system for analyzing and visualizing private ground water quality data. This project focused on private wells that tested positive for coliform (post hurricane Floyd samples) in 35 eastern North Carolina counties.

The project had three components. The first component focused on developing a geospatial database of contaminated private wells in eastern North Carolina. This work involved merging two data files: inspection data obtained from the Water Sample and Well Construction Survey (3,156 records) and water quality test results obtained from the State Public Health Laboratory (8,678 records). First, both data files were individually edited and than merged into a single data file. Second, using the latitude and longitude information for each well, we developed a geospatial database of private wells in eastern North Carolina.

A total of 2,490 private wells were included in the analyses. Of those, 2,136 wells had valid test results for total coliform, 470 wells for fecal/E.coli, 2,453 wells for nitrate, and 2,452 wells for nitrite. Overall, about one quarter of the private wells (22%, 470 wells) tested positive for total coliform. The highest percentages of total coliform contaminated wells were in Edgecombe (53%) and Halifax (51%) counties. Only wells that tested positive for total coliform (470 wells) were tested for fecal/E. coli contamination; of those, 8% tested positive for fecal/E.coli and that represents only 2% of all wells tested for total coliform. The highest percentages of fecal/E.coli contaminated wells were in Nash (14%) and Edgecombe (10%) counties. Two percent of the private wells tested for nitrate were contaminated ($\geq$10 mg/l), 5% had low level contamination (5.0-9.99 mg/l), and 93% were not contaminated ($<$0.1 mg/l). The highest percentage of nitrate contaminated wells was in Wayne County (17%). The highest percentages of low level contaminated wells were in Halifax (16%) and Johnston (16%) counties. None of the wells tested for nitrite had levels higher than 1.0 mg/l, the threshold for defining contaminated wells. Overall, a negligible number of wells (0.2%) had low level nitrite contamination (0.1-0.99 mg/l).

The second component of this project focused on enhancing the geospatial database by assembling data relevant for environmental water quality assessment of private wells. These data were acquired from various state agencies and were converted to a standard format to facilitate easy and immediate use. All data for this project are in State Plane, North Carolina, NAD83, meters. The following data layers are included in the database: private wells, Floyd flood extent, special flood hazard areas, public water distribution systems (water pipes, water service type A areas, water service type B areas, water service type P areas), landuse/landcover, animal operations, swine operations, poultry operations, cattle operations, population demographics, occupation, housing units, study area, North Carolina county boundaries, municipal boundaries, major hydrography, and river basins. We developed an Internet Map Server (IMS) application using ArcIMS 3 on-line mapping technology to provide public access to this database through the Internet. This application facilitates the use of the database by state and county officials that do not have in-house GIS capabilities. To access the database the user needs only a computer and an Internet browser.

The third component of this project focused on developing analytical procedures to answer questions concerning water quality and private wells. In demonstrating these analytical procedures we focused on spatial relationships between contaminated private wells and swine operations. Specifically, we wanted to determine if the wells that are closer to swine operations are contaminated more frequently than wells located further away from swine operations. These procedures included three proximity assessment analyses: proximity of private wells to nearest swine operation; proximity of private wells to swine operations; and proximity of swine operation to private wells. For all proximity assessments we analyzed private wells by three contaminants: total coliform, fecal/E.coli, and nitrate. Five distance classes were used for these analyses: 1) 0-0.25 mi.; 2) >0.25-0.50 mi.; 3) >0.50-1.00 mi.; 4) >1.00-2.00 mi.; 5) >2.00 mi. These analyses are intended to serve as examples for examining the spatial relationship between private wells and other factors that may affect the water quality of private wells. Because of limitations in location information for both private wells and swine operations, the results of these analyses are tenuous and should be considered as exploratory.

The first proximity assessment procedure involved examination of the number of contaminated and uncontaminated wells based on distance to the nearest swine operation. This allowed us to determine if the number of contaminated wells increased as the distance to the nearest swine operation decreased.

For total coliform this analysis revealed that the percentage of total coliform contaminated wells decreased as the distance to the nearest swine operation decreased also (Table 6). Overall, about two thirds of the wells tested positive for total coliform (61%) were more than two miles from the nearest swine operation. Within one-quarter mile of a nearest swine operation the percentage of contaminated wells was very small (6%). On the other hand, within the distance classes between one-quarter mile and two miles the percentage of contaminated wells was slightly larger than the overall percentage of wells tested positive for total coliform (24%, 24%, and 26% vs. 22%). The number of total coliform contaminated wells within these distance classes was also not negligible (17, 55, and 110).

The same analysis performed with wells tested for fecal/E.coli revealed that the percentage of fecal/E.coli contaminated wells also decreased as the distance to the nearest swine operation decreased (Table 7). Overall, about half of the wells (55%) that tested positive for fecal/E.coli were more than two miles from the nearest swine operation. No wells tested positive for fecal/E.coli within one-quarter mile of a nearest swine operation. The percentage of contaminated wells within the second distance class was also small (6%). On the other hand, the percentages of wells tested positive for fecal/E.coli within the distance classes between one-half mile and two miles of the nearest swine operation were slightly larger than the overall percentage of wells tested positive for fecal/E.coli (9% and 10% vs. 8%).

For nitrate this analysis showed that the percentage of nitrate contaminated ($\geq$10 mg/l) and low level contaminated (5.0-9.99 mg/l) wells also decreased as the distance to the nearest swine operation decreased (Table 8). Overall, about half of the nitrate contaminated wells (57%) and low level contaminated wells (54%) were more than two miles from the nearest swine operation. The combined percentage of nitrate contaminated and low level contaminated wells within one-quarter mile of the nearest swine operation was greater than the overall combined percentage of nitrate contaminated and low level contaminated wells (10% vs. 7%). The percentages of combined nitrate contaminated and low level contaminated wells within the distance classes between one-half mile and two miles of a nearest swine operation were also larger than the overall combined percentage of nitrate contaminated and low level contaminated wells (10% and 9% vs. 7%). Overall, about half of the nitrate contaminated wells (57%) and low level contaminated wells (54%) were more than two miles from the nearest swine operation.

Classifying private wells by distance to swine operations was the second approach we used to examine the spatial relationship between well contamination and swine operations. The difference between this and the previous analysis is that instead of the nearest swine operation, the wells are classified based on their distance to every swine operation. For this analysis, most private wells were classified in relation to more than one swine operation.

For total coliform this analysis demonstrated that within two miles of a swine operation the percentage of total coliform contaminated wells decreased as the distance to a swine operation also decreased (Table 9). Overall, the percentage of coliform contaminated wells within one-quarter mile of a swine operation was small (6%). On the other hand, the percentages of total coliform contaminated wells within distance classes between one-quarter mile and two miles of a swine operation were slightly greater than the percentage of contaminated wells that were more than two miles from a swine operation (23%, 24%, and 25% vs. 21%).

For fecal/E.coli this analysis revealed that the percentage of fecal/E.coli contaminated wells within one mile of a swine operation decreased as the distance to a swine operation decreased (Table 10). On the other hand, the percentage of wells tested positive for fecal/E.coli located more than one-half mile of a swine operation increased as the distance to a swine operation decreased. None of the wells located within one-quarter mile of a swine operation tested positive for fecal/E.coli. The percentage of fecal/E.coli contaminated wells within the second distance class (0.25-0.5 mi.) was also small (6%). The largest percentage of fecal/E.coli contaminated wells was between one-half and one mile of a swine operation (10%).

Similar analyses performed with wells tested for nitrate levels revealed that the largest combined percentage of nitrate contaminated and low level contaminated wells was within one-quarter mile (10%) and between one-half and one mile of a swine operation (10%) (Table 16). The combined percentage of nitrate contaminated and low level contaminated wells located between one-quarter and one-half mile of a swine operation was 6%. The same percentage for wells located between one and two miles of a swine operation was 8%.

The third proximity assessment procedure involved analyzing the number of swine operations within specified distance of a private well. This analysis allowed us to determine if the number of swine operations in the vicinity of contaminated wells was greater than the number of swine operations in the vicinity of uncontaminated wells. As with the preceding analysis, most swine operations were classified in relation to more than one private well.

For total coliform this analysis revealed that for all distance classes the percentage of swine operations in the vicinity of uncontaminated wells was larger than that in the vicinity of contaminated wells (Table 12). The number of swine operations in the vicinity of total coliform contaminated wells within the first distance class (0-.25 mi.) was very small (1 swine operation). On the other hand, the number of swine operations that may affect contaminated wells between one-quarter mile and two miles of a private well was not negligible (19, 72, 257 swine operations).

Analysis of private wells tested for fecal/E.coli showed that within two miles of contaminated wells (38 wells) there were total of 29 swine operations (Table 13). While the number of swine operations within one-half mile of a contaminated well was not notable (1 swine operation), the total number of swine operations within one and two miles of a contaminated well was not negligible (21 swine operations).

Analysis for nitrate revealed that for all distance classes the percentage of swine operations in the vicinity of uncontaminated wells was substantially larger than the percentage of swine operations in the vicinity of contaminated and low level contaminated wells (Table 14). The number of swine operations within one-half mile of contaminated or low level contaminated wells did not seem very remarkable: 7 swine operations. However, the number of swine operations between one-half and two miles of a contaminated or low level contaminated well was quite high: 137 swine operations.

CONCLUSIONS

Overall, the analysis of spatial relationships between private wells that tested positive for total coliform and swine operations revealed no clear link between contaminated wells and the proximity to swine operations. In general, the number of swine operations within one-quarter mile of a contaminated well was quite small. However, the results of all three proximity analyses demonstrated that the percentage of total coliform contaminated wells within two miles of a swine operation was slightly larger than the percentage of contaminated wells located more than two miles from a swine operation and that a large number of swine operations were within two miles of a contaminated well.

Fecal/E.coli positive tested wells showed a similar trend: very few swine operations were within one-half mile of a contaminated well. On the other hand, the percentage of contaminated wells within two miles of a swine operation was greater than the percentage of contaminated wells located more than two miles from a swine operation and, again, a large number of swine operations were within two miles of a contaminated well.

The analyses of wells tested for nitrate showed a slightly different pattern. The combined percentage of contaminated and low level contaminated wells from two distance classes–within .25 mile and >.5-2.0 miles–was larger than the combined percentage of contaminated and low level contaminated wells in the other distance classes. Also, a noteworthy number of swine operations were within one-half and two miles of a contaminated well.

Although these results did not demonstrate a direct link, they imply that swine operations may be a contributing factor to contamination of private wells. Further research is needed to examine this issue.

RECOMMENDATIONS

There are two sets of recommendations related to the work performed for this project. The first set relates to preparing a geospatial database and the second relates to analytical procedures performed to answer questions concerning water quality and private wells.

A crucial aspect of examining the water quality of private wells involves preparing a valid geospatial database. We spent an unpredictably large amount of time developing the database for this project. This was due primarily to the large number of field data collection and transcription errors. The biggest challenge was merging the inspection data obtained from the Water Sample and Well Construction Survey with the water quality test results data obtained from the State Public Health Laboratory. The major problem was the lack of consistency in recording and entering the well identification information (address, owner name etc.) in the two digital files that we had to merge. We strongly recommend that in the future a unique identifier be assigned to each well as part of initial data collection activity and that this identifier be used every time new data are collected or entered in a digital file. Using the owner name or the address information as the only identifier does not work well. Owner name and address information could be maintained in the same or perhaps a separate file also linked with this identifier. This procedure will greatly reduce the time needed to create and update the well data.

A second important aspect of preparing a valid geospatial database involves collecting and recording well location information. The main problem in plotting well positions was the different formats in which the latitude and longitude information were recorded. The best solution to the problem is to ensure that all personnel are instructed to record this information in the same format, preferably decimal degrees. If this is not possible, then the format of each GPS reading should be recorded with latitude and longitude information. This will ensure that proper transformations can be performed. Clearly, obtaining accurate spatial information for groundwater wells and potential contamination sources (such as swine operations) is crucial to the validity of such studies.

In combination, the three analytical procedures that we used to examine the spatial relationship between private wells and swine operations provide a useful basis for understanding of the relationship between contaminated wells and distance to swine operations. These procedures can be used to assess relationships between contaminated wells and distance to other features that may affect the quality of private well waters.

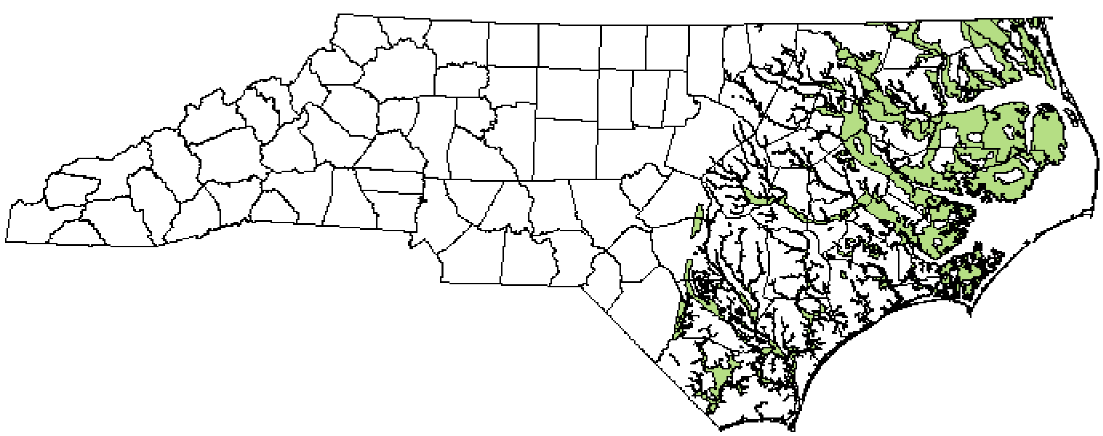
The results of these analyses revealed that there is no consistent connection between contaminated wells and their proximity to swine operations. On the other hand, the results indicate that swine operations may play a role in contamination of private wells. To further clarify this relationship, future studies should examine the construction characteristics of both contaminated wells and swine operations within two miles of each other. At certain critical locations, assessments should also include detailed analysis of surface and ground water flow characteristics, the geology of the region, soil types, percolation rates, and landuse/landcover features around contaminated wells. These analyses, coupled with the analyses of construction characteristics of contaminated wells and swine operations, would provide a more complete understanding of the relationship between contaminated wells and swine operations.

INTRODUCTION

Of the many natural disasters that threaten North Carolina communities, hurricanes, especially near coastal areas, are a recurring hazard with unpredictable impacts. According to the Federal Emergency Management Agency (FEMA) at least five hurricanes strike the United States every three years. North Carolina has experienced 25 hurricane landfalls between 1900-1996, 11 of them in category 3, 4, or 5 in the Saffir/Simpson rating system (Federal Emergency Management Agency 1997, National Hurricane Center – Tropical Prediction Center 1999).

Floyd was the most recent hurricane and struck eastern North Carolina in September 1999. The resulting devastation from the combination of winds and storm surge included: 48 deaths; more than 1,400 flooded or washed out roads; thousands of uninhabitable houses; hundreds of flood-damaged businesses; 277 flooded old landfills; more than 139 underground fuel tanks leaked, shifted or popped out of the ground; 35 flooded superfund hazardous waste sites; about 28,000 hogs killed; and untold millions of gallons of lagoon waste released into surface waters (Shiffer 1999, Price and Bickley 1999, Williams and Eisley 1999). Floyd affected all counties in eastern North Carolina, however Duplin, Beaufort, Wilson, Edgecombe, Pitt, Jones, Wayne, Nash, and Lenoir were the hardest-hit counties. The extent of flooding associated with hurricane Floyd is shown on the map in Figure 1.

Figure 1. Hurricane Floyd flood extent (FEMA, September 23 – 25, 2000 data)



The extensive flooding directly affected the quality of surface waters in eastern North Carolina. Since surface waters can influence ground waters it is likely that the quality of ground water supplies was also negatively affected by the flooding. This is mainly a result of shallow wells and shoddy construction that enable runoff to seep into the ground water. Analyses of water samples from public and private wells revealed that almost one-third of the drinking water wells showed bacterial contamination in the aftermath of Floyd. Although this level is not considered to be worse than before the flood, it indicates a persistent alarming health risk to drinking water supplies in eastern North Carolina. State and local officials need to have a better understanding of ground water contamination and the quality of drinking water supplies. Identifying contaminated wells and pollution sources that are persistent over time is needed to improve, correct or replace drinking-water wells that pose the greatest risks to human health.

The North Carolina Department of Environment and Natural Resources (NCDENR) has placed a high priority on monitoring and improving the quality of drinking-water supplies in North Carolina and supports several programs dealing with this issue. Following are some of the current efforts associated with the quality of drinking-water supplies:

- The Source Water Assessment Program (SWAP) focuses on assessment of all water sources that are used by public water suppliers in order to determine their susceptibility to contamination from several different types of contaminant sources. Source water assessments will allow the state to systematically address issues of potential contamination of public water supplies using existing data from established environmental programs. A geographic information system (GIS) will be used to locate contaminant sources relative to public water supply water sources.
- Detection, Occurrence and Risks of Microbial Contamination in Public Ground Water Supplies of the Eastern North Carolina Region Impacted by the 1999 Hurricanes and Floods deals with the quality of public water systems. This project intends to survey all public wells in the flooded area of eastern North Carolina for persistent microbial contaminants.
- The Water Sample and Well Construction Program involves sampling and inspecting each private well in eastern North Carolina that tested positive for coliform (post hurricane Floyd samples). The wells were sampled for total coliform, fecal/E.coli, nitrate, and nitrite. A water sample and well construction survey form is also completed for each well. The survey focused on well characteristics, previous flooding, and proximity to various contamination sources.

This research project builds upon and expands the last project and seeks to fill knowledge gaps in the current understanding of water quality problems that affect private ground water supplies.

PROJECT OBJECTIVES

The main purpose of this project is to contribute to the development of a comprehensive water quality database for North Carolina. The project involves building a digital geospatial database and developing a system for analyzing and visualizing private ground water quality data and focuses primarily on private wells that tested positive for coliform (post hurricane Floyd samples) in eastern North Carolina.

The project has three components. The first component focuses on developing geospatial database of contaminated private wells in eastern North Carolina. The data were provided by NCDENR, which has completed sampling and inspecting each contaminated private well that may have been affected by flooding from recent hurricanes. The completed water sample and well construction survey included the latitude and longitude of each well obtained using global positioning system (GPS) technology. Information about the well characteristics and water sample test results from the survey are included in the database. Using this database, it is possible to prepare thematic maps of private wells by type of construction, type of contamination, etc. These data are made available to all interested state and county public officials. Public access to sample maps is also being provided through the Internet using on-line mapping technology which provides interactive access to the database.

The second component of this project focuses on enhancing the geospatial database by assembling data relevant for environmental water quality assessment of private wells and by developing a visualization system for environmental water quality data. The database includes data for assessing possible pollution sources of private wells, such as flood extents (Floyd and FEMA digital Q3 flood data), landuse/landcover, animal operations, population densities, etc. The database also includes data for assessing the proximity of private wells to existing and proposed public water supply systems and for identifying population groups that are at greatest human health risk. These data include population demographics such as income distribution, urban/rural distribution, farm population, distribution of aged population, racial distribution, and population density. These data were acquired from various state agencies and have been converted to a standard format to facilitate easy and immediate use. All data have the same projection and geographic extent and are provided as a package in a ArcView GIS format for ready distribution to state and county officials. Public access to the database is provided through the Internet. This facilitates use of the database by state and county officials that do not have in-house GIS capabilities.

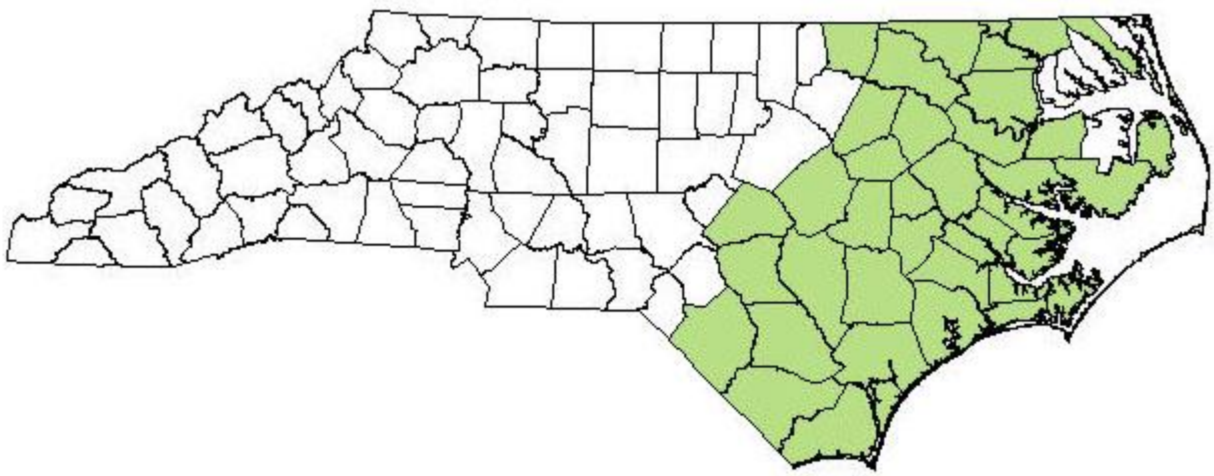
The third component of this project focuses on developing analytical procedures to answer questions concerning water quality and private wells. These analyses serve as examples for use of the database. Demonstration analyses for this project include proximity assessment of contaminated wells in relation to swine operations. A few proximity assessment procedures have been developed in an attempt to determine whether or not swine operations are an important source of contamination for private wells.

METHODS

STUDY AREA

The study area for this project encompasses the 35 counties in eastern North Carolina that are part of the Water Sample and Well Construction Program supported by NCDENR Division of Environmental Health (DEH). This program involved sampling and inspecting each private well that tested positive for coliform (post hurricane Floyd samples). The wells were tested for total coliform, fecal/E.coli, nitrate, and nitrite. In addition, well construction and contamination source data were collected for each well. These data were collected between March and July 2000. The counties included in this program are: Beaufort, Bertie, Bladen, Brunswick, Camden, Carteret, Columbus, Craven, Cumberland, Dare, Duplin, Edgecombe, Gates, Greene, Halifax, Harnett, Hertford, Hyde, Johnston, Jones, Lenoir, Martin, Nash, New Hanover, Northampton, Onslow, Pamlico, Pender, Pitt, Robeson, Sampson, Warren, Washington, Wayne, Wilson (Figure 2).

Figure 2. Counties in the study area



DEVELOPING A DIGITAL GEOSPATIAL DATABASE OF CONTAMINATED PRIVATE WELLS

The first component of this project focused on developing a geospatial database of private wells in the 35 county study area. This work involved merging two databases. The first database contained inspection data obtained from the Water Sample and Well Construction Survey (referred to as inspection data) and the second database consisted of water sample test results obtained from the State Public Health Laboratory (referred to as the test results data). In March 2001, DEH provided us with the two databases and the associated inspection survey data collection forms. Following is a description of the procedures for creating the digital geospatial database of contaminated private wells.

The Inspection Data

The DEH provided us with an electronic data file (3,156 records) containing the Water Sample and Well Construction Survey data in an Access format that we converted to a DBF file format to make it compatible with ArcView GIS software. Using the inspection survey data collection forms, we checked each record in the data file to eliminate invalid records (e.g., invalid surveys, duplicates, etc.). A final edit was performed to ensure that data in the well owner name and address fields were consistent with corresponding data in the test results data file. This procedure was necessary to facilitate merging these two data files.

The Test Results Data

This electronic data file (8,678 records) contains test results obtained from State Public Health Laboratory for water samples collected by DEH between March and July of 2000. First, we converted the original file that was provided in an Access format to a DBF file format. This data file contained multiple records for each well - one record for each potential contaminant: total coliform, fecal/E.coli, nitrate, and nitrite.

Merging the Inspection and Test Results Data

The third step in preparing the digital database was to merge inspection and test results data files into a single file. Initially, we attempted to perform automated matching procedures based on well-owner name and on well address information. However, we discovered a number of problems that caused a significant number of valid records to remain unmatched (e.g. misspelled or abbreviated owner name; misspelled or abbreviated address information; inconsistent formats for recording names (first, last name vs. last, first name); different owner name for the same well (husband/wife, father/son, etc.); multiple records for the same test result, etc.) As a result, matching was performed manually using the automated results as a guide. This work was performed county by county using well owner-name and address data. In cases where we were not able to make a decision, we consulted with Malcolm Blalock from NCDENR DEH. In the end, 7,921 test results records were matched with an inspection data record. These records corresponded to 2,618 well records. Each test results record consisted of data for total coliform, fecal/E.coli, nitrate, and nitrite followed by well inspection data.

Building the Geospatial Database

Building a geospatial database requires that location data for each feature be recorded in the same geographic coordinates (latitude/longitude). Unfortunately, we discovered that well locations were recorded on the DEH survey forms in five different formats. That problem was compounded by the fact that all location data had been entered into the electronic data file as if they were degrees-minutes-seconds. Therefore, we manually checked location data for each well, entered corrections as necessary based on information recorded on the survey form, and ultimately converted all location data to latitude and longitude recorded as decimal degrees using Avenue scripts written for ArcView 3.x. As a data quality check we inspected a plot of the well locations to make sure each well fell into the correct county. For wells that plotted incorrectly we reviewed the location recorded on the survey form and corrected the digital data as appropriate.

The final shapefile consisted of 2,490 private well records (79% of the inspection data records) and 7,520 test results records (87% of the total number of test results records). The final ArcView shapefile is in State Plane coordinate system (NAD83, meters).

The positional accuracy of well locations is directly related to the accuracy of the GPS units used by county personnel who collected the inspection data. Unfortunately, there is no record of the quality of the GPS units used. We only know that different counties used different recreation-grade GPS units. Since the well locations were recorded before the US Department of Defense eliminated selective availability, we estimate that location data of 95% of the wells are accurate to within 100 meters (Trimble Navigation Limited 1997). Using this as a guiding criterion, we included wells that plotted 100 meters of the coastline in the final database (21 wells plot off shore, but all of them are less than 50 meters from the coastline).

ASSEMBLING AND VISUALIZING ENVIRONMENTAL WATER QUALITY DATA

Data Relevant for Environmental Water Quality Assessment of Private Wells

The second component of this project focused on enhancing the geospatial database by assembling data relevant for environmental water quality assessment of private wells. The database includes data for assessing possible pollution sources of private wells, such as flood extents (Floyd and FEMA digital Q3 flood data), landuse/landcover, animal operations, population densities, etc. The database also includes data for assessing the proximity of private wells to existing and proposed public water supply systems and for identifying population groups that are at greatest human health risk. These data include population demographics such as income distribution, urban/rural distribution, farm population, distribution of aged population, racial distribution, and population density. We have also included the following geospatial data for reference purposes: study area, North Carolina county boundaries, municipal boundaries, major hydrography, and river basins. These data were acquired from various state agencies and were converted to a standard format to facilitate easy and immediate use. All data for this project are in State Plane, North Carolina, NAD83, meters. When available, we have included the original metadata files in the CD containing the environmental water quality assessment data files. Table 1 shows the list of all data included in the environmental water quality database. Following are brief descriptions of these data.

Floyd Flood Extent. These data were obtained from FEMA and represent EarthSat's final flood interpretation, as polygons, from Sept. 23 Extended High RADAR data and Sept. 25 ScanSAR RADAR data. Pre-flood TM satellite data and client-provided Q3 data had been used to help identify areas prone to flooding. The original data were clipped with North Carolina boundaries obtained from the TIGER 2000 county boundaries file provided by the NC General Assembly.

Special Flood Hazard Areas. These data were developed from FEMA county Digital Q3 Flood data for the following counties: Beaufort, Bertie, Bladen, Brunswick, Camden, Carteret, Columbus, Craven, Cumberland, Currituck, Dare, Duplin, Edgecombe, Greene, Halifax, Harnett, Hyde, Johnston, Jones, Lenoir, Nash, New Hanover, Onslow, Pamlico, Pasquotank, Pender, Pitt, Robeson, Sampson, Warren, Washington, Wayne, and Wilson. Digital Q3 flood data are not available for five counties in the study area: Gates, Hertford, Martin, Northampton, and

Washington. These data were first merged into a single coverage and then projected to State Plane, North Carolina, NAD83, meters.

Table 1. List of data layers included in the environmental water quality assessment database

Private Wells
Floyd Flood Extent
Special Flood Hazard Areas
Public Water Distribution Systems
Water pipes
Water service type A areas
Water service type B areas
Water service type P areas
Landuse/landcover
Animal Operations
Swine Operations
Poultry Operations
Cattle Operations
Population Demographics
Occupation
Housing Units
Study Area
NC County Boundaries
Municipal Boundaries
Major Hydrography
River Basins

Landuse/landcover. These data were obtained from the NC Center for Geographic Information and Analysis (NCCGIA). The original data are in ERDAS/Imagine format and represent the statewide landcover data obtained from LandSat Thematic Mapper data. These data were clipped with the study area boundary obtained from TIGER 2000 county boundaries file provided by the NC General Assembly. The legend includes land cover classes as defined in the original metadata.

Animal Operations. These data contain unverified locations of intensive livestock operations registered with the NCDENR Division of Water Quality. Since the original data are unverified, we plotted the animal operation locations to make sure each operation fell into the correct county. We deleted 182 animal operations that plotted in an incorrect county (out of a total of 2,643).

Swine Operations. These data are a subset of the animal operations data.

Poultry Operations. These data are a subset of the animal operations data.

Cattle Operations. These data are a subset of the animal operations data.

Public Water Distribution Systems. These data, obtained from the NCCGIA, include: water pipes, water service type A areas, water service type B areas, and water service type P areas. Water pipes represent locations of pipelines for water distribution. Type A water service areas are areas of existing public "Community Water Systems" for provision to the public of piped water. Type B water service areas are areas showing the boundaries of "B" water systems as defined by NC Rural Economic Development Center (NCREDC). Type P water service areas are areas to be served by proposed water systems.

Demographics. 1990 Census data by census tracts are included in the database for this project (Data from the 2000 Census were not available). Census tracts were developed from raw 1999 TIGER line files. Census tract data for each county were first converted to individual shapefiles and then merged into a single shapefile. The resulting data was projected to State Plane NAD83, meters format and then clipped with the shoreline derived from the NCCGIA major hydrography data. Following edits were necessarily made during these procedures:

- Polygons that had two records in the attribute table or census tracts made up of two or more polygons were consolidated into one record or polygon
- "Sliver" polygons were eliminated
- The most northeast and most southeast census tracts were updated (extended) based on the major hydrography data layer
- A new field "tract_av" was added to the attribute table to facilitate joining Census data to the census tracts shapefile.

The 1990 Census data were joined to the census tracts shapefile. We created three separate shapefiles: demographics, occupation, and housing units. The demographic file includes age, race, population density, and income information. The occupation data file includes occupation information, and housing units data file incorporates urban/rural housing unit information.

Study Area. This data file contains county boundaries within the study area. We developed these data from the TIGER 2000 county boundaries file acquired from the NC General Assembly and projected them to a standard projection format (State Plane, NAD83, meters).

North Carolina County Boundaries. These data were developed from TIGER 2000 county boundaries file for North Carolina acquired from the NC General Assembly. For this project the original data were projected to a standard projection format (State Plane, NAD83, meters).

Municipal Boundaries. This data file includes jurisdictional boundaries of incorporated municipalities in North Carolina that participated in the 1999 Powell Bill and was acquired from NCCGIA.

Major Hydrography. This data file includes major surface waters delineated on the US Geological Survey 1:100,000-scale published map series. Surface waters include oceans, sounds, estuaries, rivers, streams, lakes and reservoirs. For this project we deleted land polygons/islands from the original file we acquired from NCCGIA.

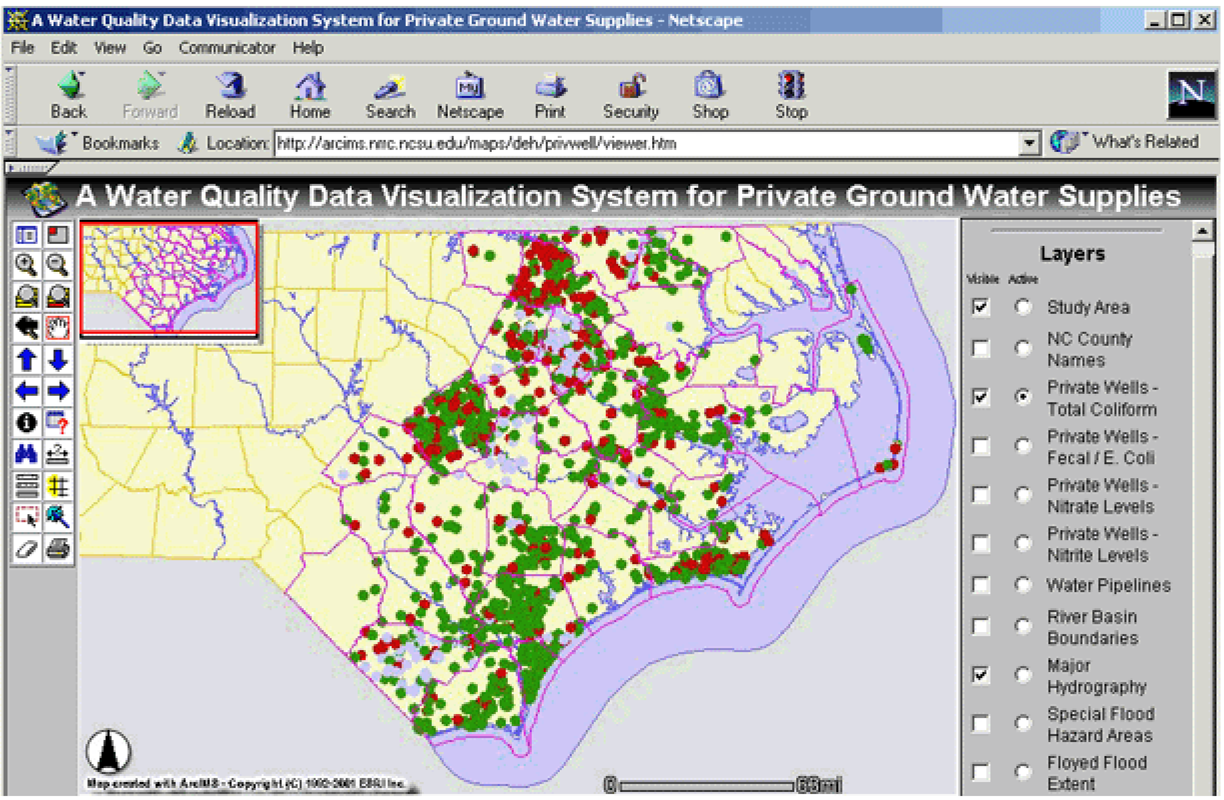
River Basins. This data file includes hydrologic units designated by the USDA Natural Resources Conservation Service (NRCS) in <u>North Carolina Hydrologic Unit River Basin Study,</u>

September 1994 and reviewed by the NC Division of Water Quality. These data were acquired from NCCGIA.

Visualizing Environmental Water Quality Data

To provide public access to this database, we have developed an Internet Map Server (IMS) application using ArcIMS 3 on-line mapping technology. This will facilitate the use of the database by state and county officials that do not have in-house GIS capabilities. In order to access this database users need only a computer and an Internet browser. This application was developed in a server located at the Center for Earth Observation at the North Carolina State University and is accessible at: http://arcims.nrrc.ncsu.edu/maps/deh/privwell (Figure 3). For continuous access to this database, we need a permanent server dedicated to this project. Work is underway to move this application to a permanent server at the NC State University Libraries.

Figure 3. Internet Map Server application



SPATIAL ANALYSES

The third component of this project focused on developing analytical procedures to answer questions concerning the water quality of private wells. As a result of discussions with representatives from NCDENR DEH (Linda Sewall and Malcolm Blalock), we decided to examine private well locations in relation to swine operations to demonstrate the analytical procedures that can broaden our understanding of contamination sources. In order to determine if there is any spatial relationship between contaminated private wells and proximity to swine operations we developed three proximity assessment procedures. These procedures examined test results based on 1) distances between each well and the nearest swine operation, 2) distances between each well and all swine operations, and 3) distances between each swine operation and all wells. Each procedure was performed for each of three contaminants: total coliform, fecal/E.coli, and nitrate. (Nitrite was excluded from these analyses because only five wells had low level nitrite contamination.) For all of these analyses the following categories were used:

- Total coliform:
  - Present
  - Absent
- Fecal/E.coli:
  - Present
  - Absent
- Nitrate (NO3):
  - Not contaminated: 0 - 4.99 mg/l
  - Low level contaminated: 5.0 - 9.99 mg/l
  - Contaminated: $\geq$ 10 mg/l

We used the following distance classes for all proximity assessments:

1. Distance class: 0 - .25 mile
2. Distance class: > .25 - .5 mile
3. Distance class: > .5 - 1.0 mile
4. Distance class: > 1.0 - 2.0 miles
5. Distance class: > 2.0 miles

Proximity of Private Wells to Nearest Swine Operation

This analysis involved examining the number of contaminated and uncontaminated wells in relation to the nearest swine operation. This procedure was accomplished using the “spatial join” procedure in ArcView 3.2. in which each well is assigned a nearest swine operation and the distance to it is calculated (Figure 4). Using this distance measurement, we classified the wells into distance categories specified above.

Proximity of Private Wells to Swine Operations

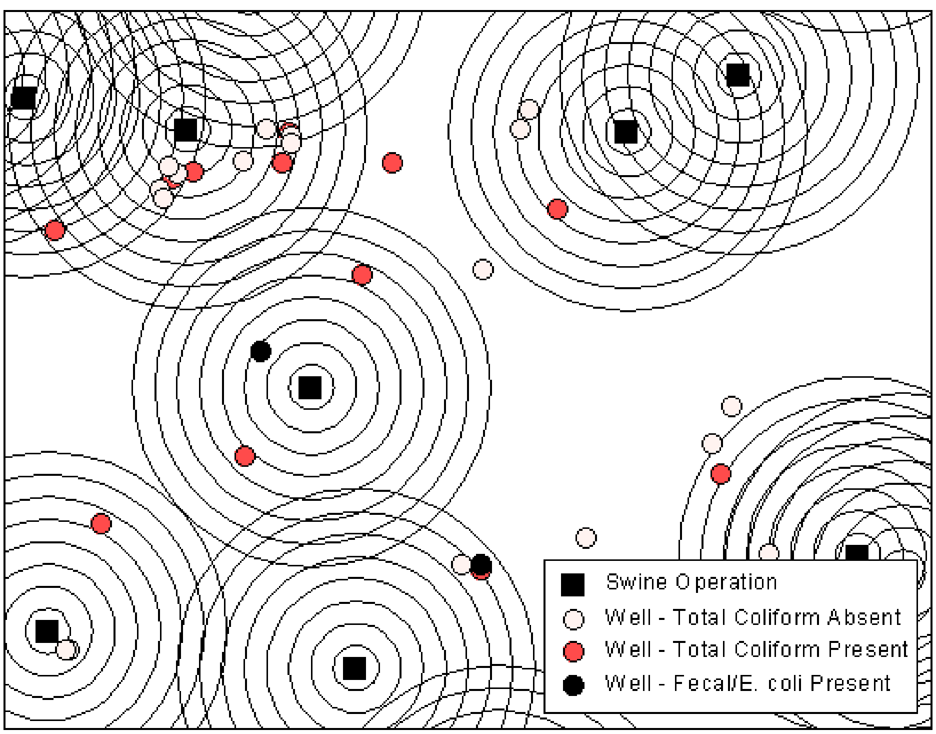
Classifying private wells by distance to swine operations is another approach for examining the relationship between well contamination and swine operations. The difference between this and the previous analysis is that instead of the nearest swine operation, the wells are classified based on their distance(s) to every nearby swine operation. This analysis involved classifying private wells by distance to each swine operation using the "create buffer" procedure in ArcView 3.2 (Figure 5). Buffers are rings around each feature at a specified distance from the feature. For this analysis, we created eight concentric buffers around each swine operation using .25 mile

Figure 4. Example from the attribute table for private wells after the spatial join procedure

Attributes of Wells_swineop1.shp

Well_id	Loccode	Invadd2	Total_coli	Coldate_fc	Control	Distance	Dis_miles
24	PENDER	Watha, NC	Absent	20000502	0	521.841	0.324257
29	CARTERET	Beaufort, NC	Present	20000523	0	8988.985	5.585495
31	CARTERET	Beaufort, NC	Absent	20000524	0	20468.553	12.718565
32	CARTERET	Gloucester, NC	Absent	20000523	0	10362.170	6.438752
33	CARTERET	Beaufort, NC	Absent	20000524	0	16895.396	10.498309
36	CARTERET	Beaufort, NC	Absent	20000327	0	8355.295	5.191738
37	EDGECOMBE	Tarboro, NC	Absent	20000525	0	7550.680	4.691774
38	HYDE	Swan Quarter, NC	Absent	20000510	0	2834.144	1.761055
39	HYDE	Belhaven, NC	Absent	20000516	0	7826.942	4.863435
40	JOHNSTON	Willow Springs, NC	Present	20000427	0	6529.298	4.057116
43	MARTIN	Williamston, NC	Present	20000515	0	11585.507	7.198898
44	PAMLICO	Oriental, NC	Present	20000517	0	8682.063	5.394782
48	PAMLICO	Oriental, NC	Absent	20000330	0	8264.948	5.135599
50	CARTERET	Beaufort, NC	Absent	20000523	0	8210.007	5.101460

Figure 5. Example of buffering procedure around the swine operations*



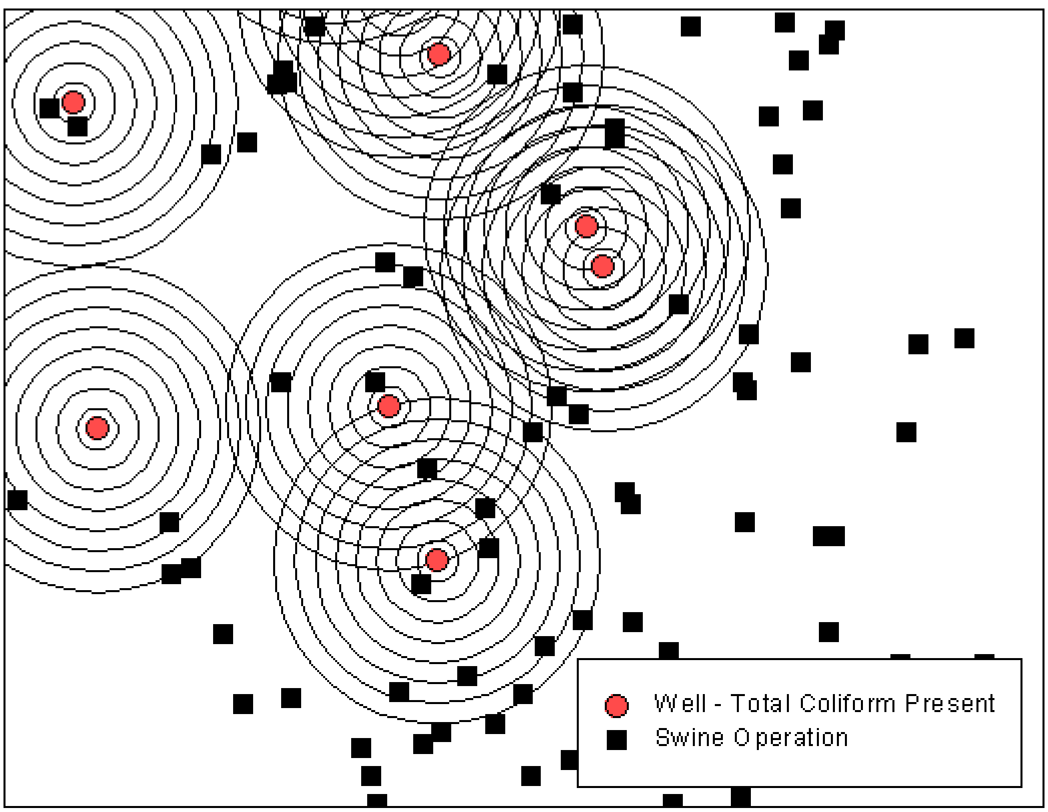
* The buffers are at .25-mile distance from each other.

increments. Then, all the wells located within .25 mile of any swine operation were assigned to distance class 1; wells that were >.25 - .5 mile from any swine operation were assigned to distance class 2; and so forth. Using this procedure many wells are assigned to more than one distance class. For example, a well located .25 mile from one swine operation and 1.5 miles from another swine operation would be counted in two separate distance classes. This analysis allows for the possibility that swine operation other than the nearest one might cause contamination, depending on the direction of flow of surface and underground waters.

Proximity of Swine Operations to Private Wells

This analysis involved analyzing the number of swine operations within specific distances of private wells. This procedure was again performed using the "create buffer" procedure in ArcView 3.2. In this case, we created buffers around the private wells and then classified swine operations based on the buffer(s) in which they were located. For this analysis, we had to create separate geospatial database for each contamination level of each contaminant (7 in total). Then, we buffered the wells in each database. (Figure 6)

Figure 6. Example of buffering procedure around the private wells tested positive for total coliform*



* The buffers are at .25-mile distance from each other.

RESULTS

TEST RESULTS BY CONTAMINANT

The first set of analyses examines the distribution of contaminated and uncontaminated wells by contaminant and by contaminant by county. In examining the distribution of contaminated wells by county, we looked only at counties with 30 or more wells. Potential contaminants include total coliform, fecal/E.coli, nitrate, and nitrite. Contaminants were analyzed by the following categories:

- Total coliform:
  - Present
  - Absent
- Fecal/E.coli:
  - Present
  - Absent
- Nitrate (NO_3):
  - Not Contaminated: 0 - 4.99 mg/l
  - Low Level Contaminated: 5.0 - 9.99 mg/l
  - Contaminated: $\geq$ 10 mg/l
- Nitrite (NO_2):
  - Not Contaminated: < 0.1 mg/l
  - Low Level Contaminated: 0.1 - 0.99 mg/l
  - Contaminated: $\geq$ 1.0 mg/l

Total Coliform

A total of 2145 wells were tested for total coliform. However, we had to drop nine wells from the analyses because the test results data were incomplete or too old. Therefore, 2,136 private wells are included in this analysis. The test results for total coliform are shown in Figure 7 and Table 2. Overall, 78% (1,666) of the wells were not contaminated and 22% (470) were contaminated. In 2 of the 13 counties with 30 or more wells, Edgecombe and Halifax, slightly more than 50% of the wells were contaminated (53% and 51%, respectively). In 8 of these 13 counties less than 25% of the wells were contaminated.

Figure 7. Sample test results for total coliform

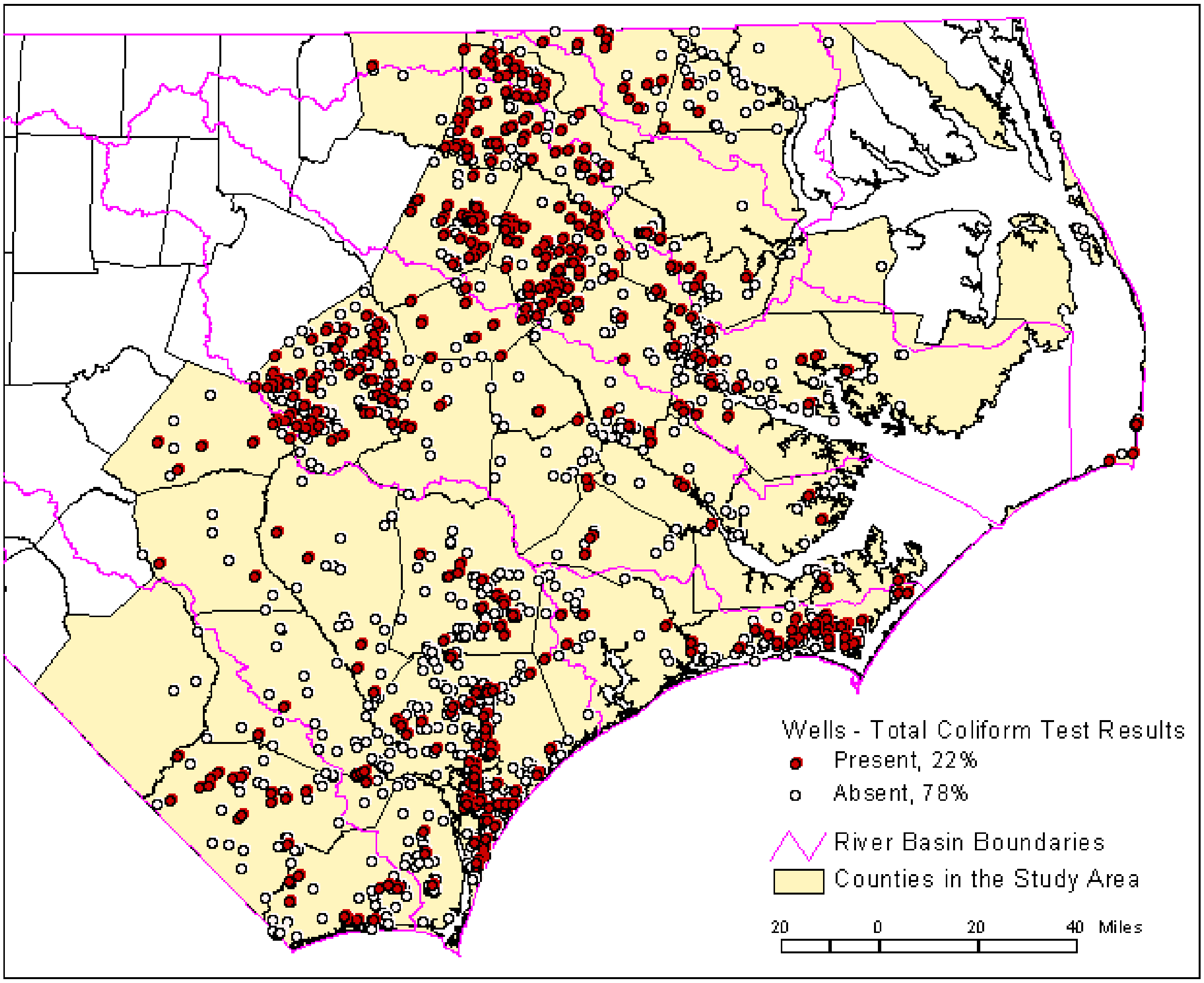


Table 2. Sample test results for total coliform by county

County	Total coliform present (%)	Total number of wells
Beaufort	12%	137
Brunswick	10	125
Carteret	23	166
Columbus	29	66
Duplin	13	120
Edgecombe	53	109
Halifax	51	118
Johnston	35	163
Martin	29	45
Nash	23	154
New Hanover	10	401
Pender	15	202
Pitt	20	59
All counties	22%	2,136

Note: Counties with fewer than 30 wells are not shown.

Fecal/E.coli

The 470 wells that tested positive for total coliform were also tested for fecal/E. coli contamination. Test results for fecal/E.coli are shown in Figure 8 and Table 3. Ninety-two percent (432) of the 470 wells were not contaminated and 8% (38) were contaminated. Thus, out of the 2,136 wells tested for total coliform only 2% (38) were contaminated with fecal/E.coli. The percenteage of contaminated wells in the 7 counties with 30 or more wells ranged from 0% (Johnston County) to 14% (Nash County).

Figure 8. Sample test results for fecal/E.coli

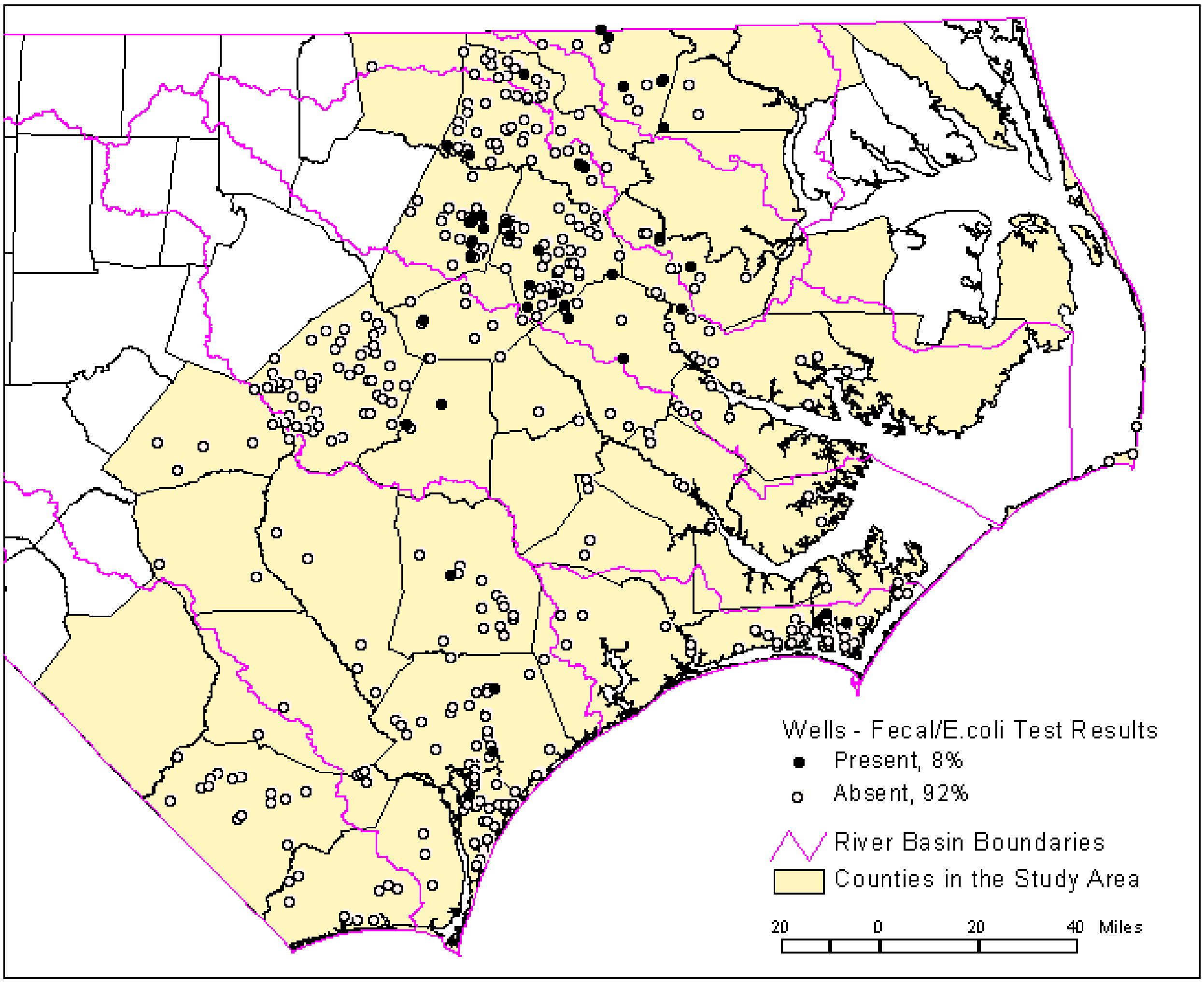


Table 3. Sample test results for fecal/E.coli by county

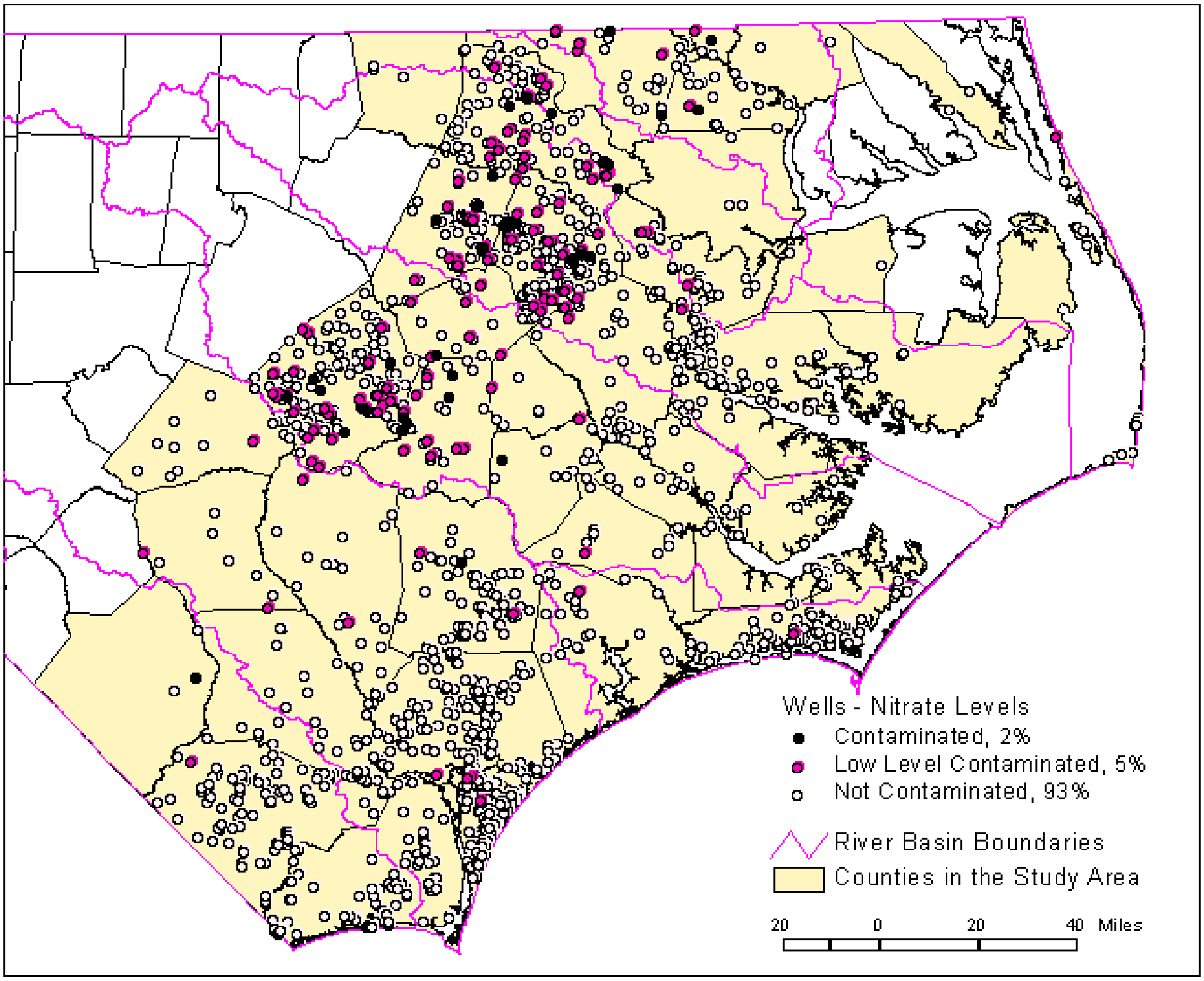
County	Fecal/E.coli present (%)	Total number of wells
Carteret	8%	38
Edgecombe	10	58
Halifax	8	60
Johnston	0	57
Nash	14	35
New Hanover	3	39
Pender	6	31
All counties	8%	470

Note: Counties with fewer than 30 wells are not shown.

Nitrate

Test results for nitrate are shown in Figure 9 and Table 4. Of the 2,453 private wells tested for nitrate, 93% (2,284) were not contaminated 5% (132) had low level contamination, and 2% (37) were contaminated. The percentage of contaminated wells in the 15 counties with 30 or more wells ranged from 0% (in 8 counties) to 17% (in Wayne County). In 6 of these 15 counties, the percentage of contaminated wells ranged from 1 to 6%. The percentage of low level contaminated wells in these counties ranged from 0 to 24%. In three counties, the percentage of low level contaminated wells was greater than 15%: Halifax (16%), Johnston (16%), and Wayne (24%).

Figure 9. Sample test results for nitrate*



* Not contaminated: 0 - 4.99 mg/l; Low level contaminated: 5.0 - 9.99 mg/l; Contaminated: $\geq$ 10 mg/l

Table 4. Sample test results for nitrate by county

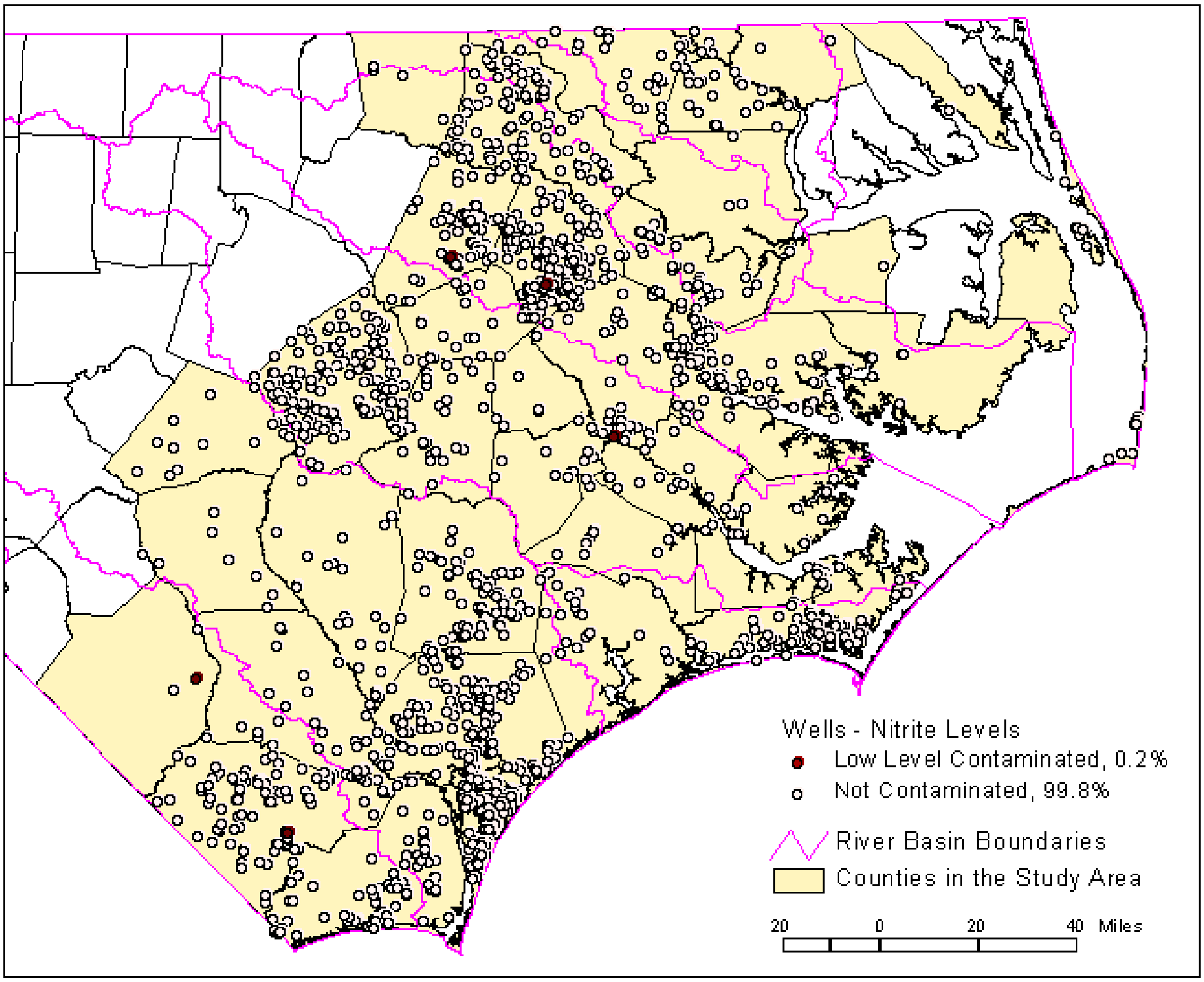
County	Low level contaminated (5.0-9.99 mg/l) (%)	Contaminated (≥10 mg/l) (%)	Total number of wells
Beaufort	0%	0%	137
Brunswick	0	0	125
Carteret	1	0	167
Columbus	1	0	144
Duplin	2	1	124
Edgecombe	10	3	243
Halifax	16	5	114
Johnston	16	4	165
Martin	9	0	46
Nash	9	2	186
New Hanover	1	0	411
Northampton	13	6	31
Pender	0	0	214
Pitt	5	0	58
Wayne	24	17	41
All counties	5%	2%	2,453

Note: Counties with fewer than 30 wells are not shown.

Nitrite

Sample test results for nitrite are shown in Figure 10 and Table 5. Of the 2,452 private wells tested for nitrite, 99.8% (2,447) were not contaminated and only 0.2% (5) had low level contamination. None of the wells had nitrite levels higher than 1.0 mg/l, which is the threshold for distinguishing low level contaminated from contaminated wells. Of the 15 counties with 30 or more wells, only 3 had low level nitrite contaminated wells and the percentage of low level contaminated wells in these counties was only 1% (Columbus and Nash Counties) or 2% (Pitt County).

Figure 10. Sample test results for nitrite*



* Not contaminated: < 0.1 mg/l; Low level contaminated: 0.1 - 0.99 mg/l;
  Contaminated: ≥ 1.0 mg/l

Table 5. Sample test results for nitrite by county

County	Low level contaminated (0.1-0.99 mg/l) (%)	Contaminated (≥1.0 mg/l) (%)	Total number of wells
Beaufort	0%	0%	137
Brunswick	0	0	125
Carteret	0	0	167
Columbus	1	0	144
Duplin	0	0	124
Edgecombe	0	0	243
Halifax	0	0	114
Johnston	0	0	165
Martin	0	0	46
Nash	1	0	186
New Hanover	0	0	411
Northampton	0	0	31
Pender	0	0	214
Pitt	2	0	58
Wayne	0	0	41
All counties	0%	0%	2,452

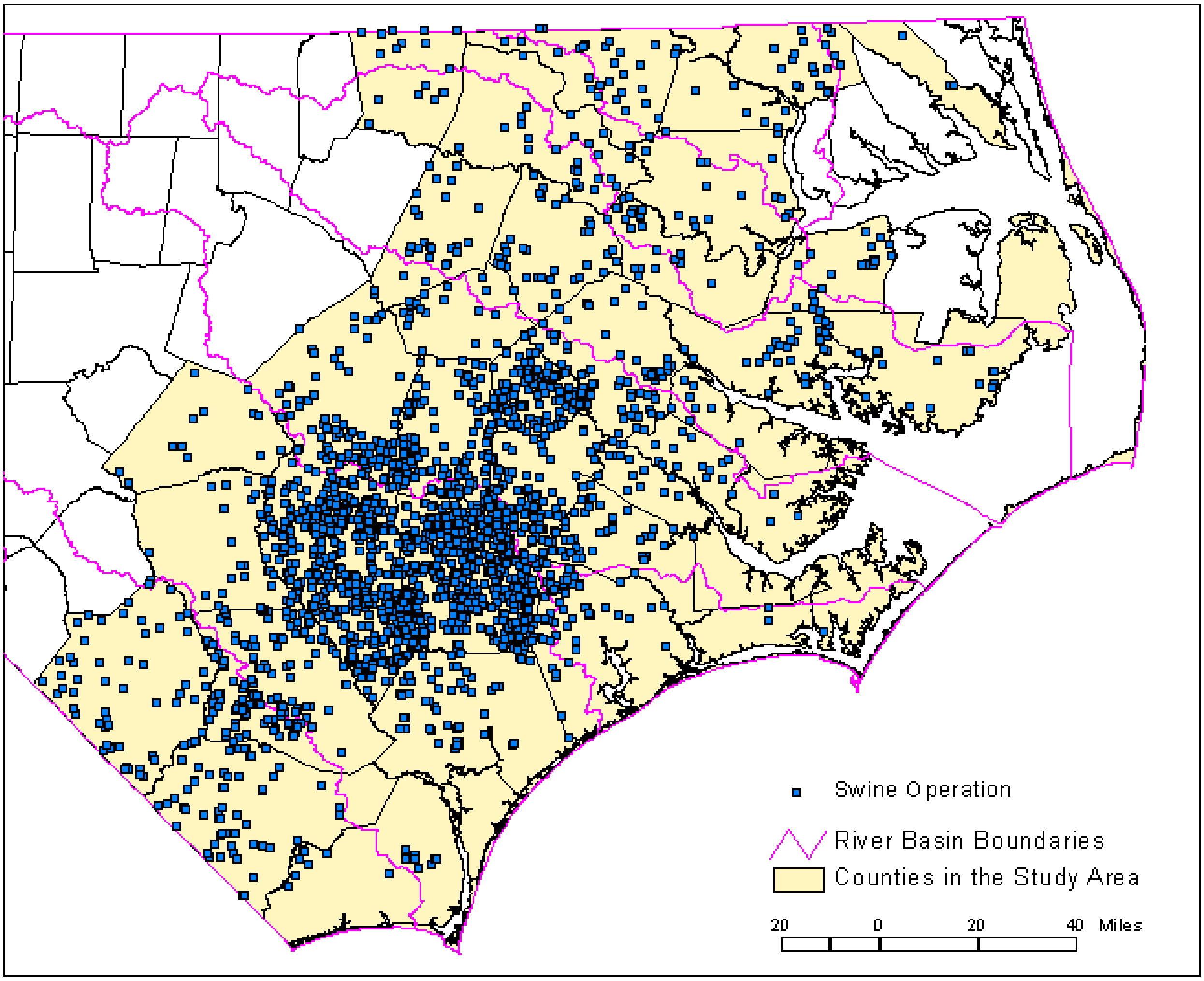
Note: Counties with fewer than 30 wells are not shown.

PROXIMITY ASSESSMENTS

Three proximity assessment procedures were performed to determine if there was any spatial relationship between contaminated wells and swine operations. We wanted to find out if the wells closer to swine operations were contaminated more frequently than wells located further away from swine operations. Because of limitations in location information for both private wells and swine operations discussed earlier (see Methods section), the results of these analyses should be considered as exploratory only.

In the study area, a total of 2,392 swine operations were registered with the NCDENR Division of Water Quality. The spatial distribution of swine operations in the study area is shown in Figure 11.

Figure 11. Swine operations in the study area



Proximity of Private Wells to Nearest Swine Operation

The first proximity assessment procedure involved examining the number of contaminated and uncontaminated wells in relation to the nearest swine operation. The objective was to determine whether close proximity to a swine operation increases the likelihood of well contamination.

Total Coliform. Overall, 2,136 private wells were tested for total coliform. Of those, 78% (1,666) tested negative (absent) and 22% (470) tested positive (present) for total coliform (see Table 2 and Figure 7).

The distribution of contaminated and uncontaminated wells by distance to nearest swine operation is shown in Table 6. As the table shows, about two thirds of all wells (65%, 1,396) were located more than two miles from the nearest swine operation and only 4 % (89) were located within one-half mile of the nearest swine operation.

Only one total coliform contaminated well (0.2%) was within one-quarter mile of the nearest swine operation. Four percent of the contaminated wells (17) were between one-quarter to one-half mile; 12% (55) were between one-half and one mile; and 23 % (110) were between one and two miles from the nearest swine operation. The majority of contaminated wells (61%, 287) were more than two miles from the nearest swine operation.

Table 6. Number of private wells tested for total coliform by distance to nearest swine operation

Distance to nearest swine operation	**Total coliform**				**Total**	
	Absent		**Present**			
	No. of wells	Col. % Row %	No. of wells	Col. % Row %	No. of wells	Col. % Row %
1. 0-.25 mi.	17	1 94	1	0 6	18	1 100
2. >.25-.5 mi.	54	3 76	17	4 24	71	3 100
3. >.5-1.0 mi.	172	10 76	55	12 24	227	11 100
4. >1.0-2.0 mi.	314	19 74	110	23 26	424	20 100
5. >2.0 mi.	1,109	67 79	287	61 21	1,396	65 100
Total	**1,666**	**100 78**	**470**	**100 22**	**2,136**	**100 100**

Looking at the numbers of contaminated and uncontaminated wells within each distance class, it is clear that private wells closest to swine operations were not necessarily more frequently contaminated. Of the wells located within a quarter mile of the nearest swine operation, only 6% (1 well) tested positive for total coliform. Within the second, the third, and the fourth distance classes, about one quarter of the wells were contaminated and three quarters were not contaminated.

Fecal/E.coli. The 470 wells that tested positive for total coliform were also tested for fecal/E. coli contamination. Fecal/E.coli contamination was present in 8% (38) of these wells (see Table 3 and Figure 8).

Table 7 shows that about two thirds of the wells tested for fecal/E.coli (61%, 287) were located more than two miles of the nearest swine operation and only 4% (18) were located within one-half mile of the nearest swine operation.

None of the contaminated wells were within one-quarter mile of the nearest swine operation. Three percent (1) of the contaminated wells were between one-quarter and one-half mile, 13 % (5) were between one-half and one mile, and 29% (11) were between one and two miles from the nearest swine operation. About half of the contaminated wells (55%, 21) were more than two miles from the nearest swine operation.

This analysis (Table 7) showed no clear relationship between distance to nearest swine operation and fecal/E.coli contamination. None of the wells located within one-quarter mile of the nearest swine operation tested positive for Fecal/E.coli. In the four other distance classes the proportion of wells contaminated with fecal/E.coli was relatively consistent, ranging from 6-10%.

Table 7. Number of private wells tested for fecal/E.coli by distance to nearest swine operation

Distance to nearest swine operation	**Fecal/E.coli**				**Total**	
	Absent		**Present**			
	No. of wells	Col. % Row %	No. of wells	Col. % Row %	No. of wells	Col. % Row %
1. 0-.25 mi.	1	0 100	0	0 0	1	0 100
2. >.25-.5 mi.	16	4 94	1	3 6	17	4 100
3. >.5-1.0 mi.	50	12 91	5	13 9	55	12 100
4. >1.0-2.0 mi.	99	23 90	11	29 10	110	23 100
5. >2.0 mi.	267	61 93	21	55 7	287	61 100
Total	**433**	**100** **92**	**38**	**100** **8**	**470**	**100** **100**

Nitrate. Of the 2,453 private wells tested for nitrate, 93% (2,264) were not contaminated, 5% (132) had low level contamination, and 2% (37) were contaminated (see Table 4 and Figure 9).

The distribution of nitrate contaminated, low level contaminated, and not contaminated wells by distance to the nearest swine operation is shown in Table 8. As the table shows, two thirds of the wells tested for nitrate levels (65%, 1,599) were located more than two miles of the nearest swine operation and only 4% (95 wells) were located within one-half mile of the nearest swine operation.

Analysis of contaminated wells by distance to the nearest swine operation shows that 3% (1 well) were located within one-quarter mile and another 3% (1 well) were located between one-quarter and one-half mile of the nearest swine operation. Thirteen percent of the contaminated wells (5) were between one-half and one mile and 24% (9) were between one and two miles of the nearest swine operation. About half of the contaminated wells (57%, 21) were more than two miles of the nearest swine operation.

Analysis of the low level contaminated private wells by distance to the nearest swine operation shows that 1% (1) was located within one-quarter mile and another 3% (4) were located between one-quarter and one-half mile of the nearest swine operation. Sixteen percent of low level contaminated wells (21) were between one-half and one mile and 26% (35) were between one and two miles of the nearest swine operation. About half of the low level contaminated wells (54%, 71) were more than two miles of the nearest swine operation.

The percentage of contaminated wells in distance class 1 (5%) was slightly higher than the corresponding percentages in distance classes 2, 3, 4 and 5 (1%, 2%, 2%, 1%, respectively). However, the percentage of low level contaminated wells in distance class 1 (5%) was equal to or lower than the corresponding percentage in the second, third, and fourth distance classes (5%, 8%, 7%, 5%, respectively).

Table 8. Number of private wells tested for nitrate by distance to nearest swine operation

Distance to nearest swine operation	**Nitrate levels***						**Total**	
	Not contaminated		**Low level contaminated**		**Contaminated**			
	No. of wells	Col. % Row %	No. of wells	Col. % Row %	No. of wells	Col. % Row %	No. of wells	Col. % Row %
1. 0-.25 mi.	18	1 90	1	1 5	1	3 5	20	1 100
2. >.25-.5 mi.	70	3 94	4	3 5	1	3 1	75	3 100
3. >.5-1.0 mi.	227	10 90	21	16 8	5	13 2	253	10 100
4. >1.0-2.0 mi.	462	20 91	35	26 7	9	24 2	506	21 100
5. >2.0 mi.	1,507	66 94	71	54 5	21	57 1	1,599	65 100
Total	**2,284**	**100** **93**	**132**	**100** **5**	**37**	**100** **2**	**2,453**	**100** **100**

***** Not contaminated: 0 - 4.99 mg/l; Low level contaminated: 5.0 - 9.99 mg/l;
Contaminated: $\geq$ 10 mg/l

Proximity of Private Wells to Swine Operations

Classifying private wells by distance to swine operations is another approach for examining the spatial relationship between well contamination and swine operations. The difference between this and the previous analysis is that instead of the nearest swine operation, the wells are classified based on their distance to every nearby swine operation. For this analysis, most private wells were classified in relation to more than one swine operation. For example, if a well was .1 mile from swine operation A and 1.5 miles from swine operation B, it was included in distance class 1 and also in distance class 4. As a result, the total number of wells within distance classes 2-4 is larger than the totals in the previous analysis.

Total Coliform. The distribution of coliform contaminated and uncontaminated wells by distance to swine operations is shown in Table 9. As the distribution of contaminated and uncontaminated private wells within each distance class shows, within one-quarter mile of swine operations only one well (6%) was contaminated. Within distance class 2 (.25-.5 mile) 17 wells (23%) were contaminated. Within the third distance class (.5-1.0 mile) 60 wells (24%) were contaminated and within the fourth distance class (1.0-2.0 miles) 154 wells (25%) were contaminated. These results revealed that the percentage of contaminated wells within one-quarter mile of swine operations was not larger than the percentage of contaminated wells in other four distance classes. The percentages of contaminated wells within the second, the third, and the fourth distance classes were relatively consistent (23%, 24%, 25%, respectively) but slightly larger than the percentage of contaminated wells located more than two miles from swine operations (21%).

Table 9. Number of private wells tested for total coliform by distance to swine operations

Distance to swine operation	**Total coliform**				**Total**	
	Absent		**Present**			
	No. of wells	%	No. of wells	%	No. of wells	%
1. 0-.25 mi.	17	94	1	6	18	100
2. >.25-.5 mi.	57	77	17	23	74	100
3. >.5-1.0 mi.	195	76	60	24	255	100
4. >1.0-2.0 mi.	465	75	154	25	619	100
5. >2.0 mi.	1,109	79	287	21	1,396	100

Fecal/E.coli. The distribution of fecal/E.coli contaminated and uncontaminated wells by distance to swine operations is shown in Table 10. Overall, the table shows that within all five distance classes the percentage of fecal/E.coli contaminated wells was noticeably small (0%, 6%, 10%, 9%, and 7% respectively) in comparison to the percentage of uncontaminated wells within the same distance classes (100%, 94%, 90%, 91%, and 93%, respectively). The distribution of contaminated and uncontaminated wells within each distance class revealed that within one-quarter mile of swine operations none of the wells tested negative for fecal/E.coli. Within distance class 2 (.25-.5 mile), of total 17 wells only one well (6%) was contaminated. Within the third distance class (.5-1.0 mile) 6 wells (10%) were contaminated and within the fourth distance class (1.0-2.0 miles) 14 wells (9%) were contaminated. These results revealed that the percentages of contaminated wells within distance classes 1 and 2 were not larger than the percentage of contaminated wells in other three distance classes. The largest percentage of fecal/E.coli contaminated wells was within the third distance class (.5-1.0 mile).

Table 10. Number of private wells tested for fecal/E.coli by distance to swine operations

Distance to swine operation	**Fecal/E.coli**				**Total**	
	Absent		**Present**			
	No. of wells	%	No. of wells	%	No. of wells	%
1. 0-.25 mi.	1	100	0	0	1	100
2. >.25-.5 mi.	16	94	1	6	17	100
3. >.5-1.0 mi.	54	90	6	10	60	100
4. >1.0-2.0 mi.	140	91	14	9	154	100
5. >2.0 mi.	266	93	21	7	287	100

Nitrate. The distribution of nitrate contaminated, low level contaminated and not contaminated wells by distance to swine operations is shown in Table 11. As the distribution of contaminated, low level contaminated, and not contaminated wells within each distance class shows, within one-quarter mile of swine operations only one well (5%) was contaminated and another well (5%) was low level contaminated. Within distance class 2 (.25-.5 mile) of total 77 wells, only one well (1%) was contaminated and four wells (5%) were low level contaminated. Within the third distance class (.5-1.0 mile) five wells (2%) were contaminated and 22 wells (8%) were low level contaminated. Within distance class 4 (1.0-2.0 miles), 12 wells (2%) were contaminated and 46 wells (6%) were low level contaminate. The largest combined percentages of nitrate contaminated or low level contaminated wells (10%) were within one-quarter mile and between one-half and one mile of swine operations. Although the combined percentages of contaminated or low level contaminated wells within distance class 3 and distance class 4 were small (10% and 8%, respectively), the total number of nitrate contaminated or low level contaminated wells within the same distance classes was noteworthy (85).

Table 11. Number of private wells tested for nitrate by distance to swine operations

Distance to swine operation	**Nitrate levels***						**Total**	
	Not contaminated		**Low level contaminated**		**Contaminated**			
	No. of wells	%	No. of wells	%	No. of wells	%	No. of wells	%
1. 0-.25 mi.	18	90	1	5	1	5	20	100
2. >.25-.5 mi.	72	94	4	5	1	1	77	100
3. >.5-1.0 mi.	258	90	22	8	5	2	285	100
4. >1.0-2.0 mi.	663	92	46	6	12	2	721	100
5. >2.0 mi.	1,507	94	71	5	21	1	1,599	100

***** Not contaminated: 0 - 4.99 mg/l; Low level contaminated: 5.0 - 9.99 mg/l;
Contaminated: $\geq$ 10 mg/l

Proximity of Swine Operations to Private Wells

The third proximity assessment procedure involved analyzing the number of swine operations within specified distance of a private well. This analysis allowed us to determine if the number of swine operations in the vicinity of contaminated wells was greater than the number of swine operations in the vicinity of uncontaminated wells. As with the preceding analysis, most swine operations were classified in relation to more than one private well. For example, if a swine operation was .5 mile from private well A and 1.75 miles from private well B, it was included in both distance class 2 and distance class 4 for this analysis.

Total Coliform. The distribution of swine operations in the vicinity of total coliform contaminated and uncontaminated wells is shown in Table 12. As the table reveals, within two miles of a private well for each distance class, the number of swine operations in the vicinity of contaminated wells was much smaller than the number of swine operations in the vicinity of uncontaminated wells.

The distribution of swine operations within each distance class showed that within distance class 1 (0-.25 mi.), the number of swine operations in the vicinity of contaminated wells was very small (1). On the other hand, the numbers of swine operations in the vicinity of contaminated wells within the second, the third, and the fourth distance classes were quite remarkable (19, 72, and 257, respectively). Within these distance classes, about one third of swine operations were in the vicinity of contaminated wells (30%, 38%, and 30%, respectively).

Table 12. Number of swine operations by distance to private wells tested for total coliform

Distance to private well	**Total Coliform**				**Total**	
	Absent		**Present**			
	No. of swine op.	%	No. of swine op.	%	No. of swine op.	%
1. 0-.25 mi.	16	94	1	6	17	100
2. >.25-.5 mi.	45	70	19	30	64	100
3. >.5-1.0 mi.	117	62	72	38	189	100
4. >1.0-2.0 mi.	600	70	257	30	857	100
5. >2.0 mi.	1,688	45	2,091	55	3,779	100

Fecal/E.coli. The distribution of swine operations in the vicinity of private wells tested for fecal/E.coli is shown in Table 13. As the table reveals, within two miles of fecal/E.coli contaminated wells there were total of 29 swine operations. The distribution of swine operations in the vicinity of contaminated and uncontaminated wells for each distance class shows that within one-quarter mile of a contaminated well, there were not any swine operations. Within distance class 2 (.25-.5 mile) there was only one swine operation in the vicinity of a contaminated well. Within the third distance class (.5-1.0 mile) there were seven swine operations and within the fourth distance class (1.0-2.0 miles) there were 21 swine operations in the vicinity of contaminated wells.

Overall, the total number of swine operations within one-half mile of a contaminated well did not seem important (1 swine operation). On the other hand, within distance class 4 (1.0-2.0 miles), the number of swine operations in the vicinity of contaminated wells was noteworthy (21 swine operations).

Table 13. Number of swine operations by distance to private wells tested for fecal/E.coli

Distance to private well	**Fecal/E.coli**				**Total**	
	Absent		**Present**			
	No. of swine op.	%	No. of swine op.	%	No. of swine op.	%
1. 0-.25 mi.	1	100	0	0	1	100
2. >.25-.5 mi.	18	95	1	5	19	100
3. >.5-1.0 mi.	66	90	7	10	73	100
4. >1.0-2.0 mi.	247	92	21	8	268	100
5. >2.0 mi.	2103	47	2364	53	4467	100

Nitrate. The distribution of swine operations in the vicinity of nitrate contaminated and uncontaminated wells is shown in Table 14. As the table reveals, within two miles of a private well for each distance class, the number of swine operations in the vicinity of contaminated and low level contaminated wells was much smaller than the number of swine operations in the vicinity of uncontaminated wells.

The distribution of swine operations in the vicinity of contaminated and low level contaminated wells by distance class showed that within distance class 1 (0-.25 mi.) and distance class 2 (.25-.5 mi.), the combined numbers of swine operations in the vicinity of contaminated or low level contaminated wells seemed not remarkable (2 and 5, respectively). On the other hand, the combined numbers of swine operations in the vicinity of contaminated or low level contaminated wells within the third (.5-1.0 mile) and the fourth (1.0-2.0 miles) distance classes were noteworthy (27 and 110, respectively)

Table 14. Number of swine operations by distance to private wells tested for nitrate

Distance to private well	**Nitrate levels***						**Total**	
	Not contaminated		**Low level contaminated**		**Contaminated**			
	No. of swine op.	%	No. of swine op.	%	No. of swine op.	%	No. of swine op.	%
1. 0-.25 mi.	17	90	1	5	1	5	19	100
2. >.25-.5 mi.	57	92	4	6	1	2	62	100
3. >.5-1.0 mi.	224	89	21	8	6	3	251	100
4. >1.0-2.0 mi.	704	87	85	10	25	3	814	100
5. >2.0 mi.	1,583	15	2,290	42	2,360	43	5,459	100

***** Not contaminated: 0 - 4.99 mg/l; Low level contaminated: 5.0 - 9.99 mg/l;
Contaminated: $\geq$ 10 mg/l

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