

QUALITATIVE IDENTIFICATION OF FECAL COLIFORM BACTERIAL SOURCES

by

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A project submitted in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING

in

CIVIL ENGINEERING

UNIVERSITY OF PUERTO RICO

MAYAGÜEZ CAMPUS

2006

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ABSTRACT

The main objective of this work is to provide a procedure to identify fecal coliform bacterial contamination sources within specific regions employing Geographical Information Systems (GIS) technology. The work presented is one of the first efforts in the stage of problem identification from bacterial sources. A Total Maximum Daily Load (TMDL) is needed to be developed within the region of Rio Grande de Añasco, Guanajibo and Yagüez Watersheds. A TMDL is a quantitative representation of the maximum load of a given water-quality constituent, from all point and non-point sources, that any water body can assimilate without violating the designated water-quality standard established by EPA. The Guanajibo and Yagüez watersheds were selected for the demonstration of the application procedures developed under this research. The simulation helped to visualize the impacted zones by Fecal Coliform Bacterial sources, leading to better management practices and TMDL modeling.

RESUMEN

El principal objetivo de este trabajo es proveer un procedimiento para identificar fuentes de contaminación bacteriana por coniformes fecales dentro de áreas designadas utilizando tecnología de Sistemas de Información Geográfica (SIG). El trabajo presentado es uno de los primeros esfuerzos en la etapa de identificación del problema para fuentes bacterianas. Un “Total Maximum Daily Load” (TMDL) es requerido para ser desarrollado en la región de las cuencas Río Grande de Añasco, Guanajibo y Yagüez. Un TMDL es una representación cuantitativa de las descargas máximas de un constituyente para calidad de agua, de todas las descargas puntuales y no-puntuales (áreas), que cualquier cuerpo de agua puede asimilar sin violar los estándares designados para calidad de agua establecidos por la Agencia de Protección del Ambiente (Environmental Protection Agency, o EPA por sus siglas en inglés). Las cuencas Guanajibo y Yagüez fueron seleccionadas para la demostración de la aplicación y procedimientos desarrollados bajo esta investigación. La simulación ayuda a visualizar las zonas impactadas por fuentes de coliformes fecales, dando ventaja para desarrollar mejores planes de manejo y modelaje en TMDL.

To God: For giving me the opportunity.

To my mother: For being my mother, and guiding me in the last years.

To my father: For being my father and supporting me.

To my sister: For supporting me.

To Dr. Rivera Santos: For being my mentor, and guiding me carefully.

ACKNOWLEDGEMENTS

First of all, thanks to God, for giving me the patience and inspiration to conclude my master degree.

Thanks to my mother for giving me life and guiding me through these 25 years.

Special thanks to Dr. Rivera Santos, for the faith he had in me. He helped me, fulfilling more than his chairman responsibilities.

Thanks to Dr. Ivonne Santiago and Dr. Rafael Segarra for being part of my graduate committee and providing me with the necessary tools to do my research.

This study was financially supported by Puerto Rico's Environmental Quality Board. The Puerto Rico Water Resources and Environmental Research Institute is thanked for providing me the software Arc Map GIS 8.3 for use in this study.

Thanks to Roy Ruiz, for answering my questions about Arc Map GIS, and for his help in deciding of some agriculture parameters.

Finally, thanks to all my family and friends that support me and had faith in me. They helped me with their encouraging words and prayers. I don't want to mention names because I don't want to omit someone, but they know who they are.

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List of Abbreviations

BMP	Best Management Practice
BST	Bacteria Source Tracking
CAFO	Confined Animal Feeding Operations
cfs	Cubic Feet per Second
CN	Curve Number
CRIM	Centro de Recaudación de Impuestos Municipales
CWA	Clean Water Act
DOQQ	Digital Ortho-rectified Quadrangles
EPA	Environmental Protection Agency
FA	Future Allocation
FCB	Fecal Coliform Bacteria
FCPRAI	Fecal Coliform Potential Risk Area Index
GIS	Geographic Information System
GSSHA	Gridded Surface Subsurface Hydrologic Analysis
HSPF	Hydrological Simulation Program FORTRAN
Km	Kilometer
LA	Load Allocation
mL	Milliliter(s)
MODRAT	Modified Rational Method
MOS	Margin of Safety
MPN	Most Probable Number
NFF	National Floodplain Frequency
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
FCPRAI	Fecal Coliform Potential Risk Area Index
POTW	Publicly Owned Treatment Works
PREQB	Puerto Rico Environmental Quality Board
PRIDCO	Puerto Rico Industrial Development Corporation
PRWRERI	Puerto Rico Water Resources and Environmental Research Institute
SSO	Sanitary Sewer Overflows
UIC	Underground Injection Control
TC	Total Coliform
TMDL	Total Maximum Daily Load
USDA	U.S. Department of Agriculture
USGS	United States Geological Survey
WLA	Wasteload Allocation
WMS	Watershed Modeling System
WWTP	Waste Water Treatment Plant

1 INTRODUCTION

The amount of the world's available drinking water is limited to less than one percent of all available water in the world and there is not "new" water (U.S. EPA, 2004). More than 20,000 waterbodies across America have been identified as polluted by microorganism, sediment, and bacteria including more than 300,000 miles of river and shoreline and 5 million acres of lakes. It is estimated that approximately 40% of US waters do not meet minimum water quality standards (U.S. EPA, 1998). The Clean Water Act (CWA) and its subsequent reauthorizations provide legislative authority for restoring polluted waters with the stated goal of making United States waters fishable and swimmable again. While the CWA is credited with significant improvements in water quality, water pollution remains a problem (Ritchie et al., 2003). In Puerto Rico, the situation is more critical because it is relatively a small island and its resources are limited. Freshwater withdrawals in Puerto Rico during 1990 were estimated at 576 MGD from surface water sources: streams and reservoirs (Molina-Rivera, 1996).

A Pathogen Total Maximum Daily Load (TMDL) is to be developed within the region of Guanajibo and Yagüez Watersheds. The study area is located on the south-west coast of Puerto Rico, and covers an area of approximately 393.41 Km² (PR Planning Board, 2004). The principal population centers within the watersheds are San Germán, Hormigueros, Mayagüez, Sabana Grande, Cabo Rojo and Maricao.

A TMDL is a quantitative representation of the maximum load of a given water-quality constituent, from all point and non-point sources, that a stream, lake, or any water body can assimilate without violating the water-quality standard for the designated use

established by Environmental Protection Agency (EPA) and state Environmental Quality Board.

1.1 Statement of the problem

The major difficulties in developing TMDLs for waters contaminated by fecal coliform bacteria are numerous and the magnitude of their sources contributions commonly are unknown.

In the Guanajibo and Yagüez watersheds much of the dwellings are unsewered and have septic systems (PRWRERI, 2005). These communities are close to waterbodies and represent a potential source of fecal coliform bacteria contamination. Human or animal activities, which pollute the water, include urban sprawl, construction, unsupervised water extraction, poorly designed septic systems, clandestine waste disposals, the use of pesticides and fertilizers, concentrated animal feeding operations, deforestation, soil erosion, and poor waste management plans. According to the U.S. Census Bureau, at least ten percent of onsite septic systems no longer function. Some communities report failure rates as high as 70 percent (U.S. EPA, 2004). Then, these poorly designed septic system lead to pollution of both ground and surface waters. Most of these represent non- point sources which make bacterial contamination tracking difficult.

1.2 Justification

A total maximum daily load (TMDL) is the pollutant maximum daily load of a water body can assimilate, from all point and non-point sources, without violating the water-quality standard for the designated use.

TMDLs are a quantitative representation of all the contaminant contributions to a stream and are defined as

$$TMDL = \Sigma WLA_s + \Sigma LA_s + MOS \quad (1.1)$$

where ΣWLA_s (waste-load allocations) represents the sum of all the point-source loadings, ΣLA_s (load allocations) represents the sum of all the non-point source loadings, and MOS represents a margin of safety. The sum of these loading terms and assigned margin of safety constitute the TMDL and represent the loading of a particular constituent that the surface waterbody can assimilate without violating the State water-quality standard. The TMDL must meet eight conditions in order to be approved by the U.S. Environmental Protection Agency (USEPA). These conditions ensure that the TMDL (1) is designed to implement applicable water-quality standards, (2) includes a total allowable load as well as individual waste-load allocations and load allocations, (3) considers the effect of background contaminant contributions, (4) considers critical environmental conditions (periods when water quality is most affected), (5) considers seasonal variations, (6) includes a margin of safety, (7) has been subject to public participation, and (8) can be met with reasonable assurance. Once a TMDL is established, source-load contributions then can be reduced through implementation of source –control management practices until the target TMDL is achieved.

One of the major difficulties in developing TMDLs for waters contaminated by fecal Coliform bacteria is that the potential sources of bacteria are numerous and the magnitude of their contributions commonly is unknown. Potential sources of fecal Coliform bacteria include all warm-blooded animals (humans, pets, domesticated livestock, birds, and wildlife). The lack of information on the bacteria sources hinders

the development of accurate load allocations and the identification of appropriate source-load reduction measures.

Information about the major fecal coliform bacterial sources that impair surface-water quality would improve the ability to develop effective watershed models and may lead to more scientifically defensible TMDLs (Moyer et al., 2003). It will allow the development of more effective pollution prevention and management plans.

The extension of this project is focused on finding potential sources of contaminant spreading and the contaminant contribution from non-point-source loadings. Remote Sensing (RS) and Geographical Information Systems (GIS) techniques will be used to improve our abilities to assess the landscape changes, urban sprawl, and lead to a better identification of the most probable non-point sources of contamination.

This project will provide fixed parameters for the identification of contaminant sources from fecal coliform bacteria. Further use of this information may lead to a better understanding of changes in water quality parameters necessary for developing superior management practices to improve water quality and enhanced modeling of a TMDL for advanced analysis.

1.3 Objectives

The main objective of this project is the development of a procedure to identify and locate potential sources of contamination employing new GIS technology. Of special interest are fecal coliform contaminant sources.

2 PREVIOUS INVESTIGATIONS

2.1 History of water pollution control

Prior to 1972, water pollution control efforts were based on the achievement of ambient water quality standards. Arguably, this is economically efficient since each source would control its discharge only to the degree necessary to meet local water quality standards (Schroeder, 1981). However, the approach proved virtually impossible to administer, because of the difficulties in translating ambient standards into end-of-pipe effluent limits for individual discharges. The result was regulatory frustration and very little cleanup. One of the factors that contributed to the frustration was that the translating technology, water quality modeling, was not fully developed.

In 1972, the Federal Water Pollution Control Act was amended to require a minimum level of control based on available treatment technology. Thus the need to determine impact on the receiving water, often the most difficult determination to make, was largely eliminated. The result was substantial reduction in pollution, even if this was achieved in areas in which cleanup was not needed to meet water quality goals. Over the next half dozen years, secondary treatment was promulgated as the minimum level for all Publicly Owned Treatment Works (POTWs) on the assumption that the expected water quality responses were worth the expenditure. Effluent limitation guidelines were established for industrial wastewaters. Wasteload allocation was used specifically for those instances in which there was some doubt that the water quality standards could be achieved by secondary treatment alone.

The pendulum continued to swing between wasteload allocation and effluent requirements. In 1977, the CWA was passed and water quality standards for toxic substances were prepared. It was clear by 1982 that the EPA strongly favored water quality based effluent limitations, rather than technology based limits, as basic water quality pollution control strategy, thereby reversing the regulatory trend. By that time, water quality modeling technology had advanced significantly and was ready to address a variety of water quality problems.

There is little doubt that the CWA of 1977 and its across-the-board abatement approach of secondary treatment required for municipal wastewaters has made substantial improvement in the water quality of many natural water systems. However, there remain a significant number of waterbodies that are water quality limited, thereby requiring additional work, leading to the development of Total Maximum Daily Load (TMDL), as outlined in Section 303 of the Clean Water Act, to safeguard the quality of these waterbodies, see appendix A (Lung, 2001).

The TMDL process identifies the maximum load of a pollutant a water body is able to assimilate and fully support its designated uses, allocates portions of the maximum load to all sources, and identifies the necessary controls that may be implemented voluntarily or through regulatory means. A TMDL can also be viewed as the total amount of pollutant that a water body may receive from all sources without exceeding water quality standards.

In order to accomplish TMDLs for Guanajibo and Yagüez watersheds, pollution sources have to be precisely and carefully identified (problem identification). Some studies have been developed for Puerto Rico and have encountered deficiencies in the problem

identification stage for different contaminants. The major deficiency of this process stage is the poor identification and location of contaminant sources.

2.2 TMDL Development in Puerto Rico

There are few Total Maximum Daily Loads formally developed for Puerto Rico. In 2003 a Total Maximum Daily Load (TMDL) for Río Cibuco Watershed Commonwealth of Puerto Rico was developed by a private company and approved by EPA converting this into the first TMDL developed for Puerto Rico. Other efforts are underway to develop TMDLs for Puerto Rico but have not yet been approved by EPA. These efforts focus on Fecal Coliform Bacteria TMDL for the Río La Plata Watershed Puerto Rico (submitted for approval) and Río Loíza (under development).

Two other efforts underway are at Río Grande de Añasco and Río Yagüez and Río Guanajibo by the Puerto Rico Water Resources and Environmental Research Institute of the UPRM. The Environmental Quality Board is concerned about the problem identification stage in the development of TMDLs for the Río Yagüez and Río Guanajibo watersheds. This stage produces a collection of data that must be managed carefully to extract the information needed to identify pollution sources. To this end the current proposed work deals only with the stage of problem identification employing GIS and RS Techniques. These tools allow researchers to pinpoint the sources of pollution and enable the load calculation and allocation for the analysis and modeling of a pathogen TMDL for the above mentioned watersheds.

2.3 Bacteria survival and movement

The entry of pathogenic bacteria into drinking water sources poses a great risk to human health. Animal manure application to agricultural land is cited as a major source of pathogenic microorganisms in surface and groundwater systems (Reddy et al. 1981).

Fecal coliforms (FCB) are identified by their ability to produce gas from lactose at 44.5°C (Geohring et al. 1999). *E. coli* is the most common FCB and although most *E. coli* strains are non-pathogenic, some strains, such as *E. coli* O157:H7, pose a serious health risk to humans. *E. coli* O157:H7 was first identified as a human pathogen in 1982 (Kudva et al. 1998).

2.3.1 Survival in soil systems

The availability of pathogens for transport in runoff and leachate during precipitation events is largely influenced by the die-off rate of enteric bacteria in the soil-waste system (Reddy et al. 1981). A wealth of information has been produced within the past 34 years on the survival of various enteric bacterial species in soil and groundwater systems. A review presented by Gerba et al. (1975) reported that survival times of enteric bacteria in soil and groundwater ranged from 2 to 4 months. Filip et al. (1988) examined the survival of several organisms in simulated conditions of saturated soil and observed that most organisms tested, including *E. coli*, survived for over 100 days at 10°C. Kudva et al. (1998) found that *E. coli* O157:H7 survived for 630 days in sheep manure that was not aerated and stored at air temperatures below 23°C. Entry et al. (2000a, 2000b) monitored concentrations of FCB bacteria in soil and runoff water from grassed buffer strips that had received liquid swine waste. After 90 to 120 days, FCB levels were not

significantly different from strips that had not received waste. Reddy et al. (1981) conducted a review of bacterial survival and attempted to develop first order rate constants to describe the die-off of several indicator organisms and pathogens in soil systems. Average first order die-off rate constants were 1.14 d^{-1} for FCB and 0.41 d^{-1} for *Fecal Streptococci*. Average rate constants for specific pathogens were 1.33 d^{-1} for *Salmonella* and 0.68 d^{-1} for *Shigella*. Sjogren (1994) assessed the survival of *E. coli* and used exponential regression to estimate survival times in soil. They estimated survival times by extrapolating the die-off curve to zero counts of bacteria. Probable survival times ranged from 20.7 to 23.3 months.

2.3.1.1 Soil Moisture

Numerous researchers have suggested that the principal factor affecting the survival of enteric bacteria in soil systems is the moisture status. Tate (1978) found *E. coli* survival to be greatest in organic soils under flooded conditions. Hagedorn et al. (1978) found *E. coli* populations highest after a rise in the water table following major rainfall events. *Streptococcus Faecalis* died more rapidly under low soil moisture conditions (Kibbey et al. 1978).

2.3.1.2 Soil type

The single soil property that appears to have the greatest impact on bacterial survival is moisture retention, which is linked to particle size distribution and organic matter content. Tate (1978) observed that the survival of *E. coli* in an organic soil over an 8-day period after manure application was threefold greater than in sandy soil. This was attributed in part to the organic soil's increased ability to retain moisture. Hagedorn et al. (1978) studied the subsurface flow of bacteria over a 32-day period. Fecal bacteria moved

faster in coarser soil materials. Chandler et al. (1980) investigated the survival of *E. coli* and *Streptococcus typhimurium* in relation to soil moisture retention and soil type. In dry loam soil, *E. coli* cells were able to survive and proliferate once moisture was restored. Chandler et al. (1981) examined the survival of bacteria on pasture, in topsoil and in subsoil and found that topsoil was the most favorable environment for bacteria. Zhai et al. (1995) also reported greater survival rates of fecal bacteria in topsoil as compared to subsoil. Mubiru et al. (2000) compared the mortality of *E. coli* in two different soil types. They stated that as well as enhancing moisture retention, fine soil particles could increase bacterial survival because of an increased ability to retain nutrients.

2.3.1.3 Soil Temperature and pH

Within the majority of the literature an inverse relationship appears to exist between temperature and bacterial mortality (Gerba et al. 1975; Reddy et al. 1981) with higher temperatures decreasing the survival times of fecal bacteria. Van Donsel et al. (1967) found that 90% of coliform bacteria died within 3.3 days of land application in the summer compared to 13.4 days in the winter. The review compiled by Reddy et al. (1981) found that die-off rates approximately doubled with a 10°C increase in temperature. Filip et al. (1988) determined that *E. coli* could survive longer in sheep; and cattle manure at temperatures below 23°C (Kudva et al. 1998). Enteric bacteria have a shorter survival period in soils possessing a low pH (Gerba et al. 1975; Ellis and McCalla 1976) with pH of 6 to 7 being optimum for bacteria survival (Cuthbert et al. 1955; Reddy et al. 1981). Sjogren (1994) found *E. coli* survived longer at a neutral to alkaline pH than at an acidic pH in soils of similar texture and organic matter content.

2.3.1.4 Manure application rate

Patni et al. (1985) found that long-term storage of manure decreased median counts of FCB, TC, and FS by 99%, however, these reductions did not occur when fresh manure was added to old manure. Aeration of sheep manure decreased survival time of *E. coli* from 21 months to 4 months (Kudva et al. 1998).

Zhai et al. (1995) also observed no influence of manure application rate on the mortality of fecal bacteria. Little work has been performed to assess the survival of fecal bacteria in soils that have received excessive application of manure.

2.3.1.5 Nutrient availability

Organic matter increases the retention of nutrients, provides a carbon source for bacterial species, and improves moisture retention properties, as noted earlier. Too much moisture, however, can have a negative effect on *E. coli* survival due to a lack of usable organic carbon, in dilute mixtures (Chandler et al., 1980). Tate (1978) revealed increased bacterial survival in organic soils. Zhai et al. (1995) speculated that higher mortality rates of fecal bacteria in subsoil, compared to topsoil, were partially due to low nitrogen (N) availability.

2.3.1.6 Bacterial Competition

Gerba et al. (1975) and Tate (1978) both reported increased pathogen survival, and sometime regrowth, in sterile soils. Competing microorganisms will limit pathogens survival in soil (Reddy et al. 1981). Enteric bacteria, which have been relocated into the soil-waste environment, must compete with resident soil bacteria for essential nutrients and water.

2.4 Groundwater Transport

The major transport modes of pathogens and indicator organisms in soils receiving manure are through movement with infiltrating water and surface runoff and with the movement of sediment and waste particles (Reddy et al. 1981). Physical filtration is believed to be the primary process which limits bacteria mobility in soil (Gerba et al., 1984). Bacteria range in size from 0.2 – 5 μm (Matthess et al., 1985) and are more subject to straining than smaller microorganisms, such as viruses, which range in size from 100 – 300 nm (Gerba et al., 1984). Adsorption is the main process which limits the movement of smaller microorganisms. Removal of bacteria occurs largely at the soil surface by straining and by sedimentation and adsorption (Gerba et al. 1975), however, it is difficult to separate the processes of filtration and adsorption (Reddy et al. 1981). Suspended particles, including bacteria which become deposited at the soil surface, can act as filter trapping more bacteria (Corapcioglu et al., 1984). The physical filtration of bacteria at the soil surface increases the likelihood of losses during runoff (Crane et al. 1981). The capacity of a soil to remove microorganisms is increased at low soil water contents and at greater soil clay contents and cation exchange capacities (Reddy et al. 1981). Bacteria are rarely free in the liquid phase of soil because most cells adhere to clay particles (Reddy et al. 1981). As would be expected, finer grained soil types, such as clays and silts, are more efficient in straining bacteria cells due to the smaller pore sizes (Canter et al., 1988). Several studies have concluded that the removal of bacteria from percolating liquid within a relatively uniform soil is inversely related to the particle size of the soil (Gerba et al., 1984).

Rahe et al. (1978) evaluated the movement of *E. coli* that had been injected into the leach lines of septic tank disposal systems that were inundated with groundwater in two different soil types (well drained and poorly drained). Movement rates of 15 m/h (0.82 ft/s) were observed at the well drained site.

Stoddard et al. (1998) performed a field experiment to measure FCB and FS survival and transport through shallow no tilled and conservation tilled soil amended with dairy manure in the fall and spring. The mortality rate of FCB after manure application has little bearing on the potential for groundwater contamination, but instead contamination depends more on soil structure and water flow.

2.5 Surface Water Transport

Fecal coliform levels in surface waters often peak after a major rain event. Thereafter, they decrease or disappear from water with time and can concentrate in sediments at high densities.

Although bacteria from manure are known to enter water resources (Goss et al., 2002) and numerous studies indicate the potential for microbial contamination from manure sources (Joy et al., 1998; Stoddard et al., 1998; Unc, 1999), there has been little progress in the way of direct analysis of the physical and chemical interactions between the manure type and bacteria that may affect the potential for contaminating water resources. Transport and retention of particulates, such as bacterial cells, in the soil is recognised as being a very complex physical and chemical phenomenon dependent on the interaction of the various complex properties of soil, cells and suspending solutions. Four major factors have been identified that influence the movement of bacteria through the soil (Fontes et al., 1991; Gannon et al., 1991a): (1) flow characteristics, which depend on

of the grain size of the porous medium, and on the soil structure that combined control the active porosity. (2) Filtration effects due to soil micropores, clogging in macropores necks, and filtration pads formed by solid components from applied manure (solid manure mostly) as a function of the size of microbial cell. (3) Straining within organic materials pads formed on soil surface, which is the sum of the filtration and the electrochemical retention to organic surfaces within the organic pads on soil surface. (4) Retention of bacterial cells on soil mineral and organic particles by adsorption and adhesion, with the ionic strength of the soil solution playing an important role. Retention is the resultant of complex interactions between components of bacterial cells, soils and soil suspending solution (Unc et al., 2003).

High densities of viruses have been found in marine waters that meet fecal coliform and total coliform standards (Berg et al., 1978; Goyal et al., 1979). This is of particular importance to marine coastal areas where discharge of sewage effluent is commonplace almost irrespective of the sewage components and its impact on public health (Cooper et al., 1984).

Suspended virus-contaminated particulate matter can be easily ingested by filter-feeding organisms like oysters, clams, and mussels that inhabit coastal waters and are harvested for consumption as raw or partially cooked seafoods (Hamblet et al., 1969; Sobsey, 1982). Predictably, the shellfish that are cultured in wastewater rich environments have been associated with hepatitis and gastroenteritis, sometimes with high human morbidity (Cooper et al., 1984).

Environmental factors like temperature, solar radiation, seasonal variability, and concentration of nutrients, are quite different in tropical as contrasted to temperate

aquatic systems. Bigger first reported the growth of coliforms in tropical waters in 1937, while in 1939 Ragavachari and Iver showed that coliforms can survive for several months in natural tropical river waters. Studies in Puerto Rico (Hazen et al., 1987; Santiago-Mercado., 1987; Valdes-Collazo et al., 1987) showed that the survival of fecal coliforms increased in marine and freshwater systems possibly because of the presence of high nutrient concentrations. Thus high counts of total coliforms and fecal coliforms do not necessarily indicate recent fecal contamination. The reliability of coliforms and fecal coliforms as indicators of recent fecal contamination in tropical waters is questionable when no identifiable source of fecal contamination has been detected (Hazen et al., 1987; Santiago-Mercado et al., 1987).

2.6 Bacteria source tracking (BST)

BST is a rapidly growing technology with various analytical techniques; the technique used depends on the study goals. In general, these techniques are based on molecular, genetics-based approaches (also known as “genetic fingerprinting”) or phenotypic (relating to the physical characteristics of an organism) distinctions among the bacteria of different sources. There are three primary genetic techniques for bacterial source tracking. Ribotyping characterizes a small, specific portion of the bacteria’s DNA sequence (Samadpour et al., 1995). Pulsed-field gel electrophoresis (PFGE) is similar to ribotyping but typically is performed on the entire genome of the bacteria (Simmons et al. 1995). Polymerase chain reaction (PCR) amplifies selected DNA sequences in the bacteria’s genome (Makino et al. 1999). Phenotypic techniques generally involve an antibiotic resistance analysis, in which resistance patterns for a suite of different

concentrations and types of antibiotics are developed (Wiggins, 1996; Hagedorn et al. 1999).

Although all the techniques mentioned above are promising for identifying bacteria sources, the ribotyping technique was used to identify the sources of fecal coliform bacteria impairing Blacks Run (Hyer et al., 2003). Ribotyping involves an analysis of the specific DNA sequence that codes for the production of ribosomal RNA (ribonucleic acid). Ribotyping has been demonstrated to be an effective technique for distinguishing bacteria from the feces of multiple animal species (Carson et al. 2001). This technique has been performed successfully and used to identify bacteria sources in both freshwater (Samadpour et al., 1995) and estuarine systems (Ongerth et al., 1994). Furthermore, the technique has been used to identify the species-specific sources of bacteria contributing to impairments in both urban (Herrera Environmental Consultants, Inc., 1993) and wilderness systems (Farag et al. 2001). Microbial source tracking was employed to determine the host origin of FCB contamination in the Río Grande de Añasco and Yagüez watersheds. Targeted sampling identified two sources of fecal contamination (Schröder et al., 2003).

2.7 Application of GIS technologies

Another tool that helps in the identification of contamination sources is the implementation of Geographical Information Systems (GIS). The contribution of GIS is to improve the mapping of areas of vulnerability by taking the spatial variability of physical phenomena into account. This method was applied to an area of France Massif Central where three different types of flow appear: surface flow, shallow surface flow and permanent groundwater flow (Laurent et al. 1998). As a result, GIS improved the

knowledge of terrain and land cover features, which in turn, was used to analyze topographic slope, channel length, land use, and soil characteristics of a watershed.

GIS was also utilized in a study in the Gunnison River Basin in Colorado (Hay et al., 1996). In that study GIS was used to: establish a common database for individuals working on different aspects of the study; develop methods for acquiring, generating, managing, and displaying spatial data required for modeling efforts, and provide spatial data such as basin boundary, river network, and precipitation station locations.

Lots of studies related to TMDLs contaminant sources identification have used GIS technologies. In the work presented here, a new perspective of GIS application for FCB identification was performed employing a new design procedure for identification employing additional extension of GIS technologies as similarly used in other investigations, as explained below.

In 2001, the Environmental Systems Research Institute (ESRI, 2001) used three extensions of ArcGIS: Spatial Analyst, 3-D Analyst and Geostatistical Analyst for the identification of areas of high risk to wildfires in Colorado's Boulder County area. A density function was built in ArcGIS Spatial Analyst to identify where most people live and to map their proximity to sensitive areas for determining wildfire risk.

The investigation also took into consideration slope hazard, as wildfires typically move faster in high slope areas (up-slope). These problems were modeled using the slope and aspect functions in ArcGIS Spatial Analyst, which create raster surfaces for aspect and slope. Other data types, such as vegetation and fuel were integrated with elevation data to dynamically display areas with dense and highly flammable vegetation.

Multiple operations were performed utilizing the Visual Basic for Application (VBA) to create a fire behavior index. A script was implemented through a user interface control that reclassifies elevation, sensitive topographic features, slope, aspect, and fuel types. All layers were then combined into one fire behavior index for displaying the areas that are most susceptible to fire damage (ESRI, 2001).

Hansen (2003), from the University of Wisconsin-Madison, used ArcGIS Spatial analyst tool to define environmental corridors in a study area in Dane County, Wisconsin. The study area encompasses the Township of Verona and a one-mile buffer surrounding the township. The model began with five shapefiles that were converted to grids. Four of the shapefiles are the basic features of environmental corridors-steep slopes, wetlands, rivers, and hydro buffer. Rights-of-way were added to remove steep slopes that are created as the result of road embankments, and floodplains were added to consider the dynamic pathways that are created over time within a water system.

Rights-of-way, steep slopes, rivers, and hydro buffers were reclassified to define where the features exist within the study area. Two layers of environmental corridors grids were created as the final results. Hansen assigned weights within and among the features so that priorities could be assigned to higher ranked corridors (Hansen, 2003).

Krivoruchko (2003), analyzed the consequences of Chernobyl's nuclear plant collapse using GIS and Spatial Statistics. He assumed that radioactive fallout from the atmosphere was stored within soils, from here transferred into vegetation and up through the food chain, ultimately increasing the likelihood of cancer. ArcGIS and the ArcGIS Geostatistical Analyst extension were used to perform detailed analysis of radiation contamination and its links to health.

Detailed meteorological data was taken into consideration due to the pathways importance of carrying these large amounts of radioactive emission. In 1986, Sweden's meteorological network consisted of more than 700 meteorological monitoring stations. Also the study took into account wind direction and the distance from Chernobyl to the Swedish border.

A geostatistical model of spatial data uses the semivariogram, a function of the distance and direction separating two locations, to quantify the spatial correlation in the data. The semivariogram is then used to define the weights in the kriging system that determines the contribution of each data point to the prediction of new values. Kriging refers to geostatistical interpolation techniques that use the statistical properties of observation. These geostatistical techniques quantify the spatial autocorrelation among measured points and account for the spatial configuration of sample points around the prediction location. Kriging has a measure of prediction uncertainty, allowing the determination of the degree of prediction accuracy.

The ArcGIS Geostatistical Analyst extension employs several models for probability mapping, each based on different assumptions. Based on the meteorological data and the probability analysis, Krivoruccko (2003) demonstrated that rain on April 29 was the cause of radiocesium soil contamination in the central and eastern parts of Sweden.

In the previous examples:

- ArcGIS Spatial Analyst is used to create reclassified grids according to factors of relative importance.
- ArcGIS Geostatistical Analyst is used to create a probability map.

- ArcGIS Spatial Analyst is used also to produce a risk assessment map.
- ArcGIS 3D Analyst maps are finally three-dimensionally displayed. A representation of the real world based on elevation.

With this new perspective one can dynamically explore the data and gain new insights about areas of special interest. From previous investigations presented above similarly techniques will be used to this project for identification of high likelihood of potential sources fecal coliform bacteria. By working with all three extensions within one geospatial environment, an analyst can gain a much better understanding of the range of factors that play a role in sources of fecal coliform contamination (identification of sources).

3 GIS DESCRIPTION

Geographic Information Systems (GIS) is defined as an information system that is used to input, store, retrieve, manipulate, analyze and output geographically referenced data or geospatial data, in order to support decision making for planning and management of land use, natural resources, environment, transportation, urban facilities, and other administrative records.

The key components of GIS are a computer system, geospatial data, and users. A computer system for GIS consists of hardware, software and procedures designed to support the data capture, processing, analysis, modeling, and display of geospatial data. The sources of geospatial data are digitized maps, aerial photographs, satellite images, statistical tables and other related documents.

Geospatial data are classified into graphic data (called geometric data) and attributes (called thematic data). Graphic data has three elements; point (called node), line (called arc) and area (called polygon) in either vector raster form which represent geometry of topology, size, shape, position, and orientation. The roles of the user are to select pertinent information, to set necessary standards, to design cost-efficient updating schemes, to analyze GIS outputs for relevant purpose, and plan the implementation.

Two main environments were used to realize this project: ArcGIS Desktop by ESRI and Watershed Modeling System (WMS) by EMS-I as described in more detailed below and through the description of the methodology employed for the developed project.

3.1 Overview of ArcGIS Desktop

ArcGIS Desktop is a collection of software products that runs on standard desktop computers. It is used to create, import, edit, query, map, analyze, and publish geographic information. There are four products in the ArcGIS Desktop collection:

- **ArcReader** is a free viewer for maps authored using the other ArcGIS Desktop products. It can view and print all maps and data types. It also has some simple tools to explore and query maps.
- **ArcView** provides extensive mapping, data use, and analysis along with simple editing and geoprocessing capabilities.
- **ArcEditor** includes advanced editing for shapefiles and geodatabases in addition to the full functionality of ArcView.
- **ArcInfo** is the full function, flagship GIS desktop. It extends the functionality of both ArcView and ArcEditor with advanced geoprocessing. It also includes the legacy applications for ArcInfo Workstation.

All ArcGIS Desktop products share a common architecture, so users working with any of these GIS desktops can share their work with others. Maps, data, symbology, map layers, geoprocessing models, custom tools and interfaces, reports, metadata, and so on, can be accessed interchangeably.

In addition, maps, data, and metadata created with ArcGIS Desktop can be shared with many users through the use of custom **ArcGIS Engine** applications and advanced GIS Web services using **ArcIMS** and **ArcGIS Server**.

3.1.1 ArcMap

ArcMap is the central application in ArcGIS Desktop for all map-based tasks including cartography, map analysis, and editing. ArcMap offers two types of map views

- Geographic data view—an environment where geographic layers are symbolized, analyzed, and compiled into GIS data sets. A table of contents interface organizes and controls the drawing properties of the GIS data layers in the data frame. The data view is a window into any GIS data set for a given area.
- Page layout view—an environment where map pages contain geographic data views as well as other map elements such as scale bars, legends, north arrows, and reference maps. The page layout view is used to compose maps on pages for printing and publishing.

3.1.2 ArcGIS Spatial Analyst

ArcGIS Spatial Analyst adds a comprehensive set of advanced spatial modeling and analysis tools to the ArcGIS Desktop. Using ArcGIS Spatial Analyst, you can derive new information from your existing data, analyze spatial relationships, and build spatial models integrating core ArcGIS Desktop and ArcGIS Spatial Analyst tools.

The capabilities of ArcGIS Spatial Analyst include find suitable locations, find the best path between locations, perform integrated raster/vector analysis, perform distance and cost-of-travel analyses, perform statistical analysis based on the local environment, small neighborhoods, or predetermined zones, generate new data using

simple image processing tools, interpolate data values for a study area based on samples, clean up a variety of data for further analysis or display.

3.2 Overview of WMS

The Watershed Modeling System (WMS) is a comprehensive graphical modeling environment for all phases of watershed hydrology and hydraulics. WMS includes powerful tools to automate modeling processes such as automated basin delineation, geometric parameter calculations, GIS overlay computations (CN, rainfall depth, roughness coefficients, etc.), cross-section extraction from terrain data, among others. WMS 7 supports hydrologic modeling with HEC-1, HEC-HMS, TR-20, TR-55, Rational Method, NFF, MODRAT, and HSPF. Hydraulic models supported include HEC-RAS, SMPDBK, and CE QUAL W2. 2D integrated hydrology (including channel hydraulics and groundwater interaction) can now be modeled with GSSHA. All of this in a GIS-based data processing framework makes the task of watershed modeling and mapping easier than ever before.

The program's modular design enables the user to select modules in custom combinations, allowing the user to choose only those hydrologic modeling capabilities that are required.

4 STUDY AREA DESCRIPTION

This chapter presents a description of the area under study. This area corresponds mainly to the Río Guanajibo and Río Yagüez watersheds, although some other small creeks are within the area. The description is based on the geomorphologic and physical characteristic of the drainage area including some social aspects such as population and community environmental practices.

4.1 Watersheds Description

The area under study is comprised of two major rivers and several small creeks and unnamed waterways. All water bodies discharge to the Mayagüez Bay. The two major rivers are the Río Yagüez and Río Guanajibo. The Guanajibo watershed, located on the west coast of Puerto Rico, covers an area of approximately 136 mi² (351 km²). This area includes the drainage area for the Caño Merle, Caño Corazones and Quebrada Llavat, as well as the coastal drainage areas. The principal population centers in the Guanajibo watershed are Maricao, San Germán, Sabana Grande, Hormigueros, and Cabo Rojo. The Río Yagüez originates near the town of Maricao, flows west, and discharges into the Mayagüez Bay. The Río Yagüez basin covers an area of about 17 mi² (43 km²), which includes the drainage area for Quebrada de Oro and other coastal areas. The Río Yagüez alluvial valleys are bounded by hills to the north, east, and south, and by the Mayagüez Bay to the west (see Figure 4.1). The principal population center in Yagüez watershed is the city of Mayagüez located on the coast, covering almost the entire Río Yagüez alluvial valley.

The major river in the region is the Río Guanajibo, flowing to the west-northwest. It originates along the western side of the Cordillera Central and flows to the Mayagüez Bay on the west coast, south of town of Mayagüez. The principal tributaries to the Río Guanajibo are the Río Rosario, Río Duey, Río Hoconuco, Río Caín, Río Cupeyes, Río Cruces, and Río Flores, draining to the south-southwest, and the Río Viejo, draining to the west-northwest. The Guanajibo watershed is characterized by a broad alluvial valley (the Central Guanajibo valley) covering about 63 mi² (162 km²). This valley is bounded on all sides by hills, except to the northwest, where it is bounded by the Mayagüez Bay. At the coast, the Guanajibo valley extends northward joining the Río Yagüez valley. A barrier of low-lying hills almost completely separates the Central Guanajibo Valley from the coast. These hills form a ridge called the Cordillera Sabana Alta that reaches its greatest elevation in the east. On the west of these hills, the shore features a fringe of beach and swampy terrain. The Central Guanajibo valley measures 14 mi (23 km) in length along its east-west axis, with a width ranging from 1.4 mi (2.3 km) in the east to 6.4 mi (10.2 km) in the west.

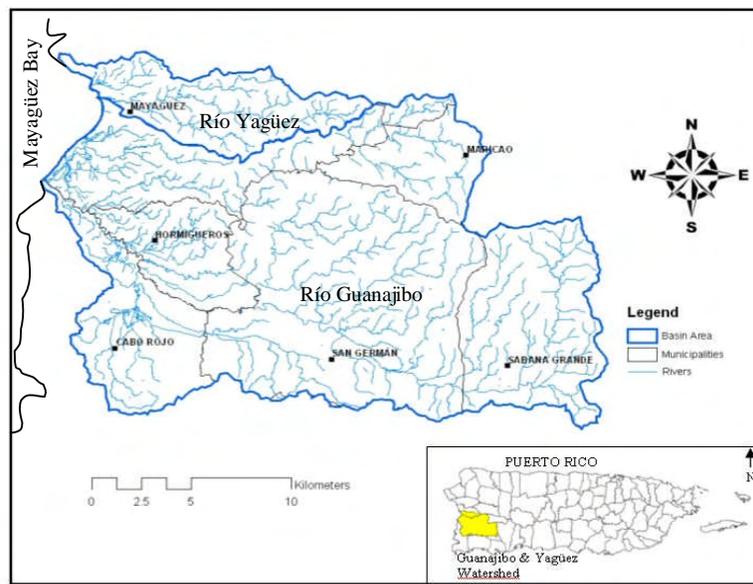


Figure 4.1 Río Guanajibo and Río Yagüez watersheds location

4.2 Topography

Elevations within the valley range from mean sea level at the coast to about 197 ft (60 meters) above mean sea level in the most east portion. Hills surrounding the valley reach maximum elevations of 3,937 ft (1,200 m) above mean sea level in the Cordillera Central in the north, (see Figure 4.2). The mountain range to the south has elevations to as much as 1,640 ft (500 m) above mean sea level.

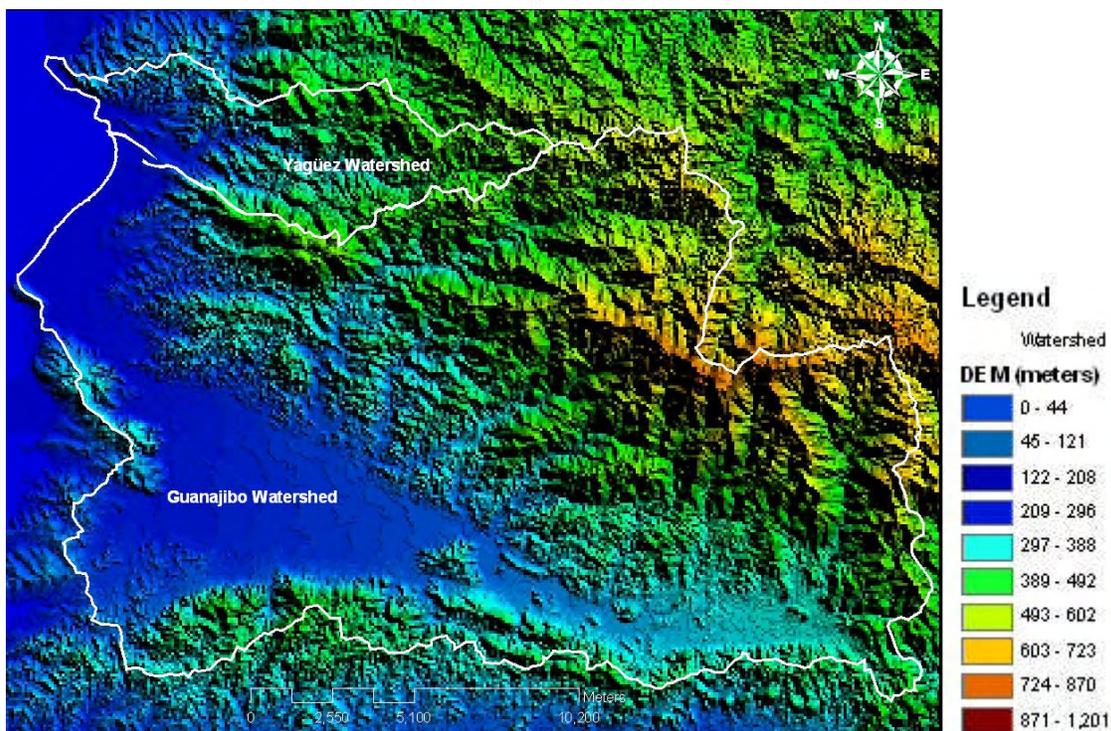


Figure 4.2 Study Area and Digital Elevation Model (DEM).

4.3 Soil Types

There are 51 different soil types over the study area. The most predominant among the watershed is the Serpentine outcrop (So) with an approximate area of 13,989.4 acres (21.9 mi², 56.7 km²) extending from south-east through north-west crossing by the center of the Guanajibo watershed. Mucara clay (MxC, MxD2, MxE2, MxF2) is also one

of the most predominant soil types over Guanajibo and Yagüez watersheds with an approximate area of 9,652.7 acres (15.1 mi², 39.1 km²). Also Caguabo clay loam (CbF2) is one of the predominant soil with an approximate area of 8,057.6 acres (12.6 mi², 32.6 km²) as seen on Figure 4.3.

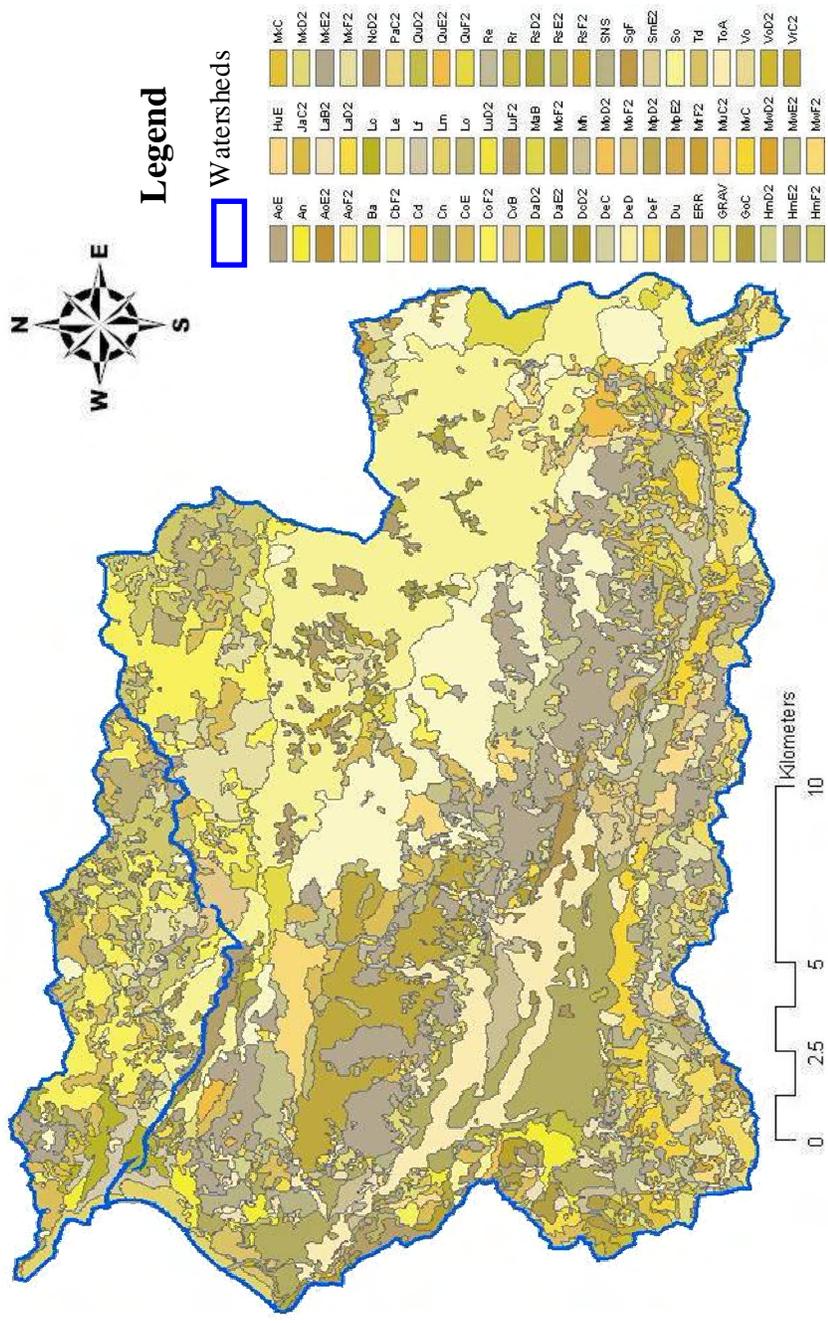


Figure 4.3 Soil Types from NRCS

4.4 Hydrologic Soil Groups

Each soil type is classified into a hydrologic soil groups as defined for the estimated watershed soil conditions (USDA, 1986). There are four groups which are: “A” having high infiltration rates (0.30 – 0.45 in/hr) (7.61 – 11.43 mm/hr), “B” with moderate infiltration rates (0.15 – 0.30 in/hr) (3.81 – 7.61 mm/hr), “C” having slow infiltration rates (0.05 – 0.15 in/hr) (1.27 – 3.81 mm/hr), and “D” with soils having very slow infiltration rates (0 – 0.05 in/hr) (0 – 1.27 mm/hr). These infiltration rates apply to saturated soils. As seen on Figure 4.4, the most predominant soil group in the study area is group “D”.

Hydrological soil groups “B” and “C” predominate along the central Guanajibo valley. Some “A” group can be found in the upper portions of the valley. Hydrologic soil groups “B” and “C” predominate the Río Yagüez watersheds.

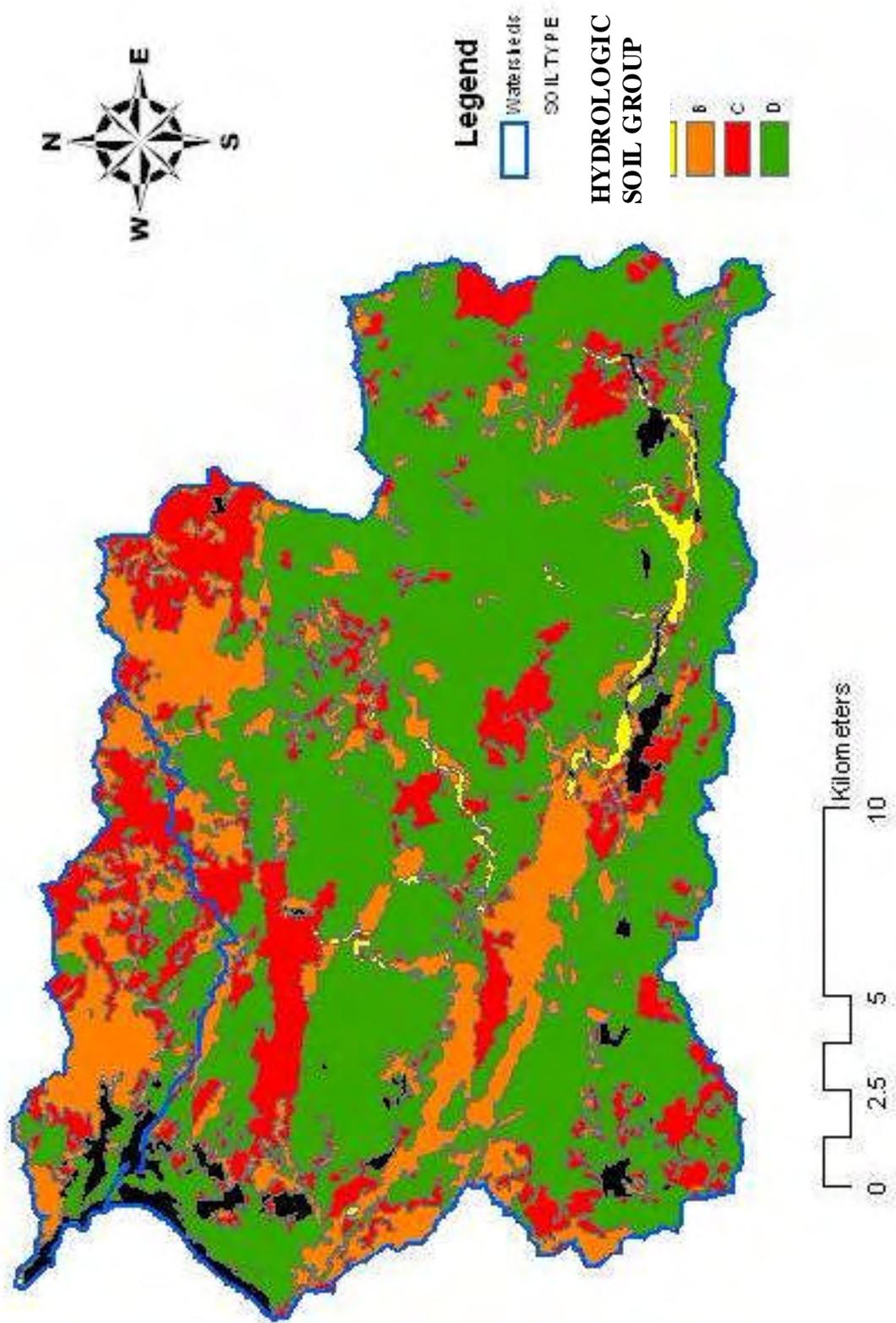


Figure 4.4 Hydrologic Soil Groups from NRCS.

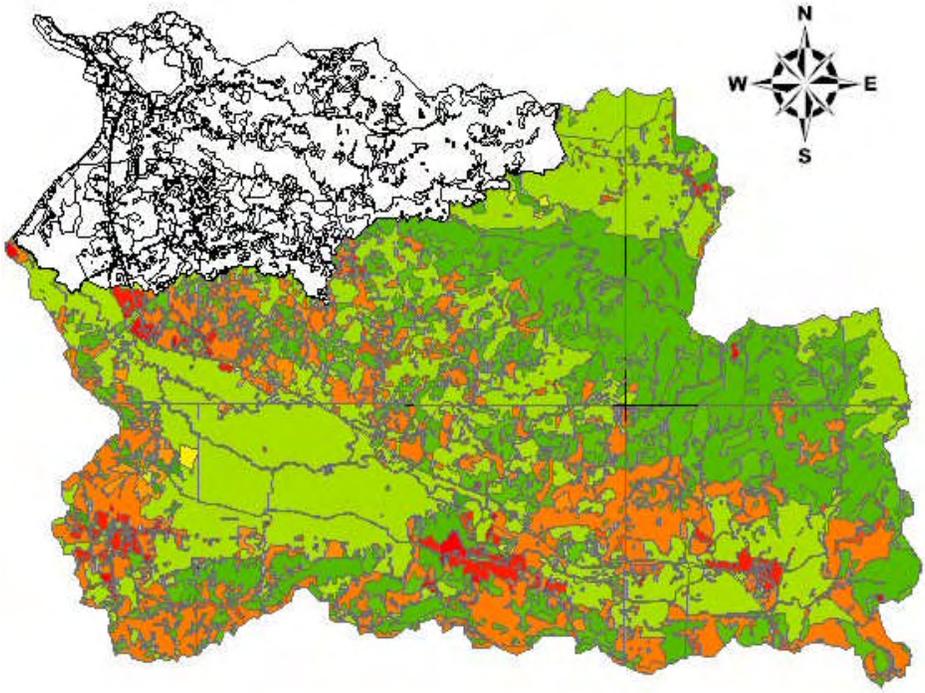
4.5 Land Uses / Land Cover

The Puerto Rico Department of Natural and Environmental Resources provides a land use/land cover map with information up to 1977. In 1977, most of the land within the watershed was dedicated to agriculture according to Figure 4.5. The Puerto Rico Water Resources and Environmental Research Institute (PRWRERI) of the University of Puerto Rico at Mayagüez, developed an updated land use map with 2003 data in response to a request from the Puerto Rico Water Quality Board (PRWQB). This is shown in Figure 4.6.

Table 4.1 presents a comparison for various land cover percentage coverage as contained in the two maps. These categories correspond to the level 1 of the Anderson's land use/land cover classification system. This comparison is graphically depicted in Figure 4.7.

Table 4.1 Percentage Land Uses / Land Cover changes

Level I	1977	2003	% Change
Urban or Built-up Land	13.24	18.40	5.16
Agricultural Land	32.44	2.64	-29.8
Rangeland	8.50	39.35	30.85
Forest Land	43.98	36.28	-7.7
Water	1.11	0.28	-0.83
Wetland	0.69	1.09	0.4
Barren Land	0.04	1.97	1.93
TOTALS	100.00	100.00	



0 2,500 5,000 10,000 Meters

Legend

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|--|---|
| <ul style="list-style-type: none"> Aeropuerto/ Pistas Aereas Agricultura Inactiva Agricultura Mixta/ Frutos Menores Almacen Comercial Arboleda Alta y Muy Densa Arboleda Densa de Mediana Altura y Copa Pequena Arboleda Poco Densa Arbustos y Maleza Area Antenas de Radio (s-6) Area Recreacional: Todos los Tipos Area de Mayor Concentracion Comercial en Zona Urbana Areas Agricolas Activas Relacionadas (d/B/E/f/p-15) Areas no Construidas Dentro de Zona Urbana Arena no Costanera (Rios) Bosque Publico (Estado) Cafe Cana Canteras Carretera Primera Categoria (3 + Carriles) Centro Comercial Cienaga Agua Dulce Cienaga Agua Salobre Citricas Comercio de Chatarra Cuerpo Artificial de Agua (+- 1 Acre) Cuerpo Natural de Agua (+- 1 Acre) | <ul style="list-style-type: none"> Estacion Telefonica Fincas Especializadas Floricultura Franja Comercial Franja Residencial Rural Franja Residencial Urbana Hotel/ Motel Industria Liviana Industria Pesada Pantano con Maleza Parcelas Parque Industrial (3 + Fabricas) Pastos Rio/ Canal Rural Alta Densidad Rural Baja Densidad Rural Mediana Densidad Subestacion de Energia Electrica Tosqueros Unclassified Urbana Bajo Construccion Urbano Alta Densidad Urbano Baja Densidad Urbano Mediana Densidad Uso Publico: Todos los Tipos |
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Figure 4.5 Land Use classifications 1977

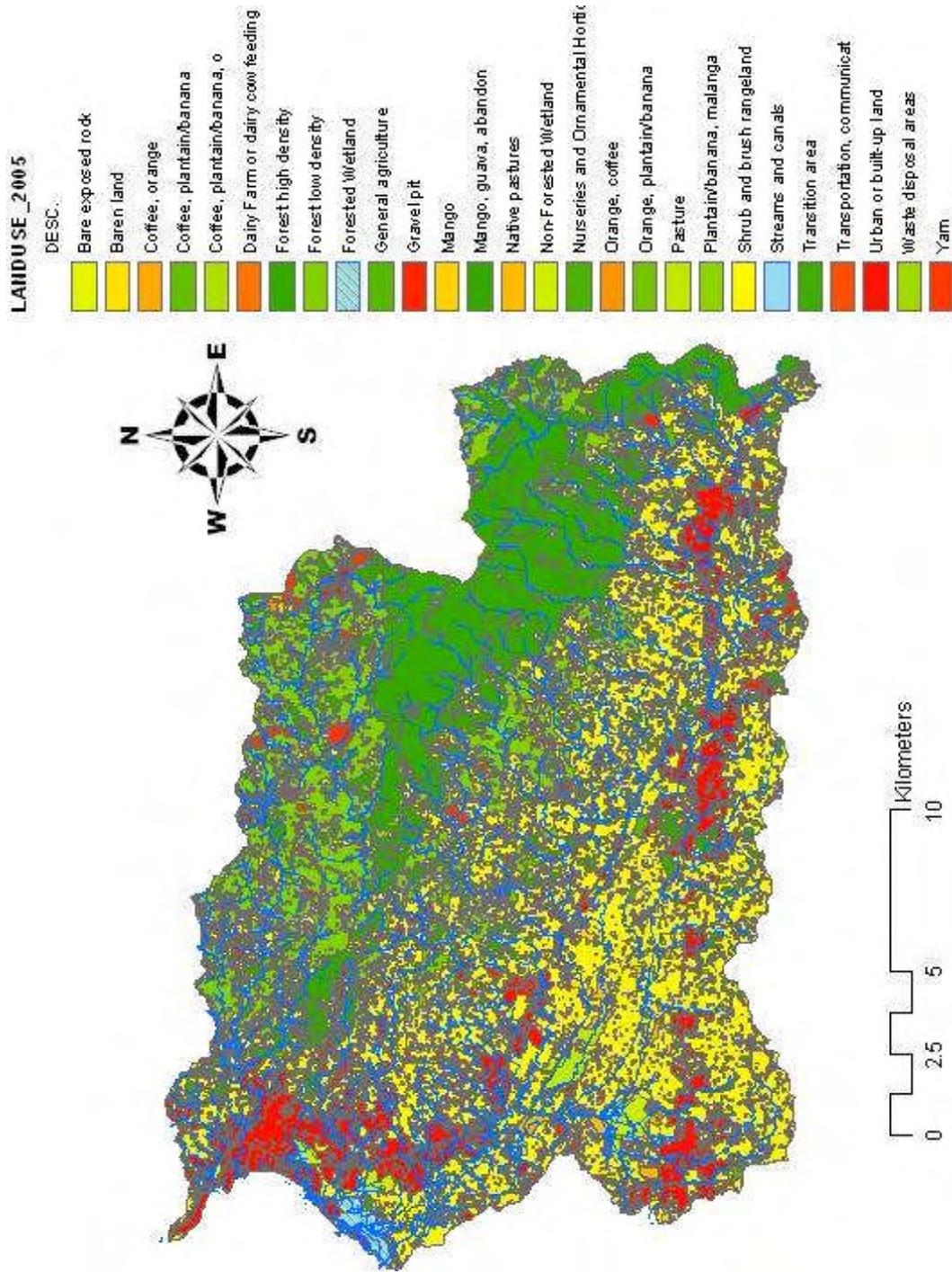


Figure 4.6 Land use classification 2005 (PRWRELI, 2005)

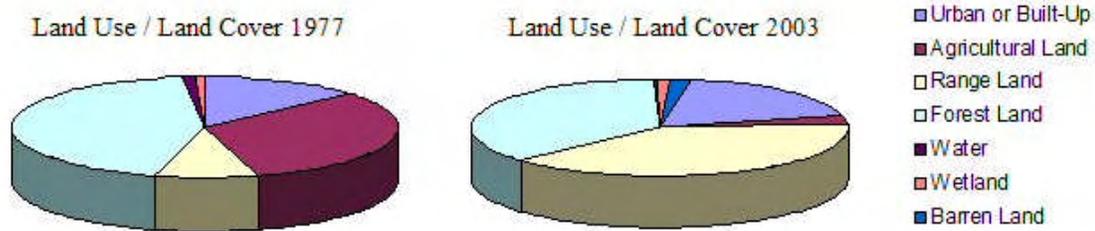


Figure 4.7 Differences in the land uses from 1977 to 2003.

4.6 Hydrology and Hydraulics of Watersheds

Hydrologic and hydraulic characteristic are important features for a watershed description. These characteristics are related to the topography, land uses, and soil types within the watershed. The Watershed Modeling System (WMS) was employed to facilitate the subwatershed delineation and in computing the composite CN (Curve Numbers) coefficients as well as other hydrologic and hydraulic parameters.

4.6.1 Curve Numbers Determination

The curve number, CN, is a parameter developed by the Soil Conservation Service (now the Natural Resources Conservation Service, NRCS) to represent the combined effect of various physical parameter over the conversion of rainfall to runoff. The curve number can be seen as a runoff coefficient with values ranging from 0 to 100. To compute the curve number for a watershed, the drainage area is divided into subbasins of hydrologic homogeneous areas. The smallest subdivisions the more homogeneous the areas are but the more the time consumed for the calculation. With the help of GIS software, these calculations are less tedious and more accurate.

The Guanajibo and Yagüez watershed were divided into small subdivisions, as shown in Figure 4.8, using the land use and soils type polygons as base. Since each subbasin has different curve number values, an area weighted CN is calculated using the following equation.

$$\overline{CN} = \frac{\sum_{i=1}^n (CN_i * A_i)}{\sum_{i=1}^n A_i} \quad (4.1)$$

where \overline{CN} is the weighted curve number value, CN_i is the curve number value of each area A_i . Using digital terrain data (DEM from the USGS), WMS automatically delineates the watershed and its sub-basins. As part of the delineation process, basin data such as area, slope, mean elevation, maximum flow distance, and many other commonly-used hydrologic parameters are automatically computed. Basin boundaries at the northern part of the watershed, from the Mayagüez bay and along the Río Grande de Añasco watershed divide were delineated manually to match known watershed boundaries.

As part of the delineation process, WMS finds all flow paths on the entire terrain model. The longest flow path in each sub-basin is stored for use with the Time of Concentration Calculator.

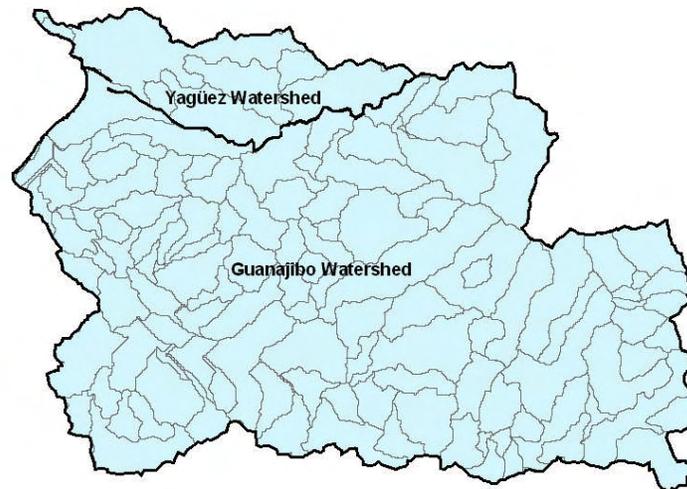


Figure 4.8 Watershed subdivision with WMS.

The curve numbers were determined by using a table relating land use to the hydrologic soil group (HSG). The hydrologic soil group can be either “A”, “B”, “C”, or “D”, where the infiltration capacity decreases from “A” to “D”, as mention before. The curve numbers for each soil group for a given land use can be found in hydrology text books. The HSG classification for each soil in U.S. and Puerto Rico is included in the publication TR-55 (USDA, 1986). A composite curve number for each basin is computed by taking an area weighted average of the different curve numbers for the different regions soil type and land use combinations within a basin as shown in Figure 4.9.

Types of land cover, such as bare soil, vegetation, impervious surface, and so on, establish runoff production potential. Important cover types for urban areas, cultivated agriculture lands, other agriculture lands, and arid rangelands are given in a table which relates the curve numbers for antecedent moisture condition II (USDA, 1986). The original table was modified according to the land use map of 2005 generated for the

Guanajibo and Yagüez watershed (PRWRERI, 2005), where the Anderson Classification System was employed as Table 4.2 shows. Only those categories applying to the Río Yagüez and Río Guanajibo watersheds were used.

Figure 4.9 shows that the Guanajibo watershed has larger curve numbers compared to the Yagüez basin. Actually, if the curve number is determined for each watershed as a whole, the CN will be 80 and 78 for Guanajibo and Yagüez watersheds, respectively. Larger CNs are found in the valleys as oppose to the mountains. This is true for both watersheds as shown in Figure 4.9.

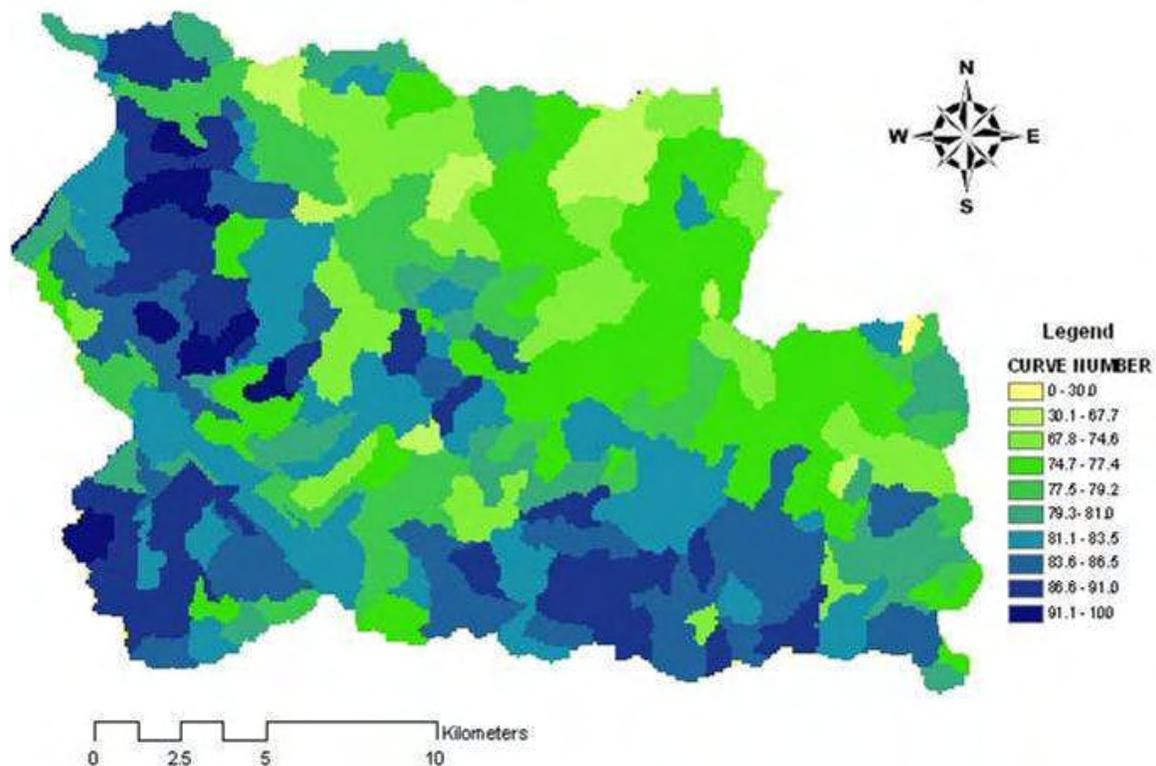


Figure 4.9 Curve numbers computed with WMS.

Table 4.2 Land Use 2003 description correlated with CN for the Guanajibo and Yagüez watershed

ID ⁽¹⁾	DESCRIPTION	A	B	C	D
1	Urban or built-up land	98	98	98	98
12	Waste disposal areas	74	83	88	90
14	Transportation, communication	98	98	98	98
21101	Avocado	57	73	82	86
21102	Yam	57	73	82	86
21103	Orange, plantain/banana	43	65	76	82
21105	Plantain/banana, orange	32	58	72	79
21106	Mango	57	73	82	86
21107	Mango, guava, abandoned	43	65	76	82
21109	Plantain/banana, coffee	32	58	72	79
21110	Coffee bajo sombra	63	75	83	87
21111	Plantain/banana, coffee, o	57	73	82	86
21112	Plantain/banana, orange	57	73	82	86
21113	Coffee, plantain/banana, o	43	65	76	82
21114	Coffee, orange	43	65	76	82
21115	Plantain/banana	32	58	72	79
21116	Coffee	63	75	83	87
21117	Plantain/banana, malanga	32	58	72	79
21118	Coffee, plantain/banana	43	65	76	82
21119	Orange, coffee	57	73	82	86
21120	Coffee, orange, plantain/b	43	65	76	82
21121	Orange, plantain/banana, c	32	58	72	79
21122	Orange	43	65	76	82
212	Pasture	68	79	86	89
213	Native pastures	49	69	79	84
214	Grass	39	61	74	80
22	Nurseries and Ornamental Horticultural Areas	30	48	65	73
24	General agriculture	74	83	88	90
242	Dairy Farm or dairy cow feeding area	39	61	74	80
32	Shrub and brush rangeland	48	67	77	83
411	Forest low density	45	66	77	83
412	Forest high density	30	55	70	77
51	Streams and canals	100	100	100	100
53	Reservoirs	98	98	98	98
55	Ponds	49	69	79	84
61	Forested Wetland	39	61	74	80
62	Non-Forested Wetland	68	79	86	89
7	Barren land	63	77	85	88
74	Bare exposed rock	46	65	77	82
75	Gravel pit	76	85	89	91
76	Transition area	59	74	82	86

⁽¹⁾ ID number refers to the Anderson Classification System.

4.6.2 Precipitation

Rainfall is measured all over the watershed as Table 4.3 indicates and is shown in Figure 4.10. A total of 18 rain gages collect rainfall within and nearby the boundaries of the basin. The mean annual precipitation is depicted graphically in Figure 4.11. The aerial mean annual precipitation for the watershed was determined using the isohyetal method and GIS software.

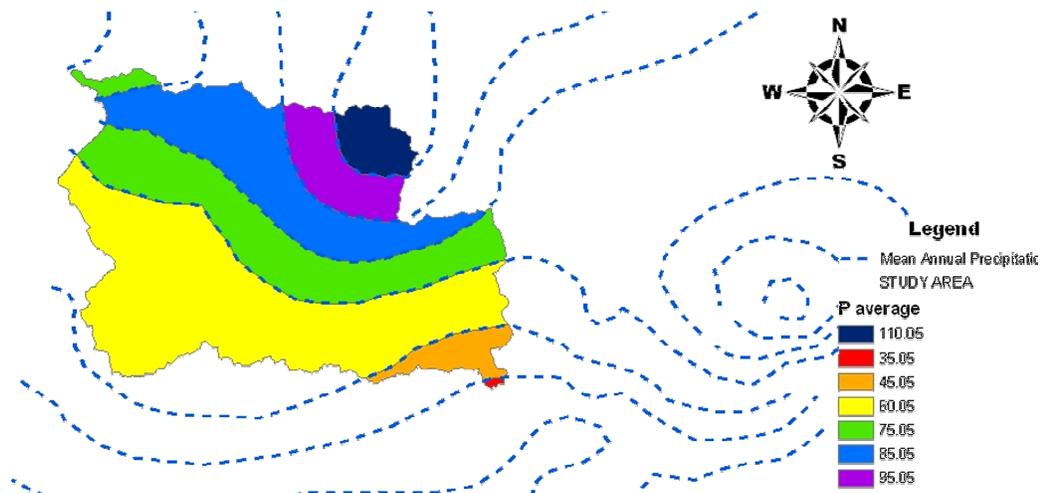


Figure 4.10 Isohyetal contour lines of the mean annual precipitation (1990-1996)

With the isohyetal method the average rainfall between each pair of isohyets, is calculated multiplying by the area between them, totaling these products, and dividing by the total area, as shown in Equation 4.2

$$\bar{P} = \frac{\sum_i \left[A_i \left(\frac{P_i + P_{i+1}}{2} \right) \right]}{A_r} \quad (4.2)$$

where \bar{P} is the average precipitation over the area, A_i is the partial area between isohyets i and $i + 1$, A_r is the total area, or watershed area, and P_i is the precipitation represented by the i^{th} isohyet. The computations above were performed in Excel with data obtained from ArcView manipulation of the information.

Table 4.3 Precipitation stations

STATION	LATITUDE	LONGITUDE	LOCATION
BNVP4	18.1167	67.1000	Hormigueros Benavente
GSGP4	18.0833	67.0333	Río Guanajibo at San Germán, San Germán, PR
HORP4	18.1500	67.1500	Río Guanajibo at HWY 100, Hormigueros, PR
LAJP4	17.9667	67.0500	Magueyes Island, Lajas, PR
LJSP4	18.0500	67.0500	Agricultural Experimental Station Lajas, PR
MAGP4	18.2167	67.0833	Hacienda Constanza, Mayagüez, PR
MARP4	18.1667	66.9833	Fish Hatchery, Maricao, PR
MAYP4	18.1667	67.0833	Río Rosario 2mi Bo. Palma ck, Mayagüez
MAZ	18.2578	67.1489	Eugenio Maria de Hostos Airport, Mayagüez
MRCP4	18.1500	66.9833	TV Station, Maricao
MRIP4	18.1500	66.9833	Maricao, Maricao
MYGP4	18.1667	67.1333	Mayagüez Fire House, Mayagüez
SBGP4	18.0833	66.9333	Sabana Grande
YACP4	18.0500	66.8667	Yauco, Yauco
YUCP4	17.9833	66.8167	Yauco, Yauco
ZOAP4	18.1233	67.0314	Río Guanajibo, San Germán
ZOCP4	18.1500	66.9667	Monte del Estado, Maricao
ZODP4	18.1856	67.0744	Río Rosario, Limón, Hormigueros

The results are presented in Table 4.4. The result is an accurate map of the rainfall pattern as a shape file. The average annual rainfall for the whole study area is 2.43 in.

Table 4.4 Isohyetal method computation results

i	\bar{P} (in)	A_i (mi ²)	$\bar{P} \times A_i$ (in - mi ²)
2	2.125	29.5349	62.7616
3	2.375	48.0540	114.1283
4	2.625	64.2325	168.6102
6	2.375	10.0597	23.8918
Totaled		151.8811	369.3920

The isohyetal method was used to estimate the average rainfall for the study area. Figure 4.10 shows the contour lines. The rainfall data was obtained from the Integrated Water Plan Office of the PRDNER as mean annual precipitation isohyets for rainfall record from 1990 to 1996.

Isohyetal method involves drawing contours of equal precipitation (isohyets) and is the most accurate method (Bedient et al., 2002). The calculated average precipitation for Guanajibo and Yagüez was 84 and 71 inches, respectively (Figure 4.11).

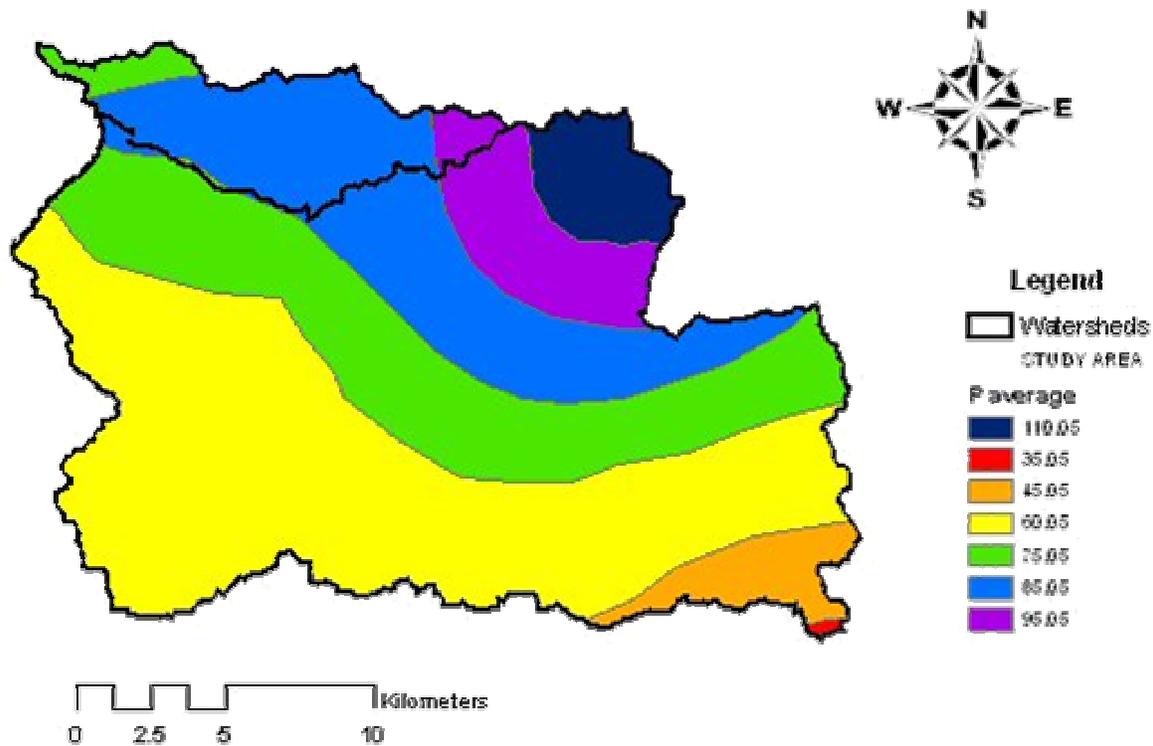


Figure 4.11 Study area mean annual precipitation.

4.6.3 Time of Concentration and Lag Time

The time of concentration t_c is the time taken for runoff to flow from the hydrological most remote point in the watershed to the outlet. The lag time L_t can be estimated as $0.6t_c$. There are many relationships proposed to calculate the t_c parameter. In this study, the time of concentration is determined using the velocity method of the TR-55 procedures. This method relates the physical properties of the watershed such as

basin area, channel geometry, lengths, and slopes. It divides the total flow path in three different patterns: sheet flow, shallow concentrated flow, and channel flow. The sheet flow is the overland flow, which is considered to occur on the first 300 ft of length from the uppermost portion of the basin. The following formula is used to determine the overland flow travel time.

$$t_t = \frac{0.007(nL)^{0.8}}{P_2^{0.5} s^{0.4}} \quad (4.3)$$

in which t_t is the travel time in hours, n is the Manning's roughness coefficient for overland flow, L is the flow length in feet, P_2 is the 2-yr 24-hr precipitation depth in inches, and s is the average land slope for that area of the watershed in ft/ft.

The shallow concentrated flow is found between the channel and the sheet flow. In this case, the average flow velocity is computed and the reach travel time is calculated using the following formula.

$$t_t = \frac{L}{3600V} \quad (4.4)$$

in which t_t is the travel time in hour, L is the length of flow, V is the average velocity in fps. In some cases this flow may not be present. For stream flow, the Manning's equation can be used to calculate average flow velocities. Since overland time of flow is limited to a certain distance, the channel flow portion of the time of concentration equation will dominate the overall value, as watershed size becomes larger.

$$t_c = \frac{Ln}{3600(1.486)R^{2/3} S^{1/2}} \quad (4.5)$$

in which t_c is time of concentration in hours, L is the length of flow in ft, n is the Manning's roughness coefficient for open channel flow, R is the hydraulic radius as A/P , where A is the cross sectional area of the channel, and S is the energy gradient assumed to be equal to the channel bottom slope. Open channel flow is assumed to begin where a channel forms and is visible from field investigations or on aerial photographs. The Manning's coefficient n for open channel flow is obtained from the table presented in Appendix C.

Whenever a drainage area consists of several types of surfaces, the time of concentration is determined by adding the travel times of different surfaces. Table 4.6 shows the open channel computations for travel time for the Guanajibo and Yagüez watersheds, respectively.

Table 4.5 Open channel t_c computations

Watershed	Depth (ft)	Channel Width (ft)	Logitudinal Slope (ft/ft)	Rainfall Depth (in)	Manning's n	tc (hr)
Guanajibo – Seg. 1	8	82	0.022	2.46	0.030	1.346
Guanajibo – Seg. 2	8	82	0.056	2.46	0.030	0.266
Guanajibo – total	8	82	0.018	2.46	0.030	1.612
Yagüez – Seg. 1	10	20	0.015	2.22	0.013	0.037
Yagüez – Seg. 2	10	20	0.031	2.22	0.025	0.237
Yagüez – Seg. 3	10	20	0.052	2.22	0.025	0.113
Yagüez - total	10	20	0.029	2.22	0.025	0.387

4.7 Climatology

The weather is typically warm, humid, with lots of sun, especially during the summer. The average annual temperature varies from 73.5 to 86.5 degrees Fahrenheit (U.S. Department of Commerce, 1986). Winds, mountains, and sea temperatures also play a major roll in the variations of rainfall and temperature throughout the land. The

rainy season occurs between August and December. A dryer period appears around December and can last until March. The southwestern coastal region is characterized by a dryer term.

4.8 Hydrology

Puerto Rico has abundant ground-water and surface-water resources due to relatively heavy rainfall over the mountainous interior of the island and receptive sedimentary rocks around the island's periphery. Ground water accounts for about 30 percent of the total amount of water used in Puerto Rico, whereas surface water accounts for the other 70 percent.

The study area counts with three discharge gaging stations. These are operated and maintained by the USGS. Table 4.6 shows the characteristics of these stations. A frequency analysis was performed for two of the three stations.

Table 4.6 USGS Discharge gaging Stations characteristics

Discharge USGS Code	USGS Streamflow Daily Gaging Stations		
	50136400	50138000	50131990
Name	Río Rosario nr Hormigueros	Río Guanajibo nr Hormigueros	Río Guanajibo at HWY 119 at San Germán
Drainage Area (mi²)	18.30	120.00	34.60
HUC	21010003	21010003	21010003
Latitude	18° 10' 22"	18° 08' 36"	18° 05' 06"
Longitude	67° 04' 31"	67° 08' 57"	67° 02' 02"
Gage Datum (ft)	164.04	120.36	147.6
Record Length	1985/10/01 - 2003/09/30	1973/01/01 - 2003/09/30	1991/01/17 - 2002/09/30
Years of Record	18	32	11

DATUM: in feet above sea level NGVD 29
LAT LONG are in Geographic coordinates
NAD 27

Discharge information was obtained from systematic record and historic data from gaging sites USGS 50136400 and USGS 50138000 stored at the USGS database WATSTORE (WATER STORAGE and RETRIEVAL) system.

Although station USGS 50136400 had only 18 years of record, the frequency analysis was carried out to estimate the discharge for various return periods. Nevertheless, these results are not to be considered good estimates due to the shortage of the record length. The USGS gaging station 50131990 has only 11 years of record and was discarded from the frequency analysis. The frequency analysis was based on Bulletin 17B guidelines (US Water Resources Council, 1981) as incorporated in the USGS' software PEAKFQ. The results for this analysis are presented in Table 4.7.

Table 4.7 Maximum annual *t*-peak discharges at gaged sites within the watersheds

Peak-discharge statistics of maximum annual floods							
USGS site identification	<i>t</i> -year peak discharges, in ft ³ /s						
	Q ₂	Q ₅	Q ₁₀	Q ₂₅	Q ₅₀	Q ₁₀₀	Q ₅₀₀
50138000	5,876	19,160	38,200	84,350	145,200	241,800	723,600
50136400	3,780	5,238	6,255	7,600	8,645	9,727	12,420

4.8.1 Direct Runoff by NRCS Method

Precipitation can be divided into three components, namely: initial abstractions, losses, and precipitation excess or direct runoff. The initial abstractions, I_a , are based on the weighted \overline{CN} value according to the following empirical equation.

$$I_a = 0.2S \quad (4.6)$$

where S is the potential maximum retention in inches and is calculated with the following relationship.

$$S = \frac{1000}{CN} - 10 \quad (4.7)$$

The \overline{CN} and I_a are related to the total accumulated runoff depth for a storm by the following relationship.

$$Q = \frac{(P - I_a)^2}{P + 0.8S} \quad (4.8)$$

where Q is the runoff depth in inches, and P is the potential runoff or total rainfall in inches.

4.9 Population

The total population of the municipalities within the Guanajibo region in 1980 was about 204,000 as seen in Table 4.4 (U.S. Department of Commerce, 1982). Between 1980 and 1990 the population increased by 7 percent to about 218,000 (U.S. Department of Commerce, 1991). However, a large portion of the population in the municipalities of Mayagüez and Maricao is outside the basin. An increase in population directly implies urban grow up in the region, along with those of septic system in rural areas and an increase in potential pathogen sources. This tends to contaminate both surface and ground waters sources.

4.10 Estimated Surface and Ground-Water Use

Ground-water withdrawals in Cabo Rojo, Hormigueros, Mayagüez, and San Germán totaled less than 5.9 Mgal/d in 1982 (Torres-Sierra and Aviles, 1986).

During the 1980's, ground water was the only source of water for public supply in Cabo Rojo and Hormigueros. Public-water supply in Mayagüez is from surface-water sources, while in San Germán both surface and ground water contribute in meeting public water demands.

Public-supply groundwater sources provided less than 5.46 Mgal/d for domestic use, while community systems supplied less than 0.43 Mgal/d (Table 4.9). Water used for industry, agriculture (livestock), and commerce totalled less than 0.27, 0.25, 0.62 Mgal/d, respectively.

Table 4.8 Population for the Guanajibo region, PR (US Department of Commerce, 2000)

MUNICIPALITY	1980 population			1990	2000
	TOTAL	URBAN	RURAL	population	population
Cabo Rojo	34,045	10,292	23,753	38,521	46,911
Hormigueros	14,030	12,031	1,999	15,212	16,614
Maricao	6,737	1,390	5,347	6,206	6,449
Mayagüez	96,193	82,968	13,225	98,434	100,371
Sabana Grande	20,207	7,435	12,772	22,843	25,935
San Germán	32,922	13,054	19,868	34,962	37,105
TOTAL	204,134	127,170	76,964	216,178	233,385*

* This corresponds to the total population of the municipalities mentioned in the table. After correction for municipalities that are partially within the watershed boundaries, the population reduces to 174,812 people.

Table 4.9 Ground-water withdrawals and estimated population served during 1982 for the Guanajibo region, Puerto Rico (Torres-Sierra and Aviles, 1986)

Use	Estimated population served	Average ground-water withdrawals (MGD)
I. Domestic Use		
A. Public Supply		
1. Cabo Rojo	28,419	1.94
2. Hormigueros	13,397	0.84
3. Maricao	-	-
4. Mayagüez	-	-
5. Sabana Grande	19,663	<1.19
6. San Germán	23,634	<1.49
Subtotal	167,466	<5.46
B. Community Systems		
1. Cabo Rojo	5,626	0.22
2. Hormigueros	633	0.03
3. Maricao	4,336	0.18
4. Mayagüez	-	-
5. Sabana Grande	-	-
6. San Germán	9,288	<0.37
Subtotal	36,679	<0.43
II. Commercial Use		
1. Cabo Rojo	-	0.28
2. Hormigueros	-	0.04
3. Maricao	-	-
4. Mayagüez	-	-
5. Sabana Grande	-	<0.07
6. San Germán	-	<0.23
Subtotal	-	<0.62
III. Industrial Use		
1. Cabo Rojo	-	0.03
2. Hormigueros	-	0.01
3. Maricao	-	-
4. Mayagüez	-	-
5. Sabana Grande	-	<0.03
6. San Germán	-	<0.20
Subtotal	-	<0.27
IV. Agricultural Use (livestock)		
1. Cabo Rojo	-	0.13
2. Hormigueros	-	0.01
3. Mayagüez	-	-
4. Sabana Grande	-	<0.04
5. San Germán	-	<0.07
Subtotal	-	<0.25
Total	104,985	<7.03

4.11 Geologic Settings

There are four major lithologically distinct rock groups present in the Guanajibo watershed (see Figure 4.12). They are the Bermeja Complex of Jurassic to Early Cretaceous age; a suite of volcanic, volcanoclastic, plutonic, and sedimentary rocks of Late Cretaceous age; limestone formations of Late Cretaceous age; and alluvial deposits of Quaternary age.

The Bermeja Complex consists primarily of serpentinite, amphibolite, basalt, and chert (Montgomery et al, 1994). It is highly deformed and metamorphism has destroyed most primary textures, bedding, and lithological relations. It is most extensively exposed in the southwestern part of the Guanajibo watershed.

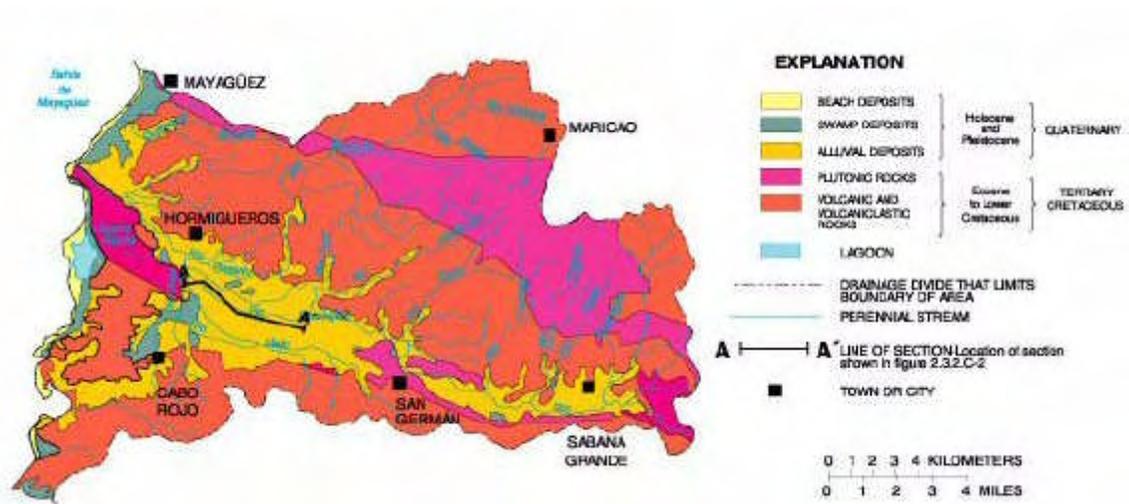


Figure 4.12 Surficial Geology of Guanajibo watershed (Colón et al., 1985)

The suite of volcanic, volcanoclastic, plutonic, and sedimentary rocks predominate in the mountains surrounding the Central Guanajibo valley as shown in Figure 4.12. Subsequent to their formation these rocks were folded and faulted, and then subjected to

extreme weathering and erosion. The Central Guanajibo valley largely lies within an anticline that has been breached by erosion and is bounded in part by faults (Colón et al, 1985).

The limestone formations in the Central Guanajibo valley include the Peñones Limestone, Cotui Limestone, Parguera Limestone, and Melones Limestone (Curet, 1986). While these various formations vary in coloration, they are generally massive to thick-bedded limestones rich in mollusk fossils. These formations overlie the Bermeja Complex and various of the volcanic, volcanoclastic, plutonic, and sedimentary rocks.

Alluvial deposits overlie volcanic and volcanoclastic rocks in the southwestern Guanajibo region and the Bermeja Complex in the Central Guanajibo valley (Mattson, 1960). Clay predominates in the surface of the alluvium. These surficial clay deposits in the alluvium are generally underlain by sand lenses and, at greater depths, gravel lenses within the clay-rich alluvium. In this fashion, where an overlay of clayey soils exist a related hydrologic soil classification of type D is present.

Figure 4.13 shows a cross section along PR Aqueduct and Sewer Authority's water extraction wells in the vicinity of Hormigueros and San Germán.

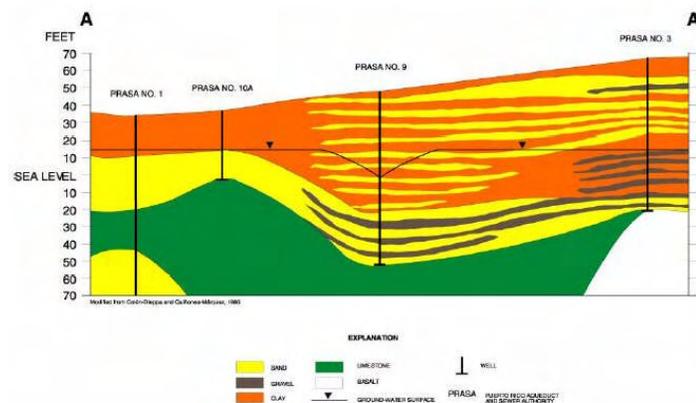


Figure 4.13 Approximate PRASA wells locations in cross section A-A

5 METHODOLOGY

5.1 Summary of the procedure

The following is a summary of the general steps to identify the pollution sources through the determination of the Fecal Coliform Potential Risk Area Index (FCPRAI). More details can be found in subsequent sections.

- Find potential contamination sources. These are sources which produce pathogens that may emigrate and reach a water body.
- Find the critical routes between sources and target (bacterial source-pathway-receiver).
- Decide which factors are important and must be included in subsequent analyses.
- Perform raster/vector analysis (Figure 5.1). Integrate all information layers for further analysis.

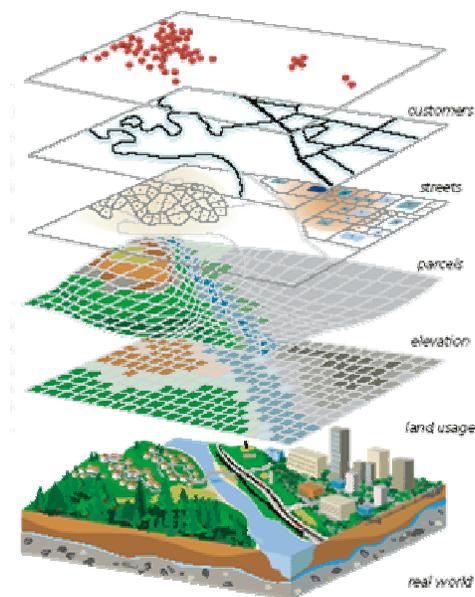


Figure 5.1 Integration example of different datasets to be analyzed (ESRI, 2001).

- Examine reclassified attributes of each dataset (layers), in turn, to decide their contribution to potential contaminant sources.
- Weight datasets according to percent influence.
- Add together reclassified datasets (as some factors are more important than others).
- Use Raster Calculator and in Map Algebra Syntax to write mathematical calculations for all layers in a matrix format. The module will run through a series of classifications and mathematical overlays to define the **Fecal Coliform Potential Risk Area Index (FCPRAI)** for the Guanajibo and Yagüez watersheds.

5.2 Data analysis and handling process

To accomplish the goals of this project, the study was divided in five parts: 1) the identification of data, sources of data, and data acquisition. Sites were visited to locate and collect field data such as the location of wastewater pumping stations, wastewater treatment plants, delineate sewer system serviced areas, and determine potential industrial and commercial sites pollution sources. 2) The second part of this project involves a qualitative sensitivity analysis of factors affecting Fecal Coliform Bacteria (FCB) transport and survival. To take into account the physical properties of the study area, a watershed morphologic characterization was performed. The morphology includes topography factors such as slope, elevation, soil type, and land use. 3) Data analysis and development of GIS layers corresponding to each factor affecting FCB from all points or non-point sources. Every layer (dataset) considered for the construction of the Potential

Fecal Contaminant Index (FCPRAI) was converted to raster format to perform analytical function calculations in spatial analyst (ArcMap GIS extension). 4) Perform spatial analytical function calculations to weight data based on the qualitative sensitivity analysis and according to different factors of transport, sources, and FCB production. 5) Determination of Fecal Coliform Potential Risk Area Index (FCPRAI). The index corresponds to areas which are highly exposed to fecal coliform contamination. These are sources with high probability of being a pollution source.

5.2.1 Data Collection

Three two-crew field teams, equipped with Trimble GPS and data loggers, GIS capable table PCs, and digital cameras, visited all municipalities within the watersheds of Río Yagüez and Río Guanajibo. The data collected was processed using GIS software. Layers of data were created to present the information graphically. These layers included watershed boundaries, river networks, roads, municipality and ward boundaries, sewer collection serviced areas, and commercial and industrial sites. The data needed to identify possible pollution sources included the following information sets.

1. Agency permits
 - a. NPDES
 - b. UIC
 - c. Material extraction
2. PRASA's facility inventory
 - a. Wastewater treatment Plants
 - b. Wastewater pumping stations

- c. Water treatment plants
 - d. Water intakes for drinking water
3. Existing GIS data – Some of these data were already available at the PR Water Resources and Environmental Research Institute and other university offices and laboratories. Other GIS data were available at government agencies such as EPA, USGS, PREQB, DNER, PRPB, DTPW, PRHWTA, CRIM, municipality's offices, etc.
- a. USGS' digital quadrangles
 - b. Watershed boundaries
 - c. Census information
 - d. Hydrography
 - e. Highways and streets maps
 - f. Municipality and ward divisions and boundaries
 - g. Land use/ Land cover maps
 - h. Soil type maps
 - i. Aerial photographs (USGS's DOQQ, IKONOS, and CRIM's photographs).
4. List of schools – This contains a listing of all rural and urban schools within the watersheds. Rural schools use septic tanks for their wastewater disposal.
5. List of churches – List up of all churches in rural areas. Churches also use septic tanks.
6. List of community meeting centers and other institutions – These facilities handle high concentrations of people at certain times. In rural areas these centers also use septic tanks for wastewater disposal.

7. List of industries – Location and type of industries within the region. Provided by the Western Industrial Association of PR and the PR Industrial Development Corporation (PRIDCO).

Every item in the lists mentioned above was graphed into a map using ArcMap GIS 8.3 with GPS coordinates to provide the exact location of these possible point and non-point contaminant sources.

To characterize watershed morphology, 658 subwatersheds were delineated within the Guanajibo and Yagüez watersheds employing WMS 7.1 and analyzed on the basis of digital terrain elevation data. The area of each subwatershed was determined by delineating along the natural drainage boundary. These drainage boundaries were identified using USGS Digital Elevation Model (DEM) 7.5-minute quadrangles from south-western Puerto Rico. The DEM coverage has a cell size of 30 meters (USGS, 1997).

5.2.2 Field Data Reduction

Equipment supplied for field data included tablet PC Toshiba, GPS Garming 76-S and GPS – 2 Trimble Pathfinder Pro XR. The instruments have real-time submeter accuracy. Once the target was located GPS X, Y coordinates marked each feature. The attribute table of each feature contains commentaries and filename of the point (point, line, or polygon).

Digital photos were taken of every feature visited for more detail. A database was created for this project to relate: **GPS coordinates + Description + Digital photographs = One Location Point.**

GPS Pathfinder Office 2.90 was used to download, clean and fix through differential correction the GPS Field data from the GPS Trimble device (recon). Differential correction is made with base files from the US Forestry Station in Isabela, PR (the closest differential GPS station). The data was exported to Shape files with coordinates Puerto Rico and Virgin Islands State Plane Datum NAD 1983.

Each data set classified by date was analyzed as individual project in Arc Map Desktop GIS 8.3. Then added to the correspondent layer for the preliminary identification of the most probable contaminant sources of fecal coliforms.

5.2.3 Census Data

Employing Geo Processing Wizard from tools menu in ArcGIS Desktop shapefile were manipulated to join the attribute table. The 234 files from tgr72001blk00 to tgr72153blk00 were merged into one polygon named Census_Blocks.shp. Then this polygon was joined to the data of the file tgr72000sf1blk with the column STFID having a length of 15 character number type, which includes a summary of the census by blocks (pop2000, pop by ethnic group, etc.). Then the polygon Census_Block.shp for the whole island was clipped according to Guanajibo and Yagüez watersheds boundaries.

A few sampling areas were taken into concern in order to facilitate the estimation of population density by area. The Figure 5.2 shows the eight sampling areas in pink color employed for every municipality.

The Census Data by block 2000 was analyzed and compared with CRIM building structures data to estimate the population by house unit. The number of house units or building structures was divided by the Census 2000 Population and the column CENSUS

(hab/bld), in the attribute table, was created as Table 5.1 shows below. Population by building structures was obtained with CENSUS 2000 and CRIM 1998 data.

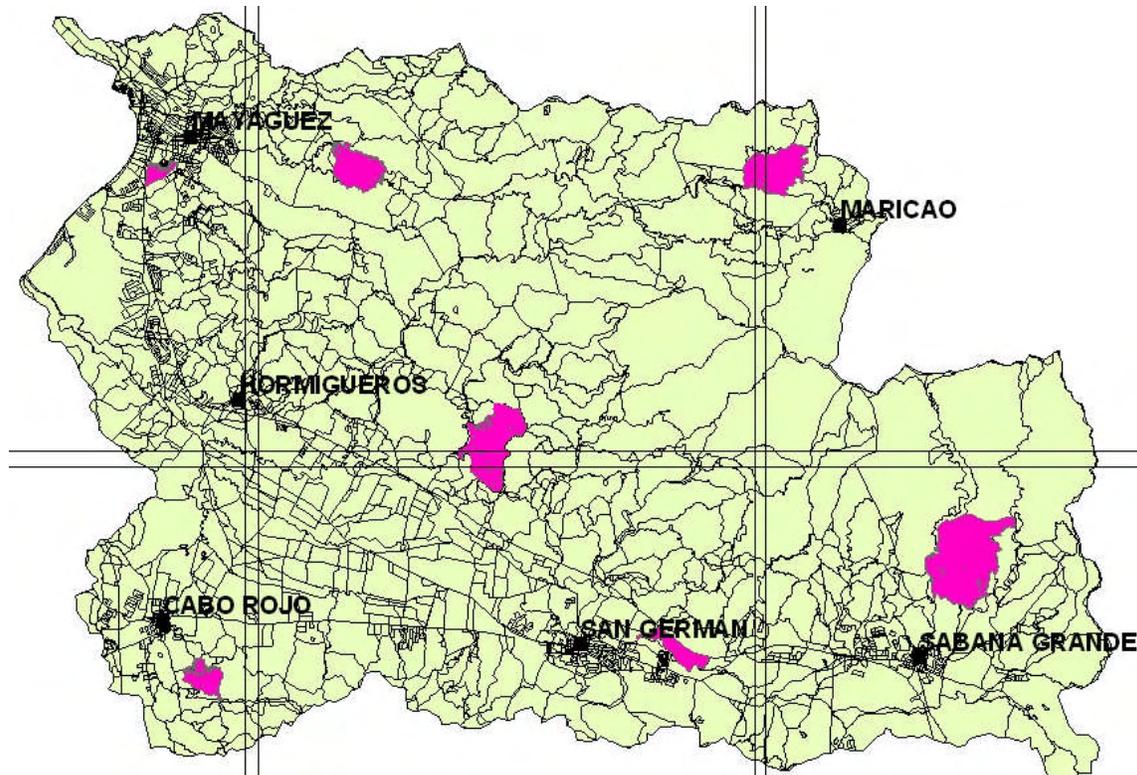


Figure 5.2 Sampling areas from Census Bureau by Block 2000

The columns CENSUS (hab/bld) and CRIM (hab/bld) sampling values were averaged. The number 2.505 is the average of CENSUS (hab/bld) column and was used to obtain the number of people and further to get the load of Fecal Coliform (FCB) contamination produced by humans.

The averaged value 1.769 from CRIM (hab/bld) column was not used to perform population density computations due to the large difference variations of about 0.912 compared with other sampling values from this column. While in column CENSUS (hab/bld) the maximum difference between the average value and the sampling data values was 0.404.

Table 5.1 Population estimation by CRIM building structures.

Municipality	SAMPLE	HOUSE/BUILDING UNITS			POPULATION BY BUILDING STRUCTURE		POP_2000	
		CENSUS 2000	CRIM 1998	Difference	CENSUS (hab/bld)	CRIM (hab/bld)		
Hormigueros	1	164	185	21	2.756	2.443	452	
Mayagüez	2	129	132	3	2.628	2.568	339	
Sabana Grande	3	68	119	51	2.529	1.445	172	
Maricao	4	22	38	16	2.909	1.684	64	
Cabo Rojo	5	135	178	43	2.222	1.685	300	
Mayagüez	6	199	245	46	2.090	1.698	416	
San Germán	7	5	14	9	2.400	0.857	12	
AVERAGE						2.505	1.769	

It is assumed that the human contribution to FCB contamination is attributed to septic systems and sewer pipe failure. The human contribution was calculated using the number of septic systems, the average number of people per septic system, and the failure rate of the septic systems. The estimated fecal coliform loading from humans is calculated as follows:

$$Load = P \times S \times Fr \times FCB \times Q \quad (5.1)$$

where P is the number of people per septic system, S is the number of septic systems in the restricted area, Fr is the failure rate of septic systems, FCB is the fecal coliform concentration of wastewater, and Q is the daily discharge of wastewater per person.

The number of people using each septic system is estimated by the ratio of the population to the number of septic systems. An estimated failure rate of 70 % was used for the total number of failing septic systems (U.S.EPA, 2004). It was assumed that each person discharges 70 gallons per day of wastewater as specified on home owner septic system design guide by EPA.

5.2.4 Soils Type

There are two places over the NRCS site in the web where soil type data can be found. One is the STASGO page which describes the soils in a general fashion for all of Puerto Rico and the other is the SSURGO page which consists of smaller areas (e.g. Mayagüez, Arecibo, Lajas, Ponce and San Juan) with more detailed information.

The files requested from the internet include the Western Area (Aguadilla, Añasco, Mayagüez, Maricao, Rosario, part of Cabo Rojo, Hormigueros, and San Germán). Other area requested was the Lajas Valley (Cabo Rojo, San German, Sabana Grande, Yauco, and Lajas). Then the Western Area and Lajas Valley were used to construct the Guanajibo and Yagüez watersheds soils type layer.

The format in which spatial data is provided depends on the spatial format option that is selected when the download is requested (Figure 5.3). Spatial data is available in the following formats: ArcView Shape File, ArcInfo Coverage, and ArcInfo Interchange.

States Department of Agriculture
Natural Resources Conservation Service

PR687 - Lajas Valley Area, Puerto Rico
San German County
Puerto Rico

Soil Data

Home State Contacts Template Databases SSURGO Metadata Logon/Regis

Please select the class of data you wish to download: (Survey Area Version 1 , Tabular Version 1 , Spatial Version 1)

Tabular Data Only Tabular and Spatial Data Spatial Data Only Template Database Only

Please select a spatial format:
ArcView Shapefile

Please select a coordinate system:
State Plane Puerto Rico & Virgin Islands (NAD83, meters)

Reset Default

Please select a template database (optional):
Clear Selection

State	MS Access Version	Template DB Version	Template DB Name	Size
US	Access 2002	32	soildb_US_2002	1.7M
US	Access 2000	32	soildb_US_2000	1.7M
US	Access 97	32	soildb_US_97	1.6M
PR	Access 2000	32	soildb_PR_2000	1.6M

Description: This is the national SSURGO Template Database for Microsoft Access 2002/2003. This database should be used only when no state specific customized SSURGO Template Database is available. This database is compatible with Soil Data Viewer 5.0.

Figure 5.3 NRCS' SSURGO Download data example

Tabular data is provided as a set of ASCII delimited files. Each file corresponds to a table in the SSURGO 2.1 data model. The tabular data is not particularly useful until it has been imported into an MS Access SSURGO template database. See appendix F for instructions about accessing and importing data from SSURGO.

Spatial data files use a naming convention that depends on the corresponding spatial format. For spatial data in ArcView Shape File format, the following file name prefixes are used as Table 5.2 shows.

Table 5.2 NRCS' shape files naming convention

File Name	Description
soilsa_a	soil survey area boundary polygons
soilmu_a	map unit boundary polygons
soilmu_l	line map units
soilmu_p	point map units
soilsf_1	line spot features
soilsf_p	point spot features
soilsf_t	spot feature descriptions

The data requested at the SSURGO database were the files soil_pr687.zip (Lajas Valley), and soil_pr684.zip (Western Area). The utilized formats for this project were ArcView format for the spatial data, and 2002 MS Access format for the tabular data. From the spatial data set the Soilmu_a.shp shape file was used and the attribute data table was joined with the re-organized table in Excel according to musym attributes (soils type and soil hydrologic groups).

5.3 Factors affecting Fecal Bacteria transport and survival

Since the major concern is the bacterial concentration and its variation along the pathway, a transport equation is needed. Consider a first order equation as follows (Muller and Thomann, 1987),

$$C_t = C_0 e^{-k t} \quad (5.2)$$

where C_t is fecal coliform bacterial concentration at time t , C_0 is the initial fecal coliform bacterial load, t is the time in days, and k is the first order decay rate (day^{-1}) given by

$$k = k_{b1} + k_{bi} + k_{bs} - k_a \quad (5.3)$$

where k_{b1} is the death rate as function of temperature, salinity, predation, k_{bi} is the death rate due to temperature, k_{bs} is the net loss due to settling (resuspension), and k_a is the after growth rate. Equation 5.3 does not consider the effect of nutrient deficiency and toxic substances. Although the importance of these factors is recognized by the author, the incorporation of them is beyond the scope of this work at this moment.

Factors affecting the FCB initial load will be considered in two groups as follows.

A. Factors associated with the source:

- These are individual landowners and public or private enterprises engaged in agriculture, forestry, or urban development (U.S. EPA, 2005).
- Contributions from dominant sources: cattle, dogs, poultry, and humans.

B. Factors associated to watershed morphology / transport mechanisms and the kinetic behavior of FCB after discharge to a water body (Figure 5.4):

- Distance to rivers
- Land use / land cover
- Soil hydrology classification
- Proximity of contaminant sources to each other within the watersheds
- Overland flow
- Temperature

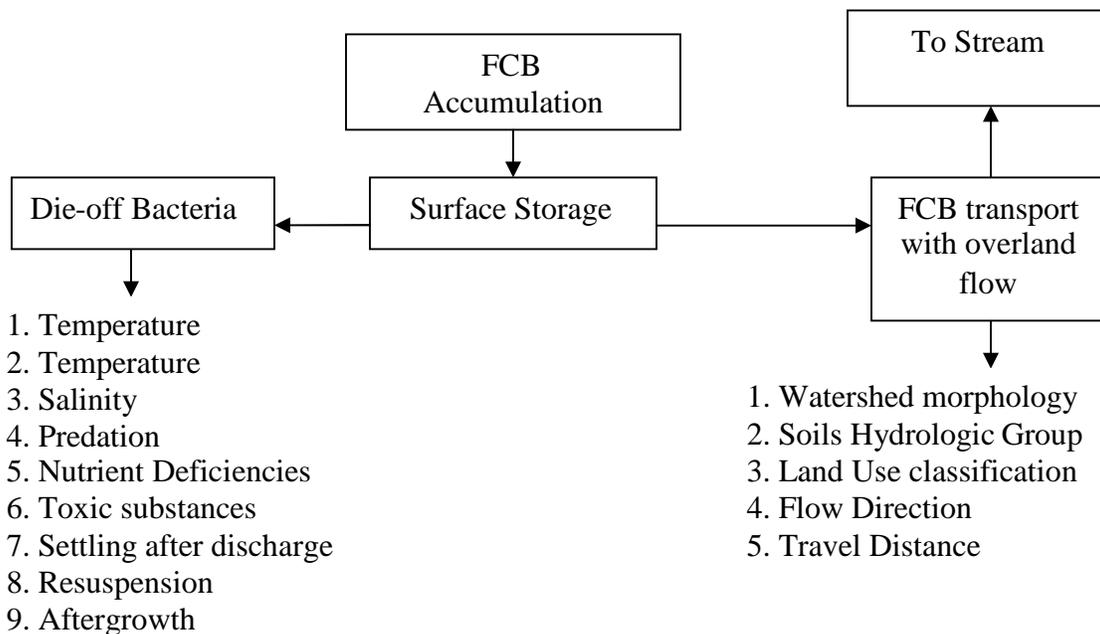


Figure 5.4 Specific bacteria transport mechanisms and kinetic behavior.

5.3.1 Analytical Functions with Spatial Analyst

Previous sections explained the data manipulation and a setup prior to analysis. This section explains in detail the analytical functions performed with Spatial Analyst.

5.3.1.1 Source to River Weighted Distance function

Using the cost raster and the source, the Cost Weighted Distance function produces an output raster in which each cell is assigned a value that is the least accumulative cost of getting back to the source.

Every cell in the cost-weighted distance raster is assigned a value that represents the sum of the minimum travel costs that would be incurred by traveling back along the least-cost path to its nearest source.

5.3.1.2 Reclassifying the data sets to a common scale

Based on hydrologic and hydraulic properties of the watershed morphology, the attributes of each dataset (point and non-point sources, rivers and creeks) were examined and normalized to a common scale in order to decide their contribution to identify the most potential contaminant sources.

5.3.1.3 Weight datasets according to percent of influence

After applying a common scale to all datasets, higher values were given to those attributes that are considered more critical within each dataset. In this project the criteria to assign weights was based on the literature review. It was found that 90 % of FCB is washed off when a storm event occurs with no consideration to infiltration into the ground (Hyer and Moyer, 2003). A higher percentage of influence was assigned to the curve numbers (CN) applying the knowledge of the concept of runoff according to Soil Conservation Service theory in which runoff is preferred over infiltration.

Since the primary target of FCB contamination are the water-bodies a higher percentage of influence was assigned the “rivers and creeks” layer. This layer has information about the distances from the water bodies to the sources. Lower values of influence were assigned to sources (non-point and point sources) and flow direction.

All datasets are, then, combined to find the most critical locations on the watershed which are those with the highest potential to produce FCB contamination.

If all datasets were equally important, one could simply combine them at this point. However, datasets can be weighted employing Raster Calculator giving each a percentage of influence. The higher the percentage, the more influence a particular dataset will have in the identification of critical sites.

5.3.1.4 Flow Direction function

This function creates a grid of flow direction from each cell to its steepest downslope neighbor. The direction of flow is determined by finding the direction of steepest descent from each cell. This is calculated using the change in elevation for a known distance as:

$$FLOWD = \frac{\Delta Z}{d} * 100 \quad (5.4)$$

where *FLOWD* is the flow direction based on the steepest descent, ΔZ is the change in elevation, and *d* is a known distance. If the descent to all adjacent cells is the same, the neighborhood is enlarged until a steepest descent is found.

If two cells flow to each other, they are sinks, and have an undefined flow direction. This method of deriving flow direction from a DEM is presented in Jenson and Domingue (1988). The output of flow direction is an integer grid whose values range from 1 to 255. Figure 5.5 shows the output raster.

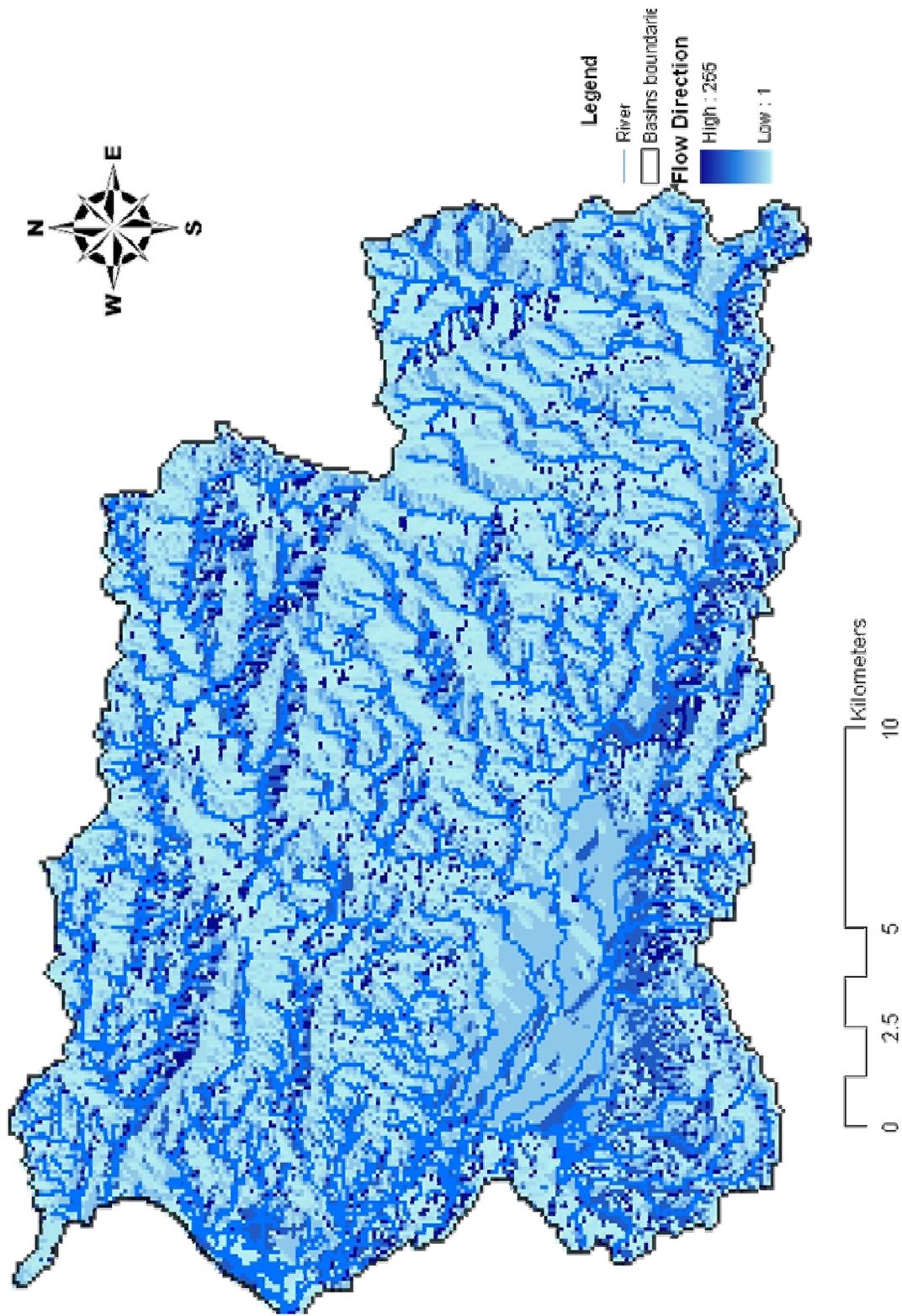


Figure 5.5 Flow direction grid computed for Guanajibo and Yagüez watersheds

5.4 Accumulative Effects of Factors Affecting Initial FCB Concentration

The GIS layer of census blocks in polygon format was changed to point features using the centroid of each polygon and assigning X-Y coordinates in State Plane NAD 1983. The population column in the attribute table was corrected to reflect a better estimate of population in blocks that are partially within the watershed borders. The structure layer of the CRIM was used to make this correction as described in section 5.2.3.

The attribute table of the centroids was exported to dbase format and fecal coliform daily production was assigned according to source type as the table below explains.

Table 5.3 Fecal Coliform Bacteria produced by source type

Source	Average daily feces produced per day (g)	Fecal coliform bacteria (Col. / g of feces)	Population number	Area (acres)
Dairy cattle	54,545	8.18×10^5	1,285	1,285.00
Hens / Chickens	28	1.82×10^5	60	0.25
Dogs	450	4.11×10^6	43,703	97,035.03
Cats	20	1.49×10^7	116,541	97,035.03
Hogs	600	1.08×10^5	204	10
Humans	150	4.66×10^8	174,812	97,035.03

The Guanajibo and Yagüez watersheds have a human population of approximately 174,812 habitants (U.S. Department of Commerce, 2000). Within the watersheds, many pathways allow human-derived fecal coliform bacteria to enter

Guanajibo and Yagüez rivers. These pathways include failing septic systems, overflowing sewer lines, bypasses at sewer pumping stations, and land applications of animal waste and farm activities.

On average, one person generates approximately 150 g of feces per day (Geldreich et al., 1962) and an estimated 4.66×10^8 col/g of Fecal Coliform Bacteria (Mara et al., 1981).

On average, one dog generates 450 g of feces per day (Weiskel et al., 1996) and an estimated 4.11×10^6 col/g of FCB (Mara et al., 1981). A value for the total number of dogs in the watershed was based on the estimate of one dog per four people (Hyer et al., 2003).

A value for the total number of cats in the watersheds was based on an estimate of two cats per three people according to census data. One cat generates 20 g of feces per day (Jutta, 2000), and an estimated 1.49×10^7 col/g of FCB (Mara et al., 1981). It was assumed that 80 percent of the estimated number of cats deposits their feces outdoors.

Other animal type FCB productions were calculated similarly using the information in Table 5.3.

5.4.1 Farm Facilities

The FCB derived from cattle feces can be transported to Guanajibo or Yagüez rivers along three possible pathways: (1) feces generated while cattle are confined are stored and later distributed over the various croplands in the watershed as manure application, and then transported to the stream network with surface runoff. (2) Feces are deposited directly on the pasture land by grazing cattle, and then transported to the stream

network through surface runoff. (3) Feces are deposited directly into main rivers and creeks by cattle standing in these streams.

The total number of animals within the watersheds is unknown; a few samples were taken in the field visits. For example a fecal production rate for hens of 28 g/day (American Society of Agricultural Engineers, 1998) and an estimated fecal coliform density of 1.82×10^9 col/g (Mara et al., 1981) were used to determine the poultry activity total fecal coliform bacteria production per day.

Because the entire poultry population is confined to poultry houses, the generated poultry litter is stored and later applied to cropland. The extent of fecal coliform bacteria die-off during poultry litter storage was determined using the first order equation for Fecal Coliform Bacterial Concentration as follows (Muller et al., 1987),

$$C_t = C_0 e^{-k t} \quad (5.5)$$

where C_t is fecal coliform bacteria load at time t , C_0 is the initial fecal coliform bacteria load, t is the time in days, and k is the first order decay rate (day^{-1}). C_0 was set to the total number of FCB produced daily by poultry. The time t these bacteria were stored was set to 90 days, which is the average poultry litter storage time. A decay rate k of 0.08 day^{-1} was used to represent the decay rate observed for poultry litter applied to the soil surface (Giddens et al, 1973). The amount of FCB remaining C_t after 90 days of storage is incorporated into Equation 5.15 as the *FCCOL* parameter.

A similar procedure was used to consider the contributions of the stored cattle manure applied to croplands within the Guanajibo and Yagüez watersheds. Assuming that some farms use anaerobic lagoons and that the decay rate k observed in an anaerobic lagoon is 0.375 day^{-1} (Crane et al., 1986).

5.4.2 General Quantification of FCB load

The amount of FCB deposited on the land surface daily is represented by *FCBA* in this project. Every source represented in the Potential Fecal Contaminant Index (FCPRAI) has a specific fecal coliform production rate. The following equation is used to calculate *FCBA* for each fecal coliform source.

$$FCBA = \frac{(FPROD * FCCOL)POP}{HAB} \quad (5.6)$$

where *FCBA* is the fecal coliform bacteria accumulation rate (number of colonies/acre/day), *FPROD* is the feces produced per day (g/day/per capita), *FCCOL* is the number of fecal coliform bacteria per gram of feces produced (col/g), *POP* is the population size, and *HAB* is the habitat area (acre).

After the required settings, computations and data manipulation of the 2000 Census and the field visit data, by source type in *FCBA*, a dbase table was constructed and exported to ArcGIS to perform density function analysis.

5.4.2.1 DFCB function analysis

A dbase table, named FCB_INDEX.DBF, was constructed (Table 5.4 shows the format), which contains the *FCBA* quantities of each source of fecal coliform bacteria. The table was uploaded at ArcMap GIS to perform a density function analysis and finally the FCB Production Rate (PR) was obtained.

Density surfaces are good for showing where point features are concentrated. For example, having a point value for each septic system with the amount of *FCBA*, representing total population, through density surfaces, it is easy to identify the spread of population over the region in a map of summarized information. As for example, a point

can represent the number of people in each block, as for the census data. It is known that not all the people in each block live at that point, but by calculating density surfaces showing the predicted distribution of the population throughout the landscape, GIS techniques can be adequately applied to manages the data and incorporate it into mathematical operations.

Table 5.4 Fecal Coliform Index table format dbase

Field Name	Format Field	Description
ID	Number, 0 decimals	Identification number
X	Number, 8 decimals	X coordinate Lambert Conformal Conic (NAD 1983, State Plane PR/VI)
Y	Number, 8 decimals	Y coordinate Lambert Conformal Conic (NAD 1983, State Plane PR/VI)
FPROD	Number, 0 decimals	Feces produced by day in grams
FCCOL	Number, 4 decimals	Fecal Coliform bacteria per gram of feces
AREA	Number, 4 decimals	Polygon areas in meters
POP	Number, 0 decimals	Population size
HAB	Number, 9 decimals	Habitat area in acres
SOURCE	Text	Fecal Coliform bacteria source type

The magnitude of the data at each sample location (line or point) is distributed throughout a landscape, and a density value is calculated for each cell in the output raster. Density maps are predominantly created from point data, and a circular search area is applied to each cell in the output raster being created. The search area determines the

distance to search for points in order to calculate a density value for each cell in the output raster.

5.4.2.2 FCB Production Rate calculations

FCB Production Rates (PR) can be calculated using density calculations (simple or kernel calculations). In a simple density calculation, points or lines that fall within the search area are summed and then divided by the search area size to get each cell's density value. The kernel density calculation works the same as the simple density calculation, except the points or lines lying near the center of a raster cell's search area are weighted more heavily than those lying near the edge. The result is a smoother distribution of values. Figure 5.6 shows the command window for the selection input data, type of computations, and search radius preferences.

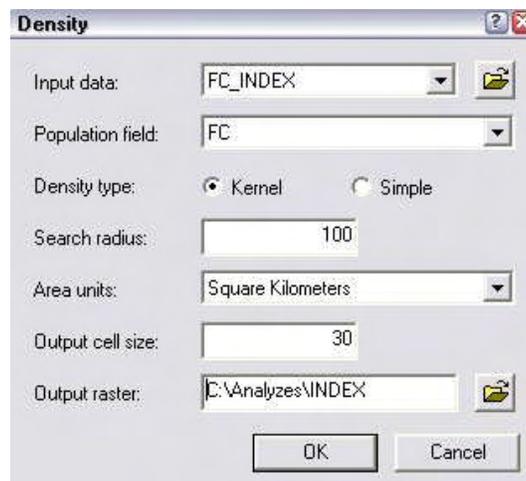


Figure 5.6 Density function command window

For the determination of PR, the kernel density was employed using different search radiuses as Table 5.5 explains. The results of density computations by kernel were smoother and more precise patterns than using simple density calculations.

Finally different density maps of Fecal Coliform Bacteria production rate (*PR*) were constructed varying the search radius. For example, Figure 5.7 shows the FCB *PR* over the basins with a designated search radius of 1000 meters.

Table 5.5 Density surfaces computed parameters

NAME	SEARCH RADIUS	DENSITY TYPE
FCCI_1	100	Kernel
FCCI_2	300	Kernel
FCCI_3	500	Kernel
FCCI_4	665	Kernel
FCCI_5	1000	Kernel
FCCI_6	1609	Kernel
FCCI_7	2000	Kernel
FCCI_8	2500	Kernel
FCCI_9	3000	Kernel
FCCI_10	5000	Kernel
FCCI_11	10000	Kernel

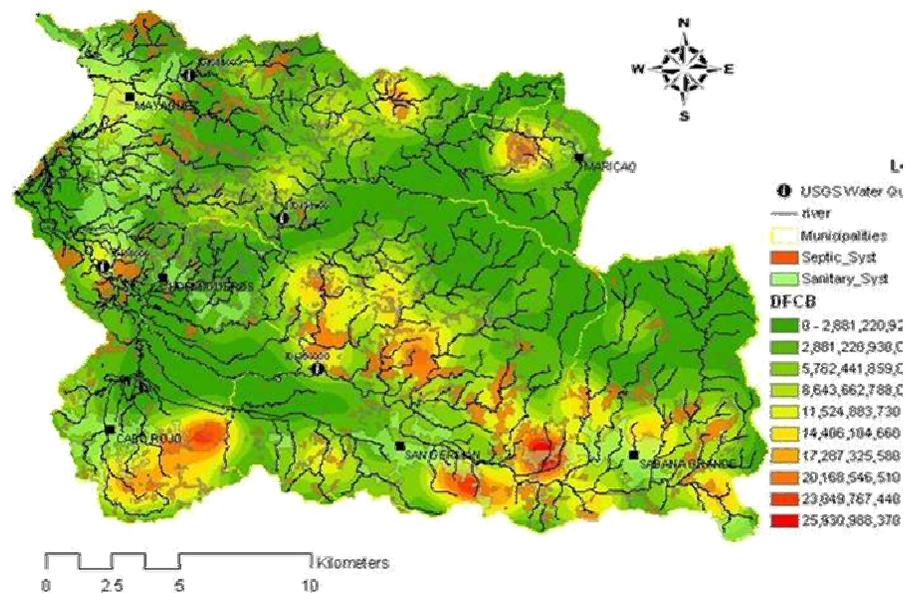


Figure 5.7 FCB production rates (PR) over the Basins with search radius of 1000 m.

5.5 Temperature

The temperature effect for bacteria is often approximated by

$$(k_b)_T = (k_b)_{20}(1.07)^{T-20} \quad (5.7)$$

where $(k_b)_T$ is the decay rate due to temperature, $(k_b)_{20}$ is the kinetic decay rate, and T is the exposed temperature in $^{\circ}\text{C}$.

The effect of temperature has been evaluated in a variety of studies (Gameson et al., 1974). Their results for surface data (0-5 cm) in direct temperature are summarized in Table 5.6. However, it must be recognized that solar radiation varies with elevation.

Table 5.6 Effect of temperature on bacterial decay rate

% frequency of occurrence of decay rate (\geq)	K_b (day^{-1})	T_{90} (hr)
5	80	0.7
50	18	3.1
95	7	8.0

The simplest model uses the overall net low rate k_b as the measure of bacterial kinetic and no attempt is made to describe the individual mechanisms or the kinetic structure. At most, k_b is considered as a function of temperature. This simple model recognizes that there may be considerable uncertainty in the input loads in certain problem context and that it is really not practical or meaningful to describe the kinetic structure at any significant level of detail.

Temperature is directly related to sunlight incidence over the earth surface. High temperatures are associated to places where shadows are scarce. The opposite is true. In mountainous terrain, with step slope, shadows are common and lower temperatures are

expected. In flat terrains temperature are high since the incidence of the sun lights' continuous all day long. In this study, this principle was used to determine areas where high temperatures will prevail. As a result, areas with lower temperatures were also identified.

An analysis of how temperature varies through the day jointly with the hill shade function of ArcMap GIS software allowed the construction of a layer with this information. Sun light inclination and azimuth were selected to correspond to midday conditions. Figure 5.8 presents information used to determine the azimuth while Figure 5.9 shows how the hill shade code varies along a day.

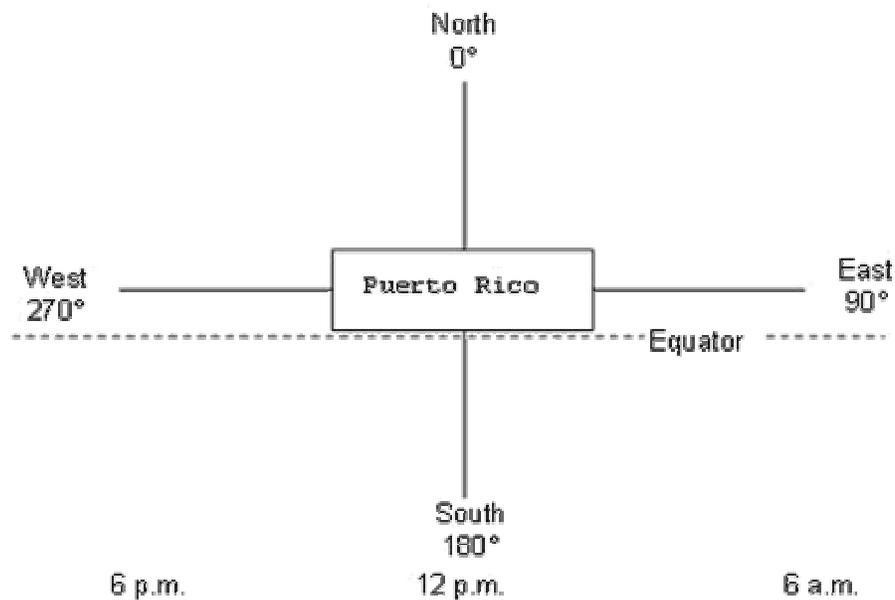


Figure 5.8 Sun positions depending on earth rotation

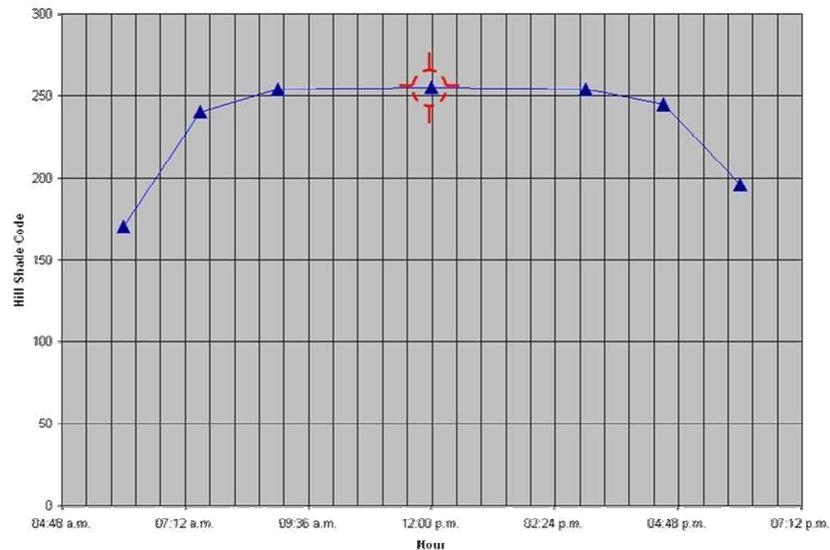


Figure 5.9 Temperature at 12:00 p.m. trends related to Hill Shade coded values.

5.6 Fecal Coliform Potential Risk Area Index (FCPRAI)

The base equation perform FCPRAI takes into account the above mentioned parameters.

$$FCPRAI = TM + PR - TEMP \quad (5.10)$$

where, TM is the Transport Mechanisms dataset due to infiltration properties, distance to the rivers, and slope; PR is the Production Rate of fecal coliform bacteria from different sources; $TEMP$ is the hill shade code as it relates to temperature.

FCPRAI identifies areas of high risk of FCB contamination. These areas represent specific sites where ambient conditions are appropriate to promote pollution in nearby water bodies. These areas not necessarily are pollution sources but contain all necessary condition to become a source. In practice, these areas should be field recognized and carefully examined to find pollution sources of FCB. If this is the case, then quantification through an appropriate monitoring program is the next step.

6 APPLICATION OF THE FECAL COLIFORM POTENTIAL RISK AREA INDEX

This chapter presents an example of the application protocol derived in the previous chapter to determine the Fecal Coliform Potential Risk Area Index (FCPRAI) for the Guanajibo and Yagüez watersheds. The discussion will explain the data requirements, parameters, and finally, the determination of the FCPRAI for the study area.

6.1 Data description

The required data, as well as the depository locations where they can be obtained, are listed in Table 6.1. These specific data were used to determine the FCPRAI in a GIS environment.

Table 6.1. Identification of the required data and their sources.

Required Data	Depository	Description
Digital Elevation Model (DEM)	U.S. Geological Survey	Topographic relief mapping; 30 meter resolution; supports watersheds delineations and modeling
Reach File Version 3 (RF3) Alpha	U.S. EPA	Provides a detailed stream network and supports development of stream routing for modeling purposes
Land Use and Land Cover	University of Puerto Rico at Mayagüez	Boundaries associated with land use classifications
State Soil and Geographic (SSURGO) Database	USDA Natural Resources Conservation Services (NRCS)	Soils information including soil component data and soils. Of special are the interest Hydrologic Soil Groups (HSG)
Census Block Demographics (SF1)	Census US Bureau	Census 2000 population by block. Of special interest are House Units and Population
Water Quality Stations Data	U.S. Geological Survey	Location of selected water quality stations and monitoring information used to compare the probability index location of identified sources of contamination

6.2 Parameters of concern in FCPRAI

The following main factors were considered in the development of the protocol to determine the potential fecal contamination index. These are transport mechanisms, fecal coliform bacterial production rates, and temperature as it relates to temperature of hill shadows.

6.2.1 Transport Mechanisms

This layer considers accumulative effects of factors affecting transportation of fecal coliform bacteria (FCB). It is based on the following datasets: runoff coefficient, point and non-point sources aerial density, flow direction preferences, and distance to river. Data manipulation and critical parameters considered for each dataset were explained in previous chapter. Datasets were normalized to a common scale of 1 to 10. Table 6.2 shows a summary about the construction of transport mechanisms dataset. The resulting transport dataset is shown in Figure 6.1.

Table 6.2 Parameters selected for transport mechanisms dataset

Layer Input	Search Radius (m)	Reclassification Preferences	Assigned Name	Influence Weight
Curve Number		High Curve Number = 10	CN	0.3
Flow Direction		Low values of Flow = 10	FLOWD	0.2
Point and Non-Point Sources	2,000	Close to source = 10	SOURCES	0.2
Rivers and creeks	1,200	Close to Rivers = 10	RIVER	0.3
			SUM =	1.0

6.2.1.1 Flow paths determination

Transport of bacteria is mostly passive, being determined by the presence of rapid water fluxes, although cell motility can play a significant role in movement in suspension over short distances.

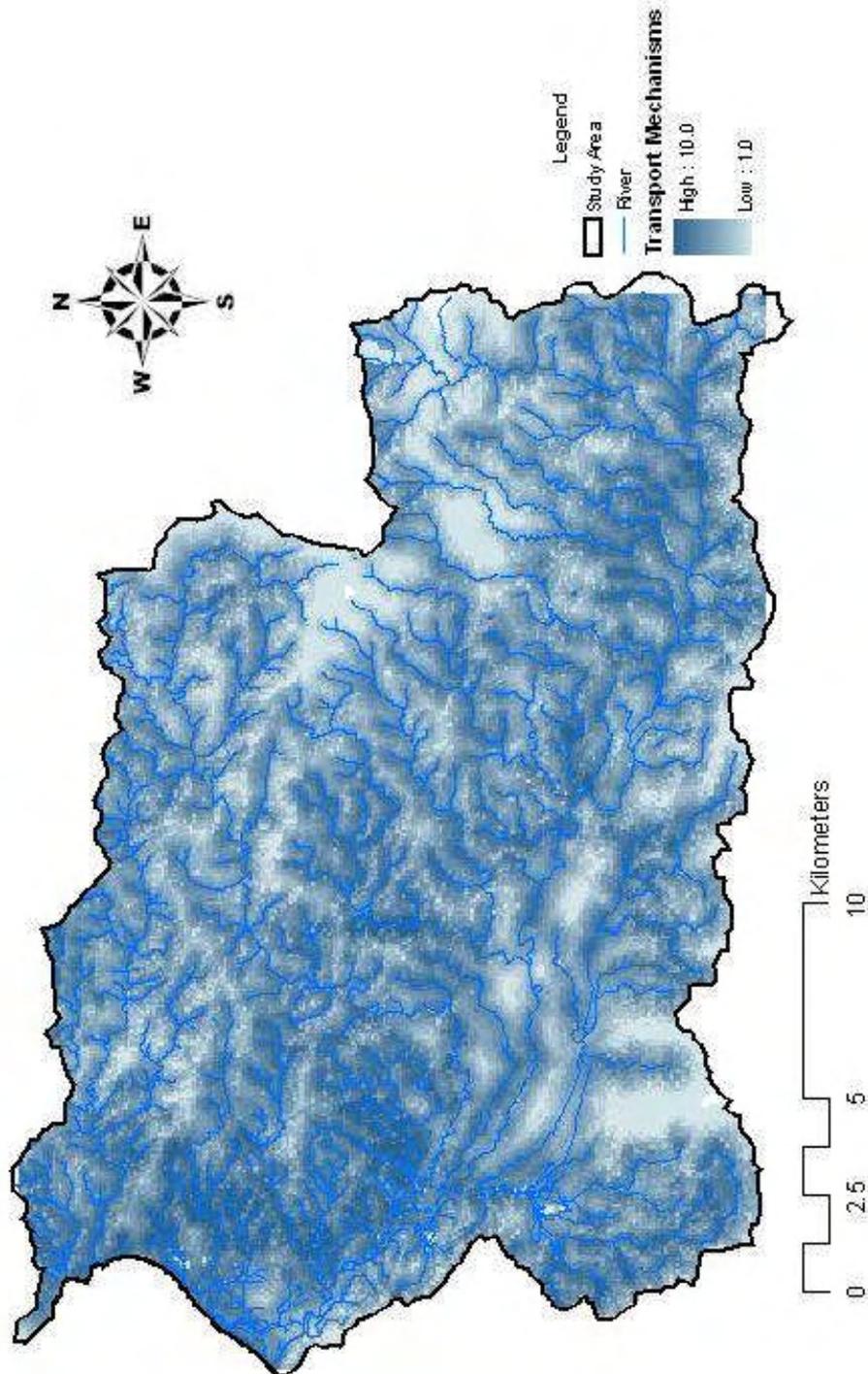


Figure 6.1 Transport Mechanisms dataset.

Therefore, the path followed by water, infiltration or surface runoff, determines the direction of transport of bacteria from non-point sources. Partition of rainfall or irrigation waters into infiltration and runoff is a function of the soil hydraulic properties, soil cover, slope, and the characteristics of the precipitation. Accordingly, this partitioning of the precipitation water is the main factor that determines the resource that is at risk of contamination (surface water or groundwater) and the rate at which the bacteria will move from the source.

The principal use of flow path computation was to know the distances from sources to a water body. Prior to find the shortest path automatically by ArcMap GIS, a base map with assigned weights was required in order to perform the computations. A description of the parameters used in the determination of the delivery index is shown in Table 6.3. The resulting layer is shown in Figure 6.2.

Table 6.3 Parameters selected for construction of cost raster dataset.

Layer Input	Search Radius (m)	Reclassification Preferences	Assigned Name	Influence Weight
Curve Number		High Curve Number = 1	CN	0.25
Flow Direction		Low values of Flow = 1	FLOWD	0.25
Point and Non-Point Sources	2,000	Close to source = 1	SOURCES	0.25
Rivers and creeks	1,200	Close to Rivers = 1	RIVER	0.25
			SUM =	1.0

Figure 6.3 shows the complete calculation of the shortest path for every source (point and non-point sources) within the watersheds. Figure 6.4 is a close up for a specific area of the watershed showing the best route from source to river.

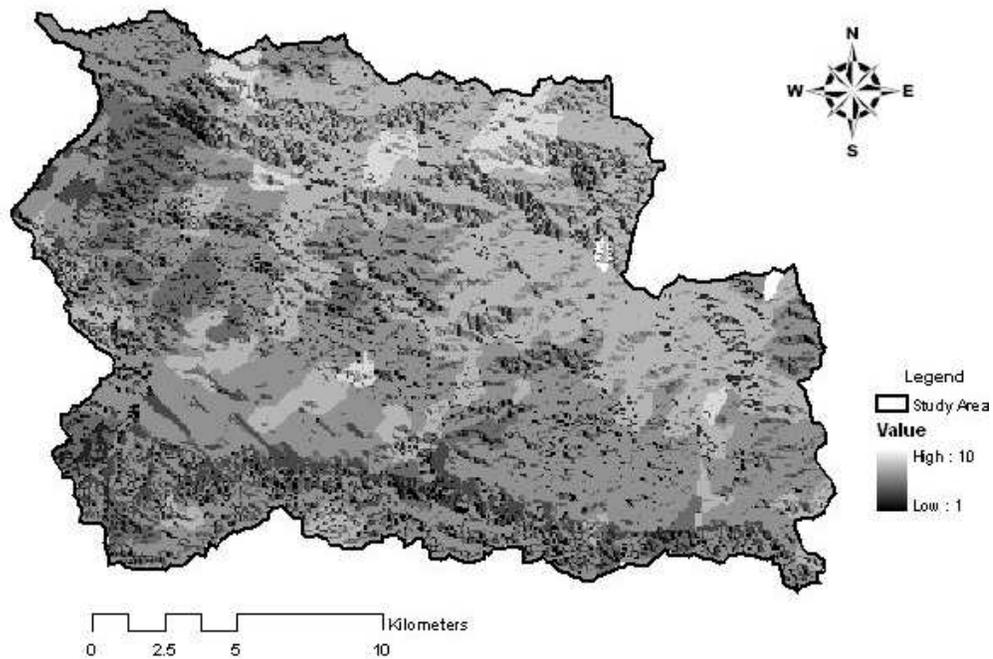


Figure 6.2 Cost raster dataset for fecal coliform bacteria within the watershed.

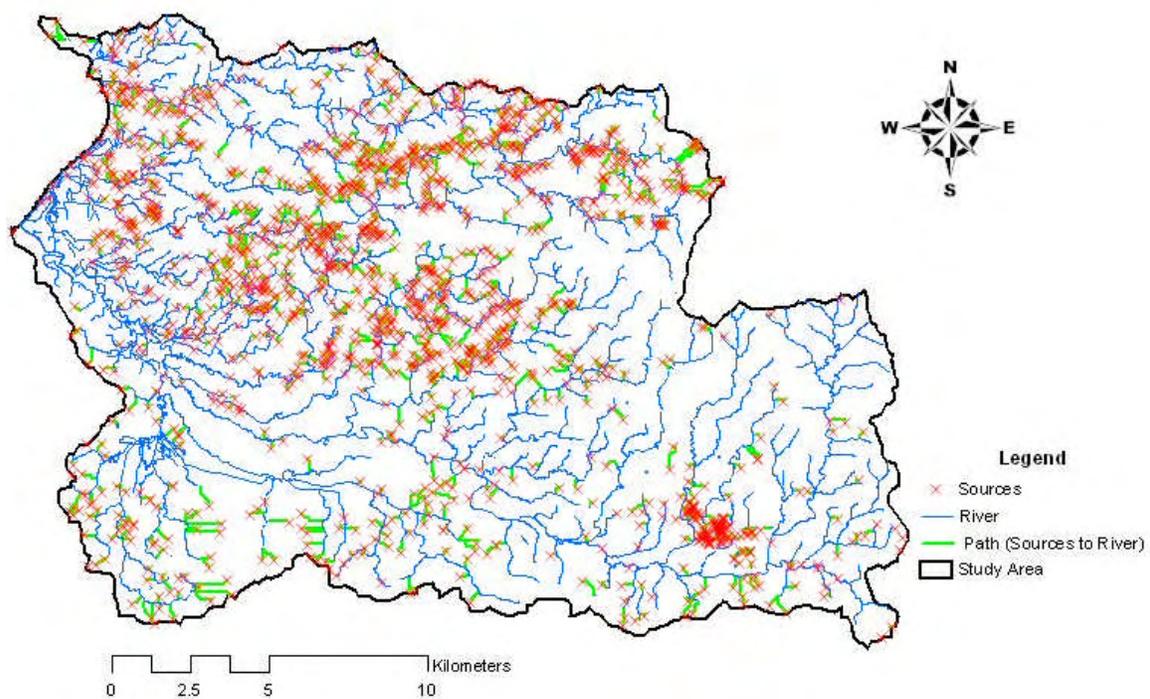


Figure 6.3 Shortest path routes (sources – pathway – river).

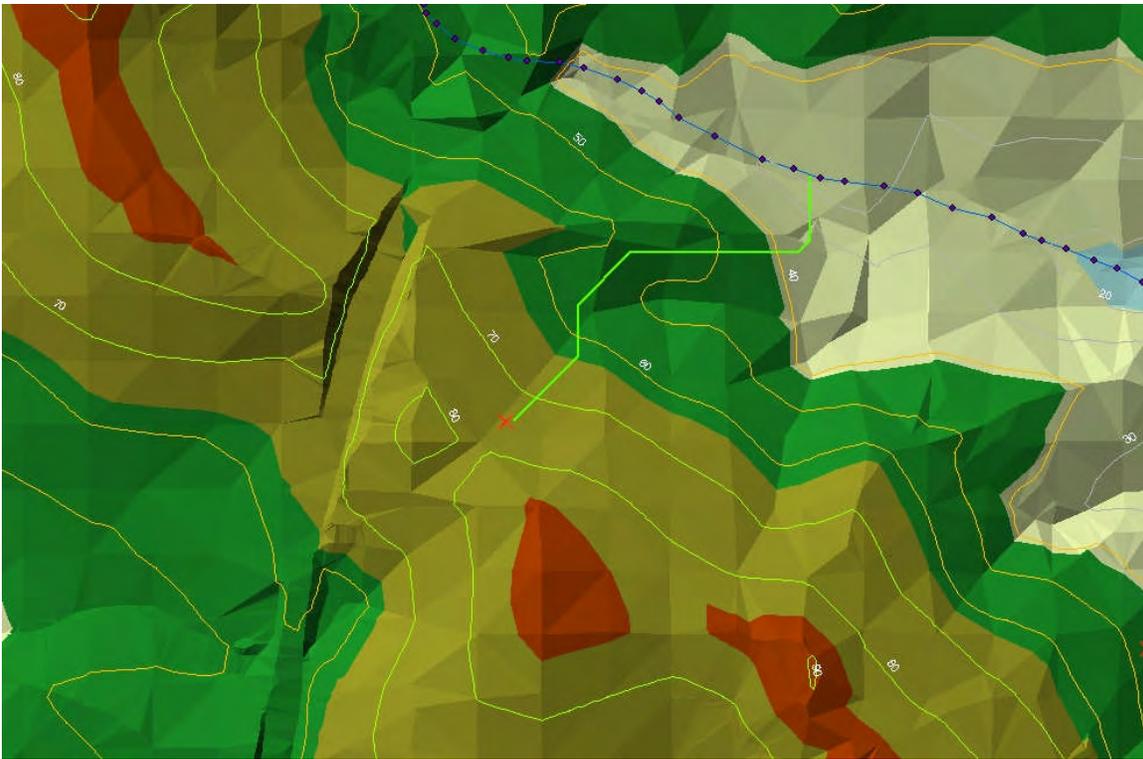


Figure 6.4 Close up of the shortest path for a specific area. The red cross marks the source and the blue line the nearest water body.

6.2.2 Bacterial Production Rate

The concentration of a given micro-organisms in manure applied to soil is an important parameter determining the potential for contamination of water resources. The greater the concentration, the more likely it is that some will be transported (Goss et al., 2002).

This step performs density function analysis considering different production rates of FCB sources such as animals (dairy farms, swine farms, coffee processing facilities, agricultural farms), and humans (rural septic system failures, sanitary system failures). Census data manipulation was explained in previous chapter, as well as the

percentage of failure for every source contribution. Density dataset is normalized to a common scale of 1 to 10. The resulting dataset is shown in Figure 6.5.

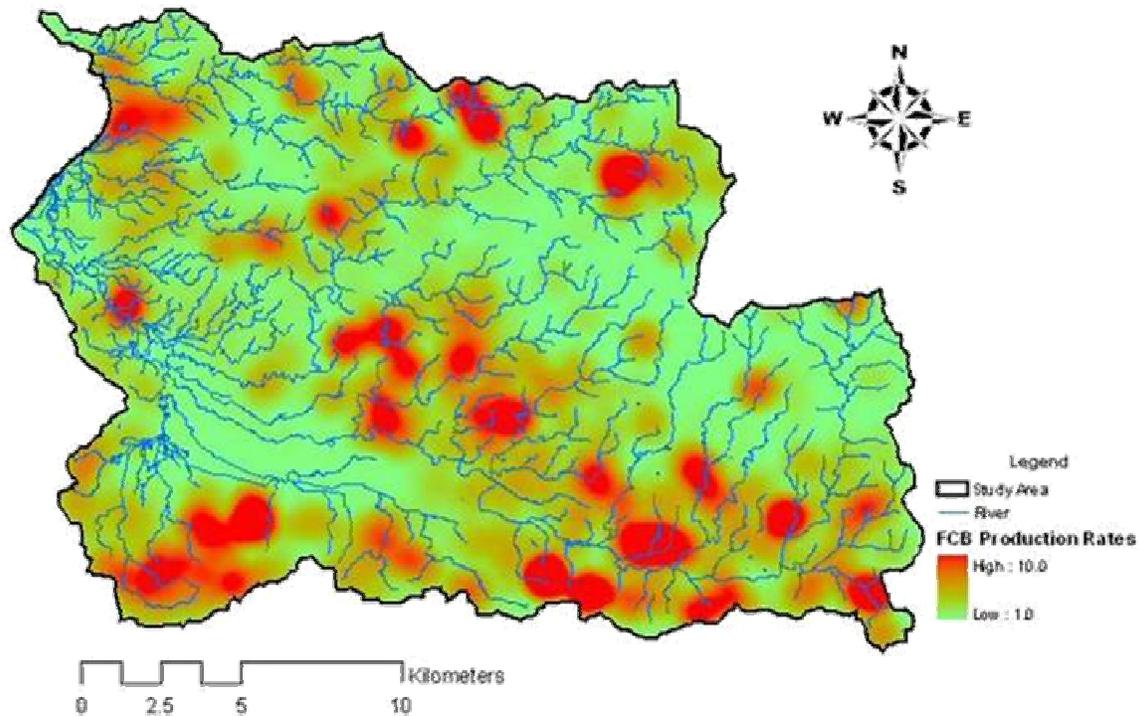


Figure 6.5 Fecal Coliform Bacteria Production Rate dataset.

6.2.3 Hill Shade as Temperature Index

Temperature parameter was incorporated as a function indirectly correlated with the hill shadows produced with the DEM. This parameter considers hills shadows with different sun inclinations as Table 6.4 and Figure 6.6 explain. 255 hill shade code values resulted as default after hill-shade computation with ArcMap GIS.

The shadow values were normalized to a common scale of 1 to 10. Higher daily temperatures are registered between 9 a.m. and 3 p.m. hours. At least 10 % of the area is continuously under shadow during this period. These shadows mark the locations where bacteria are more likely to survive since are not exposed to direct sun light and so, lower

temperatures. The identified high temperature areas (the other 90% of the area) were considered negative effect in Equation 6.1 as the *TEMP* parameter.

Table 6.4 Sun angles for different times of the day.

TIME	AZIMUTH	ALTITUDE
06:00 a.m.	90	0
07:30 a.m.	112.5	22.5
09:00 a.m.	135	45
12:00 p.m.	180	90
03:00 p.m.	225	45
04:30 p.m.	247.5	22.5
06:00 p.m.	270	0

The azimuth is the angular direction of the sun, measured from north in clockwise degrees from 0° to 360°. For example, an azimuth of 270° corresponds to due west. Altitude is the slope or angle of the illumination sources (sun) above the horizon. The units are in degrees, from 0 on the horizon to 90 overhead.

The resulting shade layers for all different sun angles in Table 6.4 were analyzed and the highest hill shade code noted. An analysis of the variation of the hill shade code for different time of the day revealed that from 9:00 am to 3:00 pm the variation stabilized to a value close to 250. This means that the shades in the watershed remain quasi-constant during this period of time (see Figure 6.6). For the purpose of the project, sun lighted areas at 12:00 noon were used for the *TEMP* parameter. The resulting layer is shown in Figure 6.7.

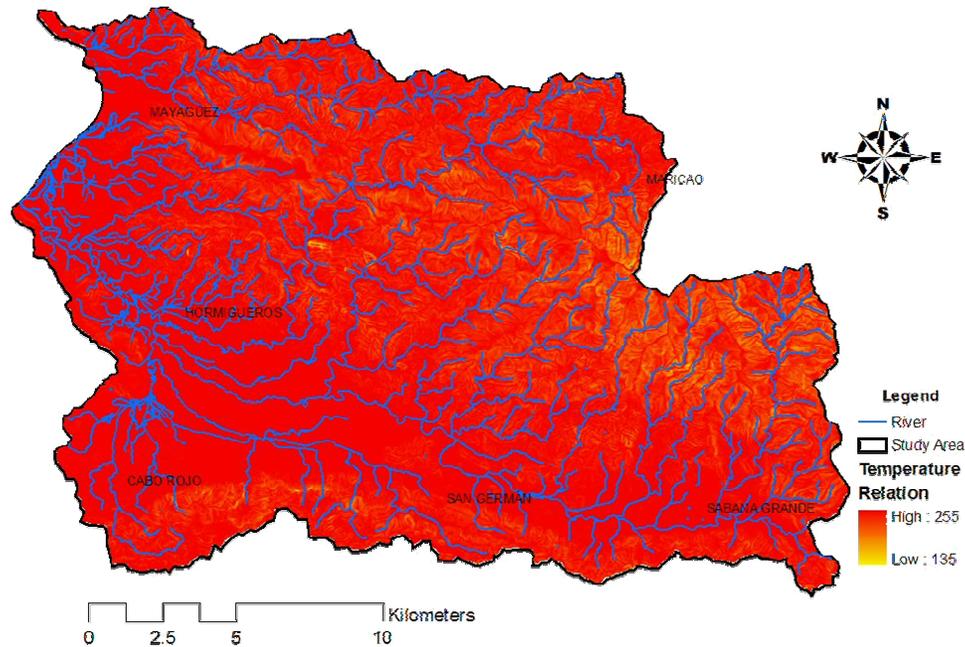


Figure 6.6 Temperature trends related to Hill Shade coded values.

6.3 Fecal Coliform Potential Risk Area Index (FCPRAI) determination

Parameters for the bacteria transport mechanism, production rate, and temperature were combined and their effect saved to a layer. This layer contains the FCPRAI as determined by equation 5.7. The result after enter the datasets and equation into Map Raster Calculator is displayed in Figure 6.9 and shows the most probable fecal contamination sources. The Figure 6.10 shows the same computations but with a scale graded from low to high labels.

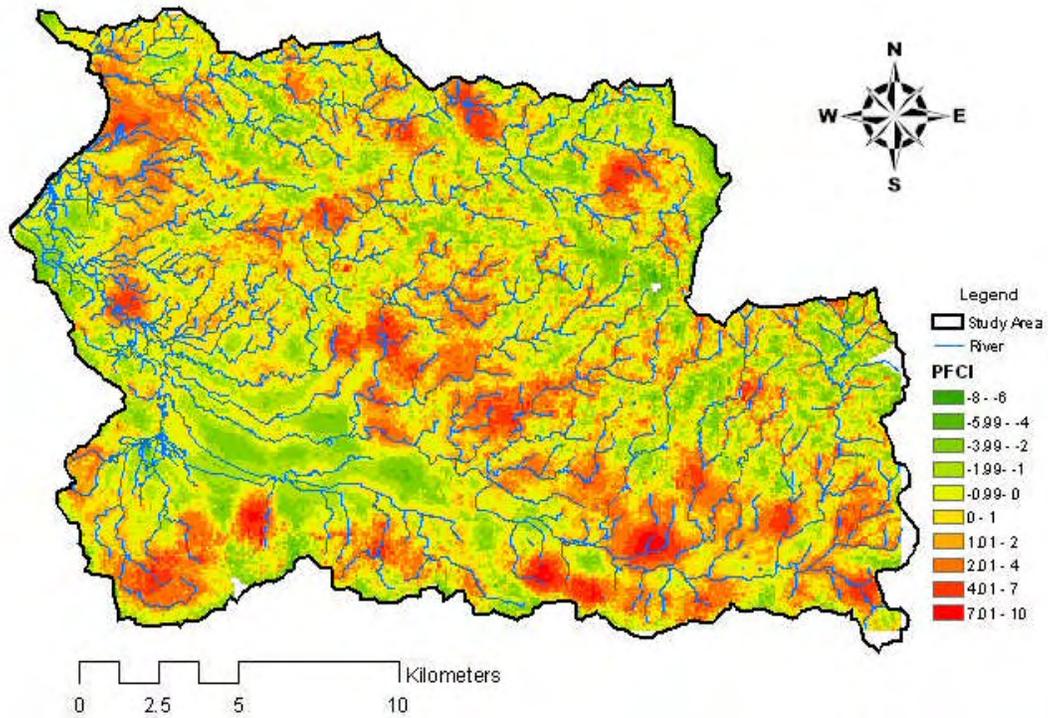


Figure 6.7 Fecal Coliform Potential Risk Area Index for Guanajibo and Yagüez watersheds.

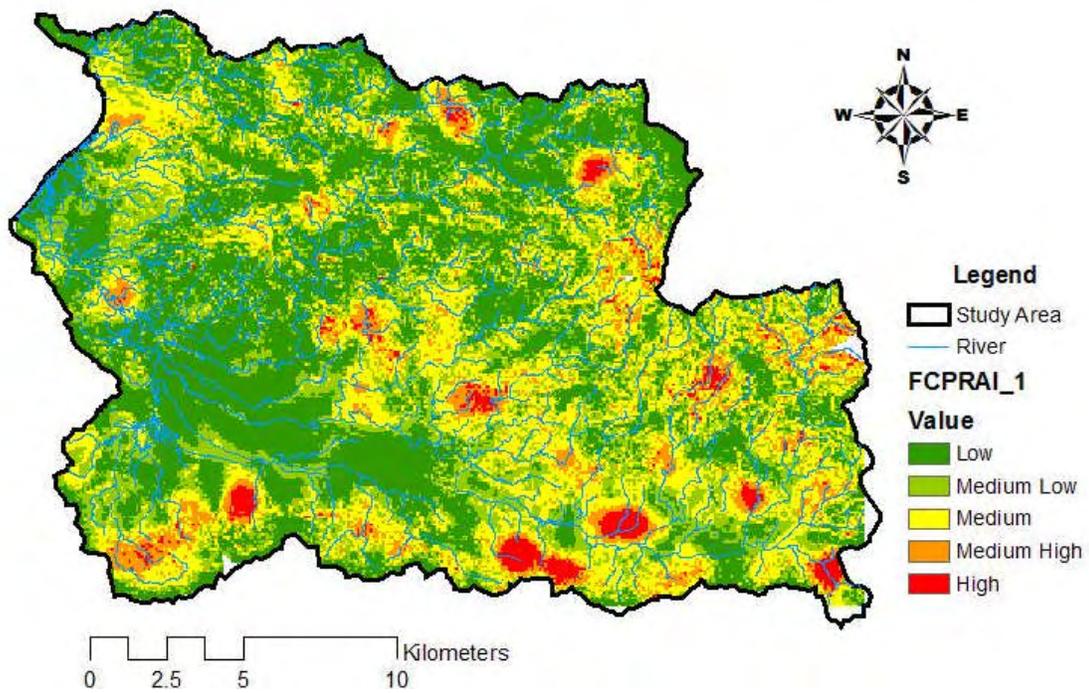


Figure 6.8 Fecal Coliform Potential Risk Area Index for Guanajibo and Yagüez watersheds (simple scale).

To test the effect of the TEMP parameter in Equation 6.1, an analysis was conducted leaving this parameter out of the equation. The resulting layer is presented in Figure 6.11. A close review of the figure reveals that the coverage of high risk areas increased. This results in a conservative analysis but deviates from the original objectives which were to save effort and time in field inspection and source identification. The number of areas that must be surveyed now is greater and will take longer time to complete an exhaustive field inspection. The monitoring program for water quality will be more extensive and costly.

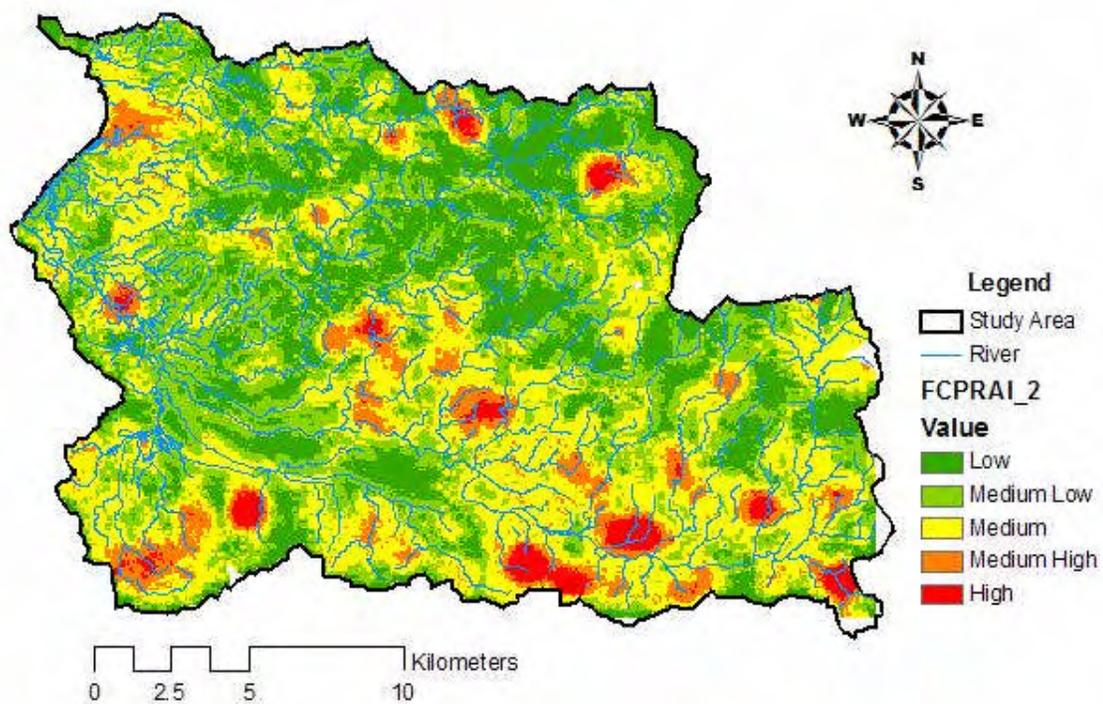


Figure 6.9 FCPRAI eliminating TEMP parameter.

6.4 Discussion of Results

The results of the FCPRAI were analyzed and are explained in this section. Equation 5.10 integrates all three parameters explained before (TM, PR, and TEMP). Every parameter was normalized to a common scale from 1 to 10. Considerable uncertainty is associated with this reclassification; however, decisions on to which conditions were more critical have been made according to facts reported in the literature. The choice of weighting factors is an example of this. An assumption made is that no distinction is made within the mechanism of transport or to how bacteria are transported, whether attached to sediment and clumps of faecal material or as dispersed coliform-forming units suspended in overland flow. The range interval of the FCPRAI is from a minimum value of (-) 8 to a maximum of 10.

The FCPRAI result is shown in Figure 6.11. An analysis is now made to corroborate that the locations with higher FCPRAI values indeed correspond to actual FCB production centers. Next figures compare the FCPRAI with the available data taken at field. The field data include rural septic systems, sanitary sewer systems, sanitary landfills, organic fertilizer treated farms, and dairy and swine farms. The type and number of micro-organisms can vary with the animal species, age of animals, the type of bedding used, the method of storage (liquid or solid) and the storage period.

Figure 6.11 shows a comparative analysis between the FCPRAI and the sanitary sewer systems. In the analysis it was assumed a sewer failure of 15 % due to broken pipelines, infiltration at joints, and pump station failures. Most of the sewer systems are in urban areas which have paved surfaces and some open spaces. It was assumed that 90% of bacteria is washed out with runoff when a storm event occurs. Several sewer

served areas coincide with high risk spots. Although this does not mean that the sewer systems are actually polluting nearby water bodies, sewer systems laying in high risk areas should be carefully field inspected.

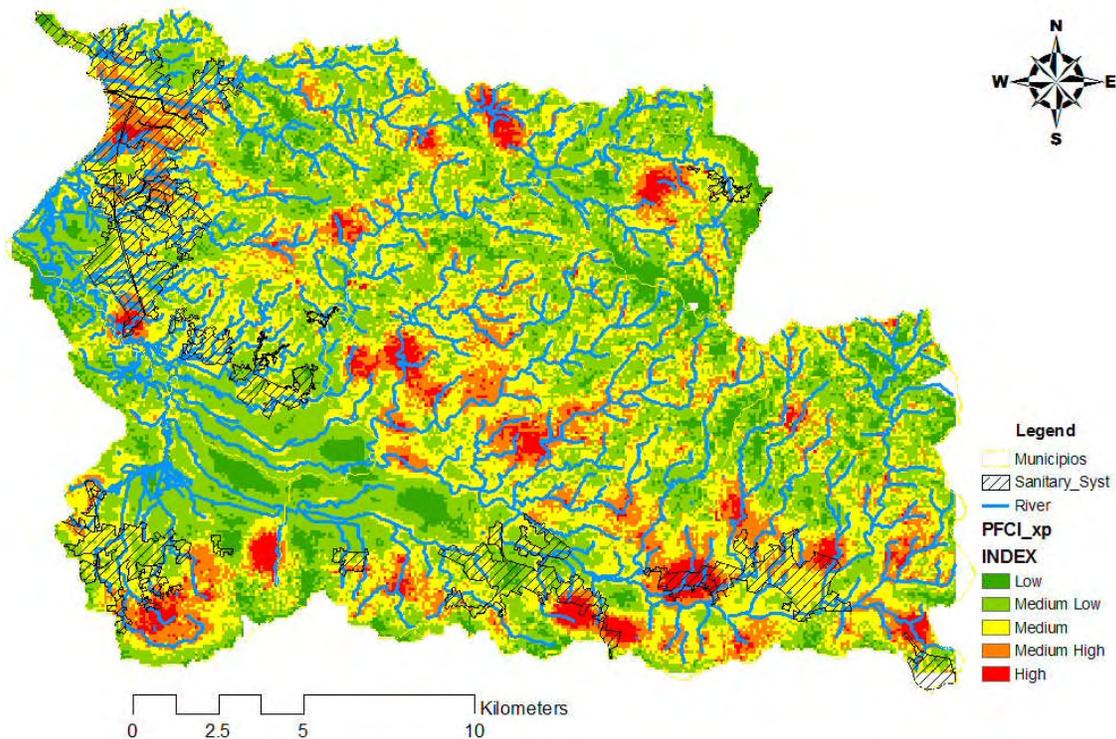


Figure 6.10 Sanitary sewer systems location vs. FCPRAI.

Rural septic systems are the most predominant potential source of contamination according to Figure 6.12. It was assumed a 70 % failure rate of septic systems according to US EPA (2004). Failed septic tank effluent divides between underground and surface flow. At this time no data is available to estimate the surface flow, so an arbitrary 15% of the 70% collapsed tanks is assumed. Although vegetation prevails in rural areas, and this vegetation can act as natural buffers in some cases, many of the potential sources (septic system communities) were too close to rivers. Some of the rural communities lay on high

risk areas. These communities must be surveyed to determine if indeed their septic systems are FCB contamination sources. As it can be seen in the figure, not all rural communities will pollute water bodies.

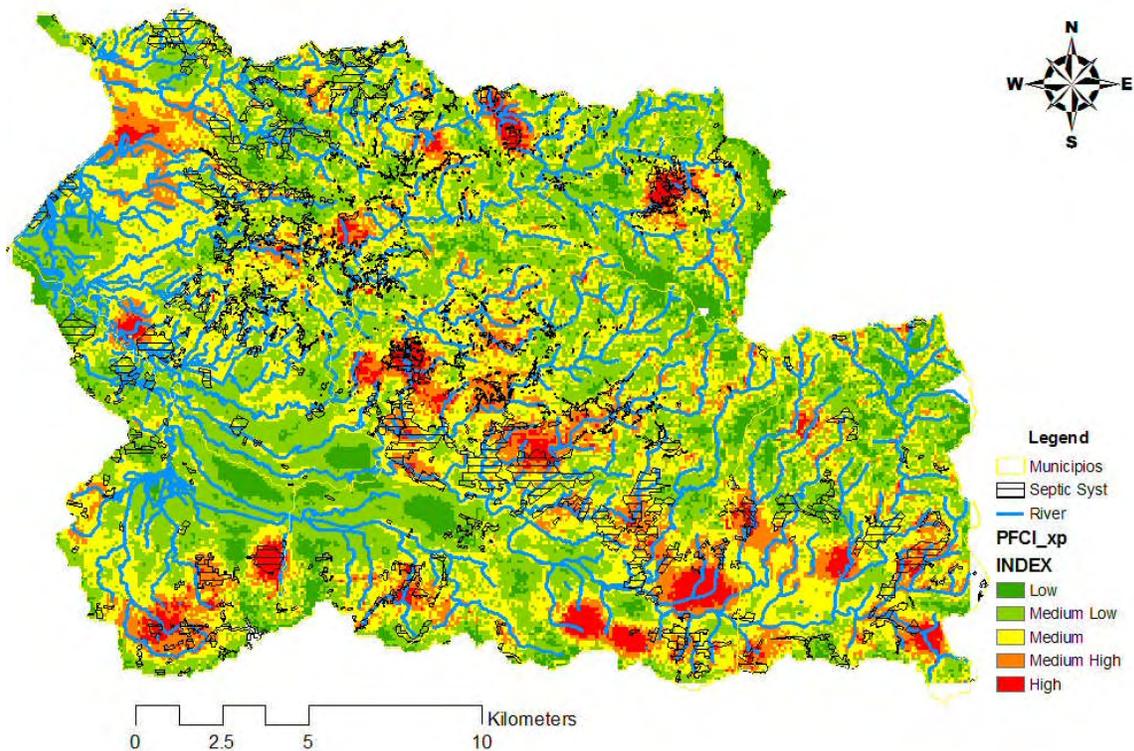


Figure 6.11 Septic systems location vs. FCPRAI.

Figure 6.13 shows a combination of sanitary sewer areas and rural septic systems. The figure shows several critical areas under the influence of both sewer and septic systems. These areas are near downtown center of Cabo Rojo, Hormigueros, and Sabana Grande.

Other possible sources of pollution were also compared to high risk areas. These are sanitary landfills, organic fertilizer treated farms, and dairy and swine farms. Figures 6.14 to Figure 6.16 show the comparisons, respectively. From these figures one can said

that sanitary landfill are located in low risk areas. Although this does not mean that sanitary landfill would not be a pollution source, it means that any pollution from these landfills would probably hardly reach a water body. Similarly, organic fertilizer treated farms are located in low risk areas. These areas are located mostly in the flood plain of Río Guanajibo between Hormigueros and San Germán. Under normal conditions, these farms would not contribute significantly to the river CFB contamination. Under flood conditions, it is expected that flood flows wash out most of the FCB and deliver it rapidly to the Mayagüez Bay.

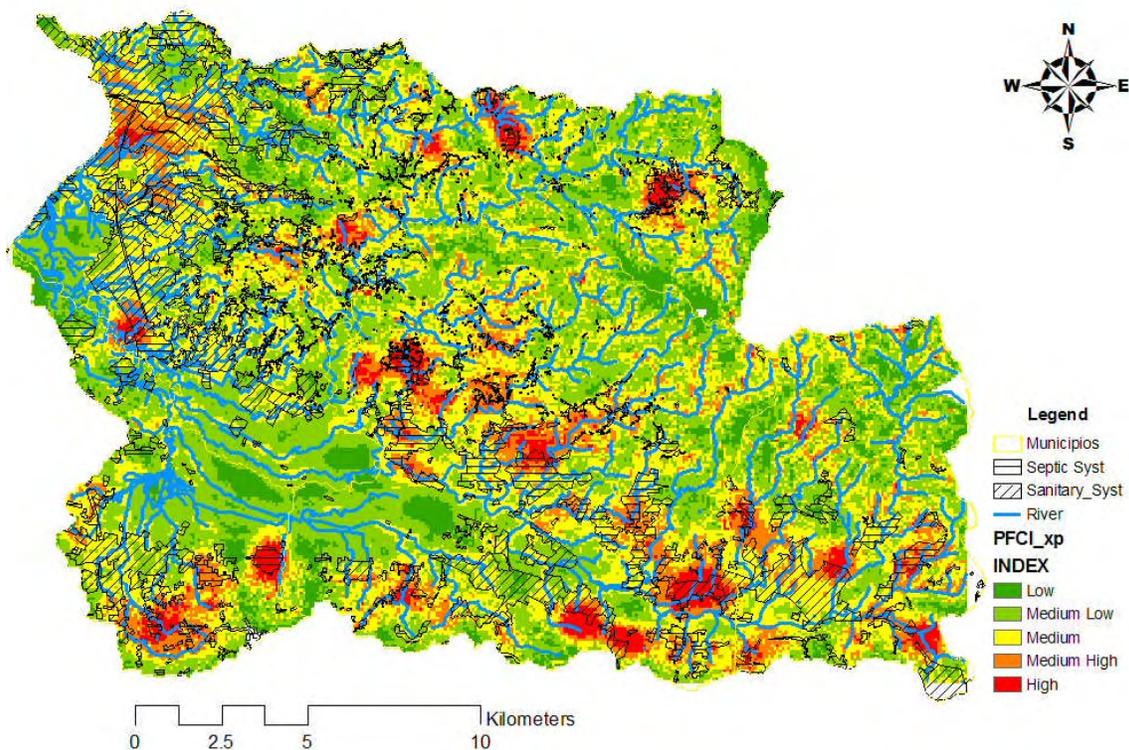


Figure 6.12 Combination of sanitary sewer areas and septic systems areas vs. FCPRAI.

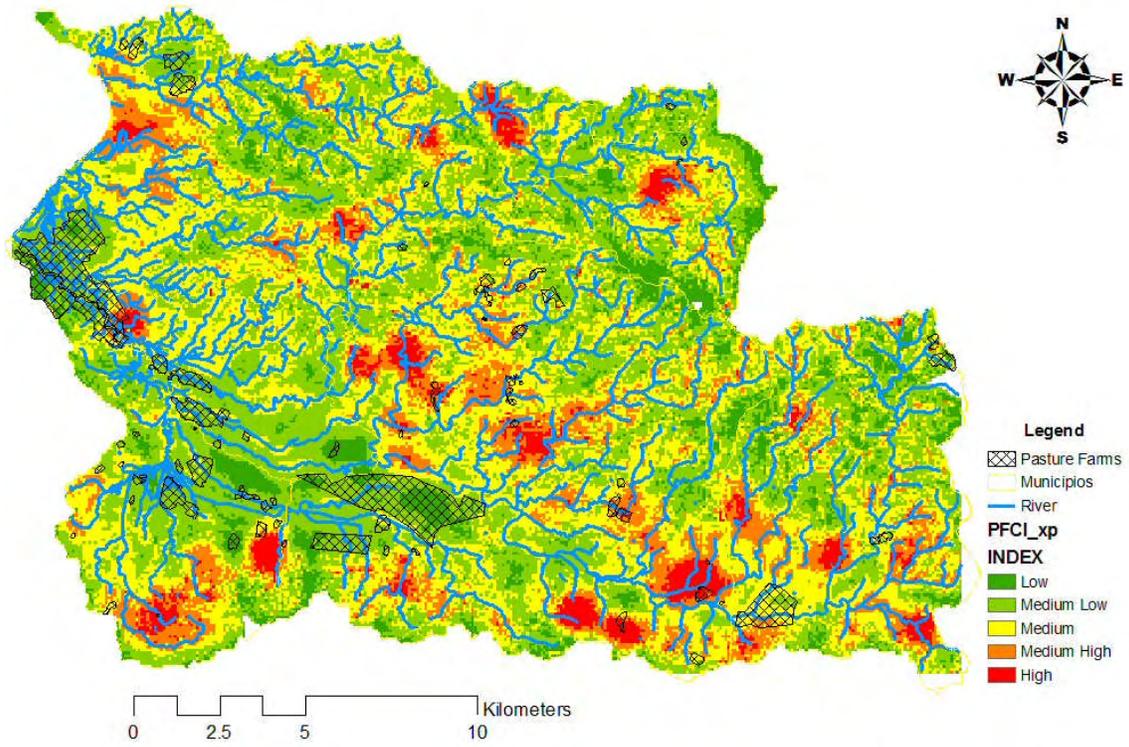


Figure 6.13 Organic Fertilizer treated farms vs. FCPRAI.

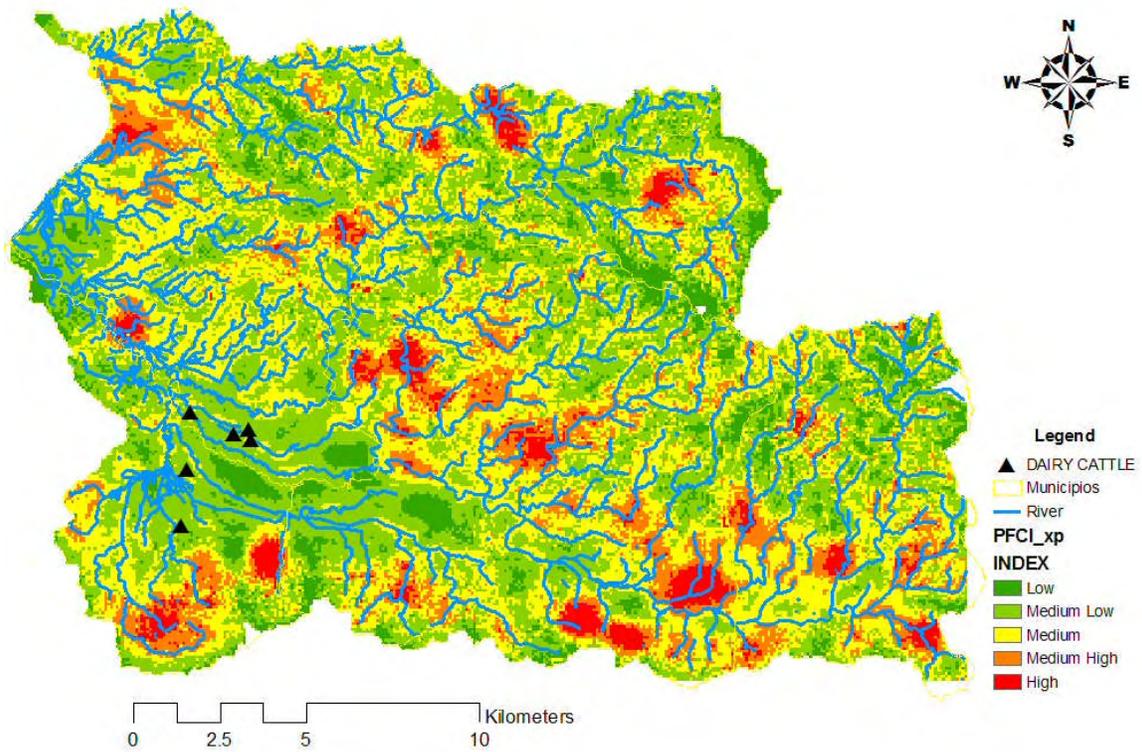


Figure 6.14 Dairy farms vs. FCPRAI.

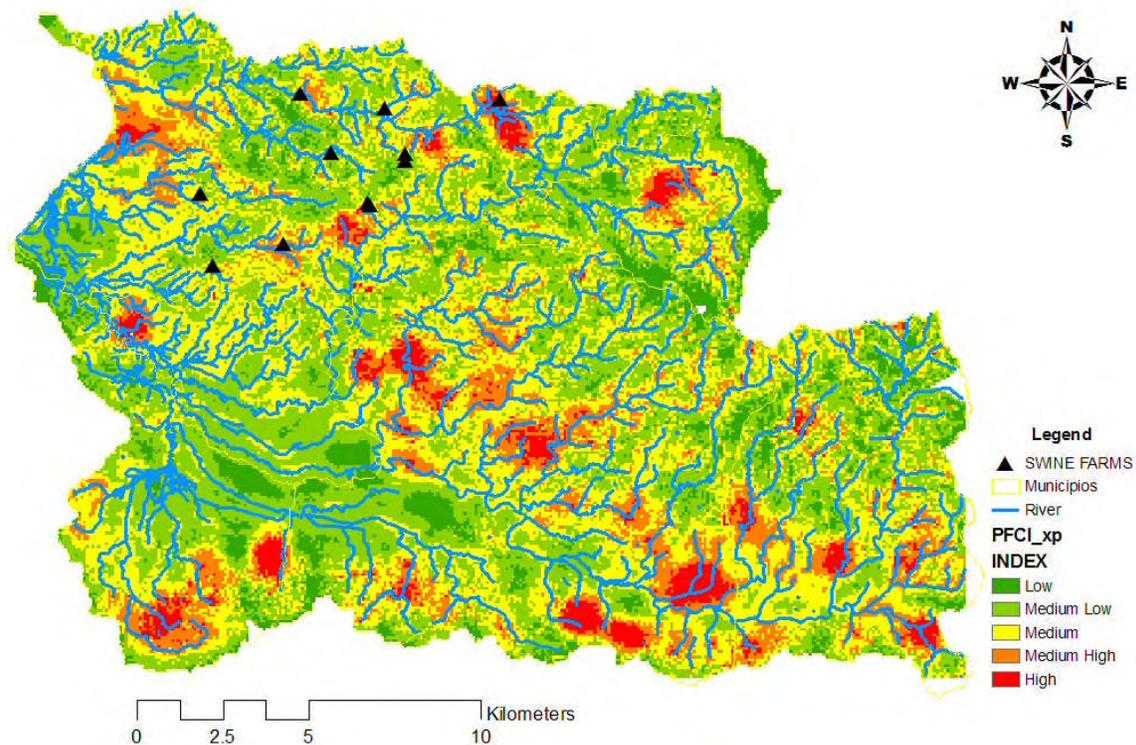


Figure 6.15 Swine farms vs. FCPRAI

Dairy Farms are located in the Río Guanajibo flood plain near Cabo Rojo. These are low risk areas according to Figure 6.15. The interpretation of these results is similar to those of Figure 6.14. On the other hand, several swine farms are located in medium to high risk areas (see Figure 6.16). These farms are within the Yagüez and Río Hondo watersheds. Swine farms are significant contributor of FCB, especially those poor waste management systems. These farms should be revisited and carefully inspected for direct discharges to rivers and creeks. Figure 6.17 shows the combined effect of all possible FCB contamination sources over the FCPRAI layer. From this figure it can be seen that, at different degrees, most of the possible pollution sources may be contributors to the overall river contamination.

In summary the more probable sources of contamination identified according to the resulting layer of Fecal Coliform Potential Risk Area Index (FCPRAI) are the swine farms and septic system served communities.

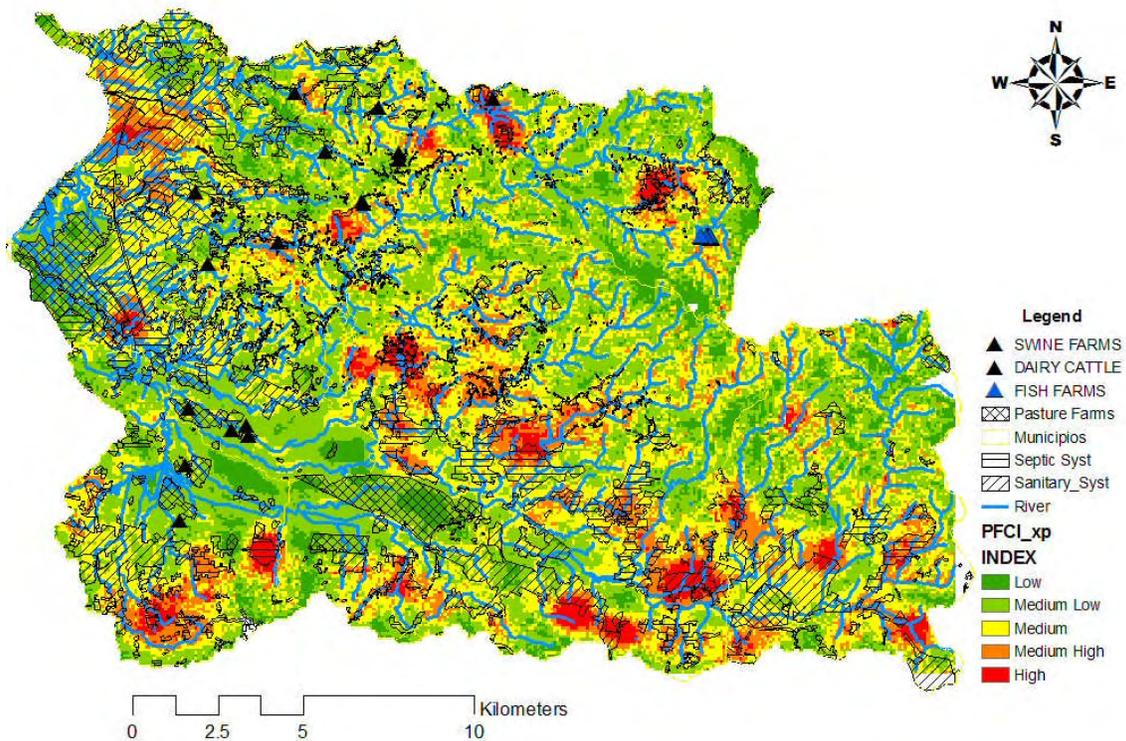


Figure 6.16 Combined effect of all possible FCB contamination sources over the FCPRAI layer.

7 CONCLUSIONS & RECOMMENDATIONS

This chapter presents the conclusions of this work and recommendation for future works. It also presents the limitations of the developed methodology.

7.1 Conclusion

Obtaining and formatting digital data is often the most time-consuming task in watershed modeling. Hydrologic processes vary both in space and time. To account for these variations, the Guanajibo and Yagüez watersheds were divided into a big number of nearly homogeneous sub-basins. The larger the number of sub-basins the greater the accuracy of the simulation, since hydrologic response changes can be assessed using sub-basins of small size.

Using GIS techniques, the management of the watersheds geomorphologic characteristic variability saves time and eases the task of defining and adding new features of the watersheds. Characteristics such as area, slope, travel time for the concentration time (t_c) determination, CN, flow paths, among others, are examples of watershed features that can be managed more easily. Nevertheless, despite of the watershed complexity and heterogeneous systems, the results are repeatable by employing GIS techniques and the appropriate data sets to other watersheds.

Many investigations have been developed within the information era employing GIS techniques. Until now, none of them have taken into account mortality rate factors such as temperature patterns, flow accumulation preferences, and FCB production rates to identify areas of high pollution risk. As a result of the use of these techniques, a Fecal

Coliform Potential Risk Area Index has been developed. The values of the FCPRAI identify areas of low to high fecal contamination risk. FCPRAI values range from -8 to 10, being 10 the highest risk value. An application of the FCPRAI could be a better informed decision on the determination of the location of water quality stations.

This project has demonstrated that fecal bacterial transport to surface water systems would be expected under current swine farms practices. The presence of fecal and bedding particles at the soil surface has an impact on the likelihood that water from precipitation will enter the soil and through runoff being transported to the streams.

The adoption of a contamination index avoided the complexity associated with simulation of cell to cell transport of water and bacteria. Considerable uncertainty is associated with it, since many arbitrary assumptions have been made. Nevertheless, these assumptions can be improved and better supported as field data becomes available.

In conclusion the most probable contaminant sources could be septic systems and swine farms. Field inspections must focus on these possible sources and FCB loadings determined. This would be the basis for future water quality modeling efforts.

7.2 Recommendations

The location and utilization of water systems receiving agricultural tile drainage outflow should be assessed on a farm by farm basis. The risk of fecal contamination of recreational and drinking water sources should be acknowledged by both farmers and municipal authorities controlling public water systems.

Field studies are desirable to quantify the variation of delivery with slope, soil, and distance to stream. Similarly, although the role of seepage zones as a source of fecal contamination has been identified (septic systems), understanding of their behavior remains incomplete (for example, the moist shady conditions within seepage zones may aid microbial survival, relative to elsewhere upon the hillside), and TEMP representation is currently based only a preliminary hill shade instead of considering the trees height on a more small environment.

Riparian buffer strips may improve bacterial water quality both by eliminating livestock defecation in and near streams, and by trapping of bacteria by the riparian vegetation.

It would be great to use a stock history of farms (dairy cattle, agricultural farms, swine), to the excretion rate of *E. coli* direct to the stream network. Cattle behavior studies are required to improve quantification of direct deposition for modeling with other programs such as HSPF and or field investigations.

Given the many possibilities for handling manure on farms, the opportunity to modify the source strength of the pathogens as well as the form of the material that may gain access to the wider environment, guidelines for farmers are important for limiting the negative impact of agricultural activities on the water resources. However, appropriate recommendations for manure management to protect water resources from pathogens cannot be formulated without a detailed understanding of the factors affecting the survival and transport of micro-organisms from manure between source locations and surface or groundwater bodies.

There is no information available on the short-term impact of different manure types on the soil properties relevant to bacterial transport. It will be good to perform field tests with different manure types.

Thus, future research is required to evaluate the effect of manure composition on soil properties controlling water transport, the flow regime within the soil, and the potential impact of manure components on the water partitioning at the soil surface. There is a need to bridge the gap between the practical information on the contaminant potential of manure and the detailed assessments that are relevant to the interaction of bacterial cells with soil surfaces. More understanding is required on how soluble and colloidal organics in manure interact with the surfaces of bacteria and affect their retention to soil surfaces. Given that many of the studies on surface properties have been performed in laboratories, there is a need to evaluate the level at which surface properties derived from such studies can be used to estimate bacterial retention and transport in field soils.

The methodology developed in this work can be improved by incorporating additional factors that affect the transport mechanism of the FCB. Field investigation is necessary to establish more realistic values for sewer and septic systems failure rates. The addition of biological datasets as vegetative buffer dataset in the determination of the FCPRAI would give in return more reliable values in the calculated index.

7.3 Limitations

The results obtained in this work are applicable only to Guanajibo and Yagüez watersheds. Other watersheds could be included following the same protocol and after the corresponding databases or data sets are generated.

The use of DEM 30 meter resolution for the shortest routes (source-pathway-river) determination produces coarse estimates. DEMs with higher resolution are needed for better results. Understanding of the relationship between the delivery of bacteria within surface runoff and stream proximity is particularly limited. *E. coli* concentrations in a rural stream have considerable uncertainty with respect to some of the processes represented. This limits confidence in the assessment of the impact of various management practices upon levels of fecal contamination.

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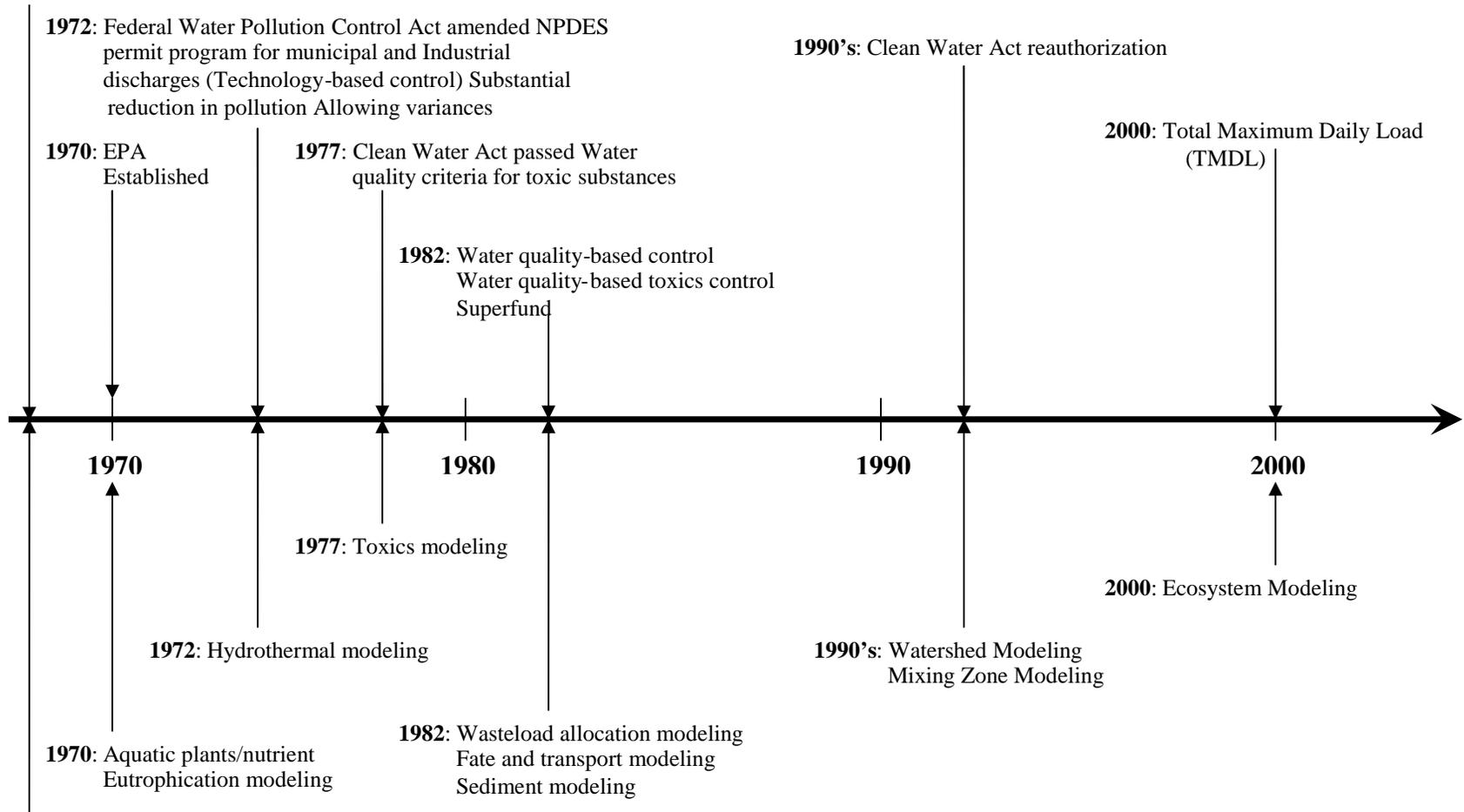
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APPENDIX A

HISTORY OF WATER POLLUTION CONTROL AND WATER QUALITY

MODELING APPLICATIONS

Pre-1970's: To achieve ambient water quality standards
Impossible to administer
(translating ambient standard into
end-of-pipe effluent limits)



Pre-1970's: BOD/DO modeling

History of water pollution control and water quality modeling applications (Lung, 2001)

APPENDIX B

ESTIMATED HOUSE UNITS AND POPULATION BY CENSUS 2000

SUBDIVISION BY BLOCKS

ESTIMATED HOUSE UNITS AND POPULATION BY CENSUS 2000					
SUBDIVISION BY BLOCKS					
ID	FID	HSE_UNITS	FIPSSTCO	HSE_UNITS_CRIM	POP_2000 Estimate (hab/bld)
1	0	155	72121	3	8
2	1	96	72121	7	18
3	2	96	72121	0	0
4	3	70	72121	2	5
5	7	73	72079	0	0
6	11	230	72121	1	3
7	12	1	72023	5	13
8	13	71	72079	0	0
9	14	71	72079	0	0
10	15	20	72125	3	8
11	17	226	72023	9	23
12	21	0	72121	0	0
13	23	95	72121	102	256
14	24	0	72125	5	13
15	26	230	72121	93	233
16	27	39	72023	3	8
17	28	71	72079	0	0
18	29	39	72023	2	5
19	31	193	72079	23	58
20	33	59	72023	11	28
21	34	89	72079	0	0
22	35	49	72125	1	3
23	36		72023	0	0
24	38	59	72023	7	18
25	40	13	72125	8	20
26	41	24	72079	1	3
27	42	282	72079	0	0
28	53	20	72125	12	30
29	54	49	72125	0	0
30	55	49	72079	11	28
31	56	37	72121	34	85
32	57	158	72121	126	316
33	65	102	72121	36	90
34	66	69	72023	0	0
35	68	111	72023	46	115
36	71	69	72023	21	53
37	75	59	72023	69	173
38	77	69	72023	1	3
39	84	6	72125	13	33
40	92	35	72125	63	158
41	93	19	72125	17	43
42	101	21	72125	12	30
43	106	135	72125	120	301
44	108	169	72121	114	286
45	118	21	72125	3	8
46	119	9	72125	17	43

47	120	54	72125	39	98
48	129	31	72125	36	90
49	136	89	72023	51	128
50	142	251	72125	276	691
51	159	20	72023	20	50
52	175	353	72121	250	626
53	181	103	72023	137	343
54	199	316	72125	361	904
55	366	120	72023	4	10
56	401	6	72023	15	38
57	410	64	72023	59	148
58	487	115	72023	12	30
59	627	7	72121	13	33
60	900	115	72023	12	30
61	910	265	72023	33	83
62	1037	47	72023	1	3
63	1059	22	72023	0	0
64	1071	95	72023	67	168
65	1091	22	72023	4	10
66	1115	23	72023	1	3
67	1136	9	72153	3	8
68	1161	17	72023	13	33
69	1175	170	72023	9	23
70	1199	9	72153	0	0
71	1213	8	72153	0	0
72	1284	1	72023	4	10
73	1299	8	72153	3	8
74	1316	8	72153	0	0
75	1317	170	72023	46	115
76	1323	8	72153	2	5
77	1367	8	72153	2	5
78	1403	8	72153	3	8
79	1428	56	72023	17	43
80	1429	9	72023	23	58
81	1431	93	72023	0	0
82	1435	26	72153	0	0
83	1486	93	72023	5	13
84	1531	2	72093	2	5
85	1550	26	72153	1	3
86	1553	32	72093	0	0
87	1578	94	72093	0	0
88	1598	94	72093	2	5
89	1609	31	72121	74	185
90	1610	26	72153	0	0
91	1613	94	72093	0	0
92	1626	93	72023	5	13
93	1773	1	72023	7	18
94	1776	33	72023	63	158
95	1777	37	72023	2	5
96	1929	71	72093	82	205

97	1963	22	72093	45	113
98	1965	71	72093	17	43
99	2121	17	72093	67	168
100	2168	10	72093	4	10
101	2341	10	72093	10	25
102	2466	42	72083	2	5
103	2469	10	72093	0	0
104	2487	42	72083	8	20
105	2540	42	72083	1	3
106	2550	4	72083	1	3
107	2553	12	72083	0	0
108	2554	9	72083	0	0
109	2556	9	72083	0	0
110	2569	34	72083	0	0
111	2571	42	72083	2	5
112	2576	42	72083	0	0
113	2594	60	72097	13	33
114	2595	34	72083	2	5
115	2596	98	72083	2	5
116	2597	3	72083	6	15
117	2608	35	72097	3	8
118	2611	53	72097	0	0
119	2621	19	72097	10	25
120	2624	190	72097	221	554
121	2627	53	72097	12	30
122	2628	35	72097	0	0
123	2693	103	72097	151	378
124	2710	35	72097	0	0
125	2720	9	72097	25	63
126	2724	9	72097	1	3
127	2727	42	72097	3	8
128	2732	26	72097	5	13
129	2733	35	72097	3	8
130	2746	103	72097	1	3
131	2748	12	72097	10	25
132	2750	103	72097	23	58
133	2751	12	72097	0	0
134	2752	44	72097	58	145
135	2756	1	72097	0	0
136	2758	65	72097	0	0
137	2761	42	72097	23	58
138	2765	105	72097	28	70
139	2767	5	72097	4	10
140	2768	40	72097	8	20
141	2773	105	72097	1	3
142	2776	49	72097	21	53
143	2777	37	72097	6	15
144	2778	43	72097	45	113
145	2782	26	72097	11	28
146	2785	102	72097	13	33

147	2789	167	72097	29	73
148	2793	23	72097	6	15
149	2795	20	72097	0	0
150	2796	167	72097	21	53
151	2797	83	72097	23	58
152	2799	326	72097	81	203
153	2801	72	72097	0	0
154	2803	147	72097	22	55
155	2805	143	72097	9	23
156	2807	115	72097	147	368

APPENDIX C

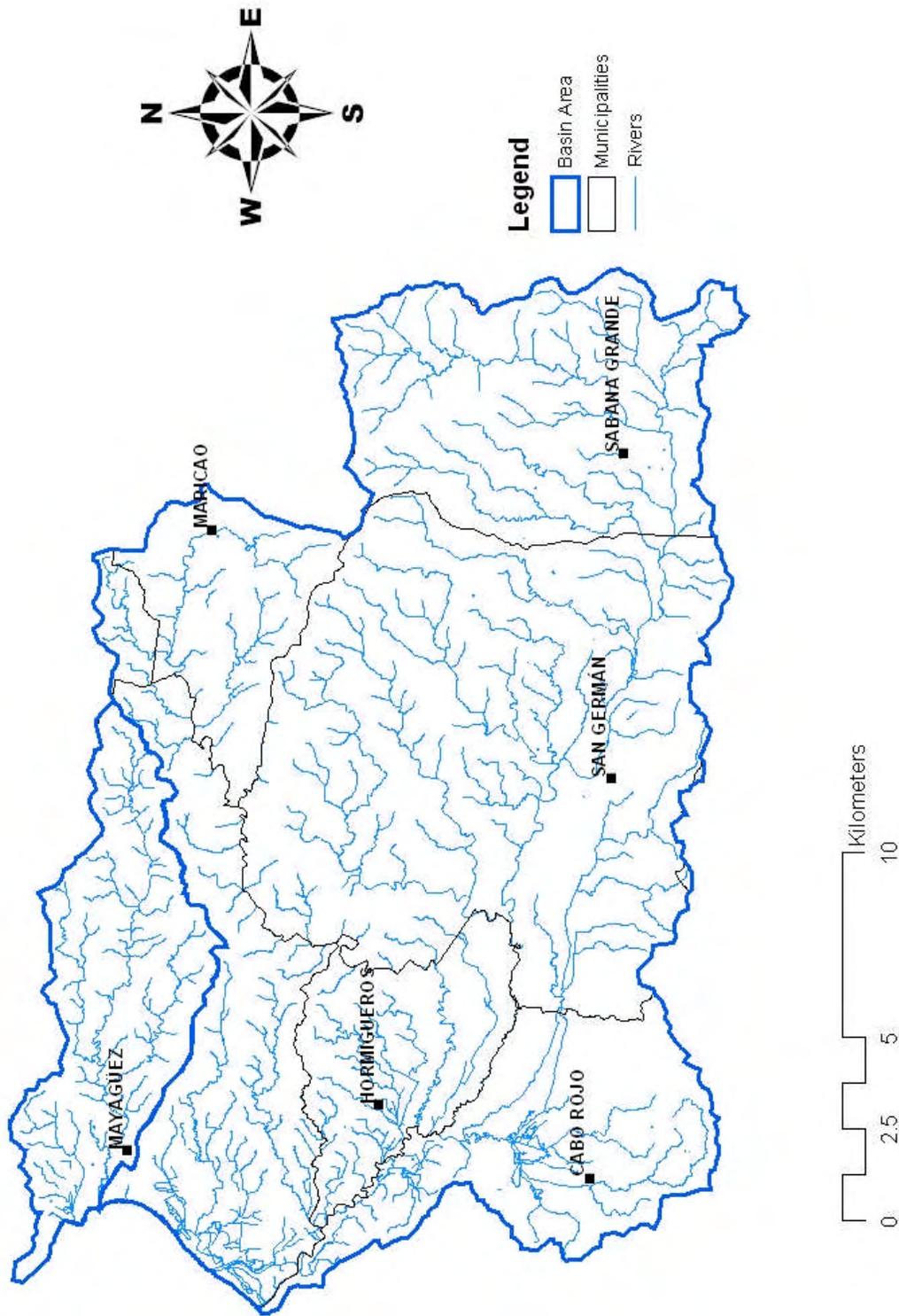
MANNINGS' ROUGHNESS COEFFICIENTS

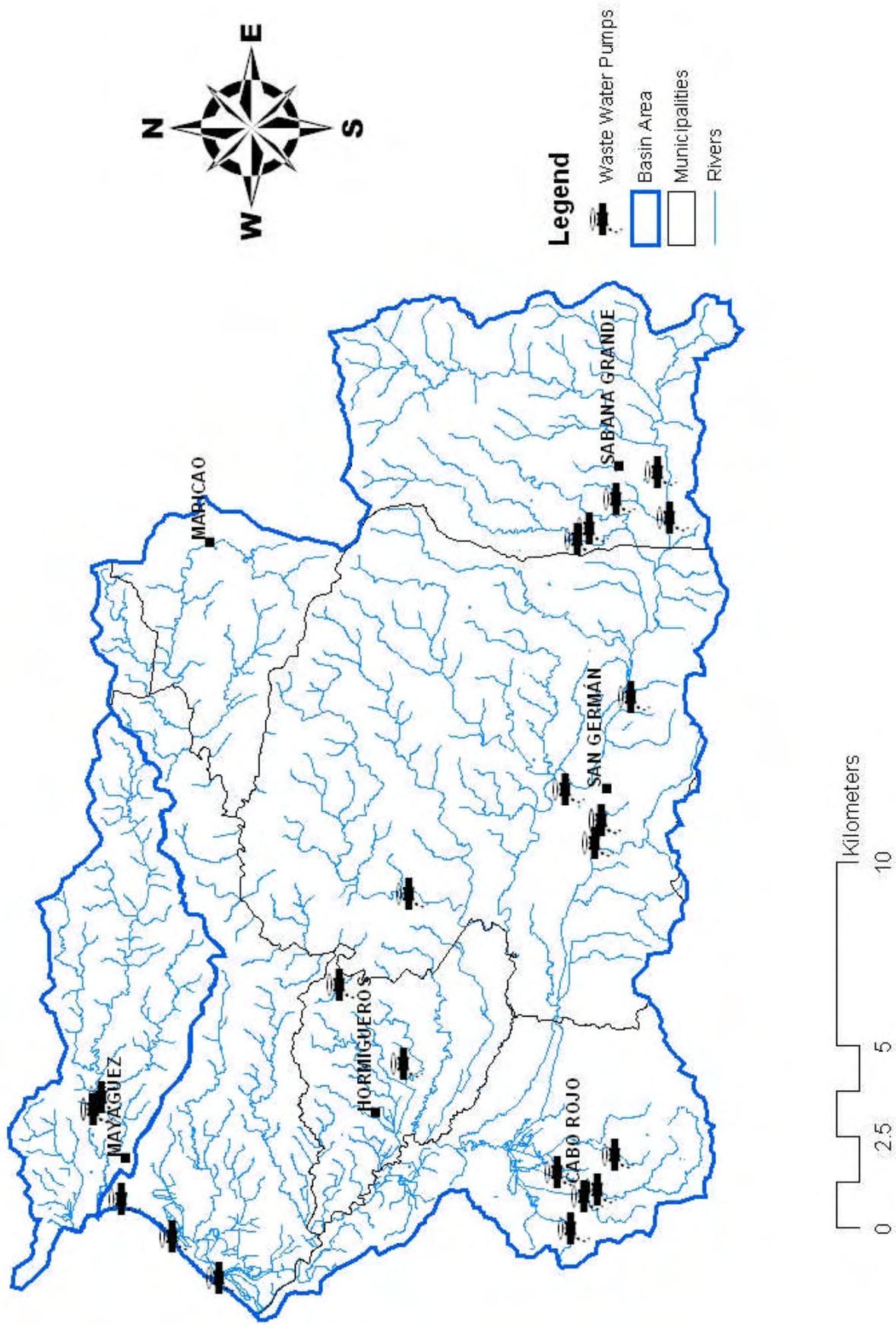
TABLE 10.6 VALUES OF MANING'S ROUGHNESS COEFFICIENT

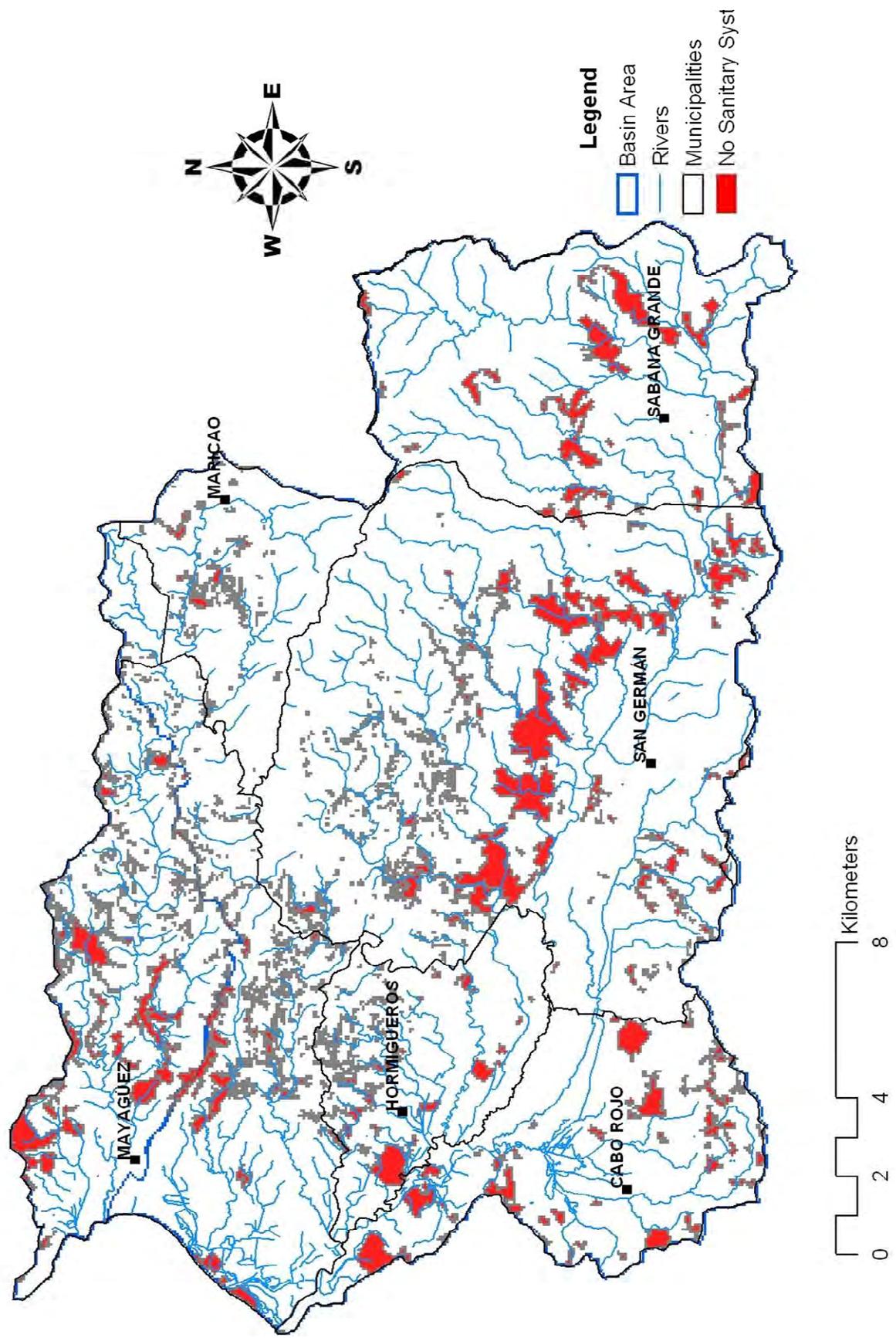
CONDUIT MATERIAL		MANNING n
Closed conduits		
Cement		0.011 - 0.015
	Brick	0.013 - 0.017
	Cast iron coated	0.010 - 0.014
	Cast iron uncoated	0.011 - 0.015
	Wrought iron	0.012 - 0.017
	Concrete (monolithic)	
	Smooth forms	0.012 - 0.014
	Rough forms	0.015 - 0.017
Steel		0.010 - 0.014
	Corrugated-metal pipe	
	Plain (storm drain)	0.022 - 0.026
	Paved invert (subdrain)	0.018 - 0.022
	Sanitary sewer	0.012 - 0.016
	Plastic pipe	0.011 - 0.015
	Vitrified clay	0.011 - 0.015
	Wood	0.010 - 0.014
Open channels		
Lined Channels		
	Asphalt	0.013 - 0.017
	Brick	0.012 - 0.018
	Concrete	0.011 - 0.020
	Rubble or riprap	0.020 - 0.035
	Vegetal	0.030 - 0.400
Excavated or dredged		
	Earth, straight and uniform	0.020 - 0.030
	Earth, winding, fairly uniform	0.025 - 0.040
	Rock	0.030 - 0.045
	Unmaintained	0.050 - 0.140
Natural channels		
	Fairly regular section	0.030 - 0.070
	Irregular section with pools	0.040 - 0.100

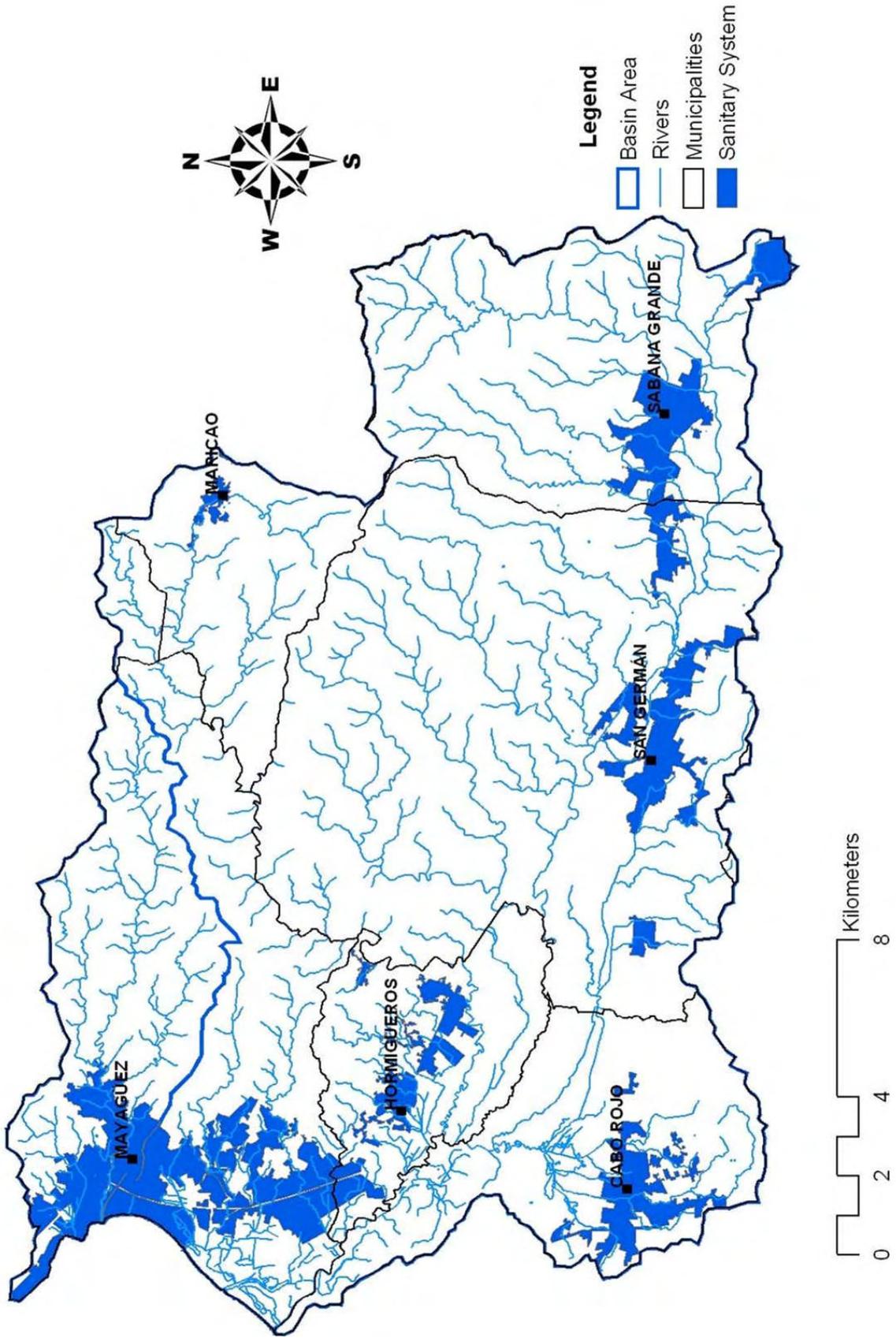
APPENDIX D

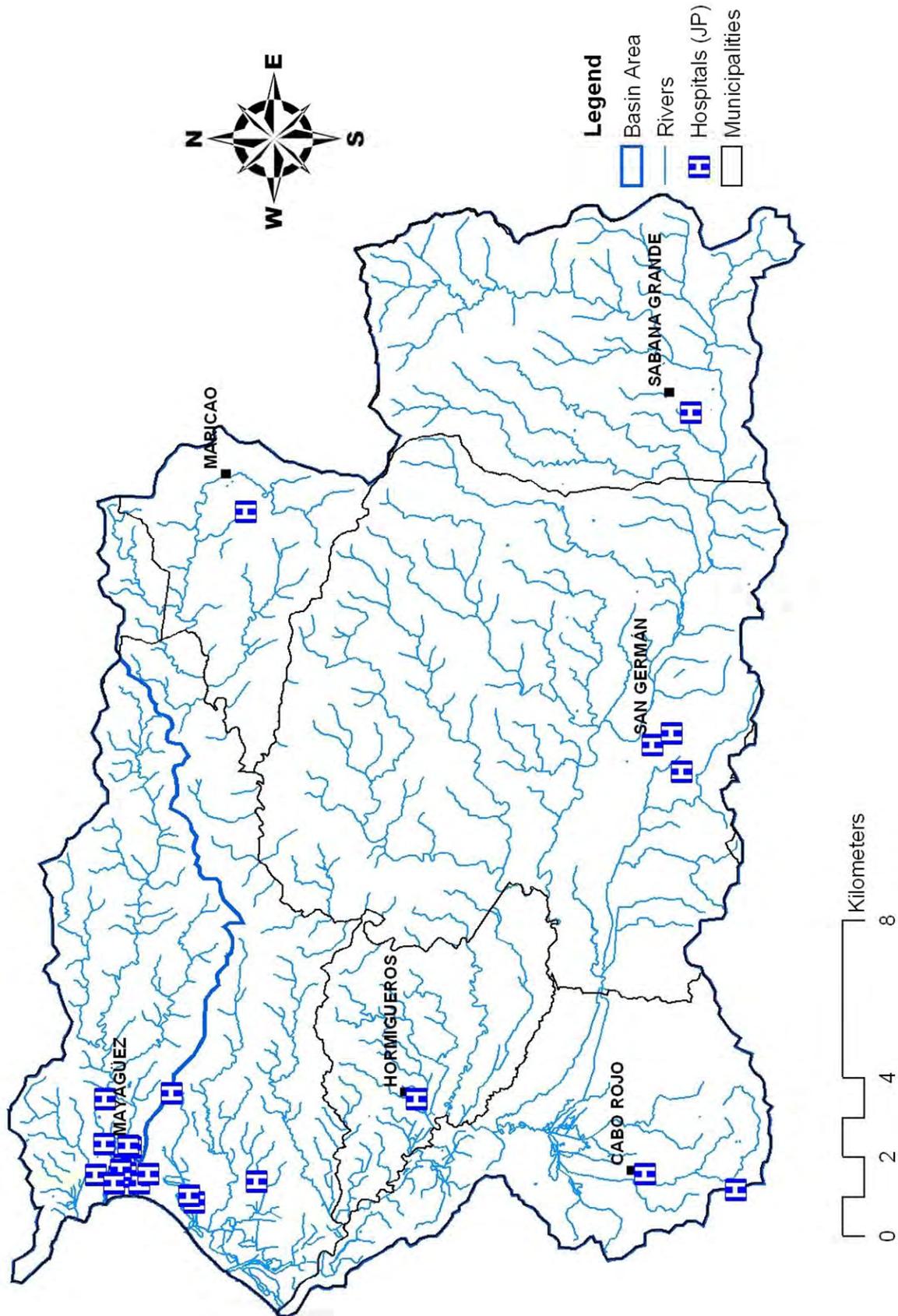
**LAYERS PRODUCED FOR THE DEVELOPMENT OF THE POTENTIAL
FECAL CONTAMINATION INDEX**

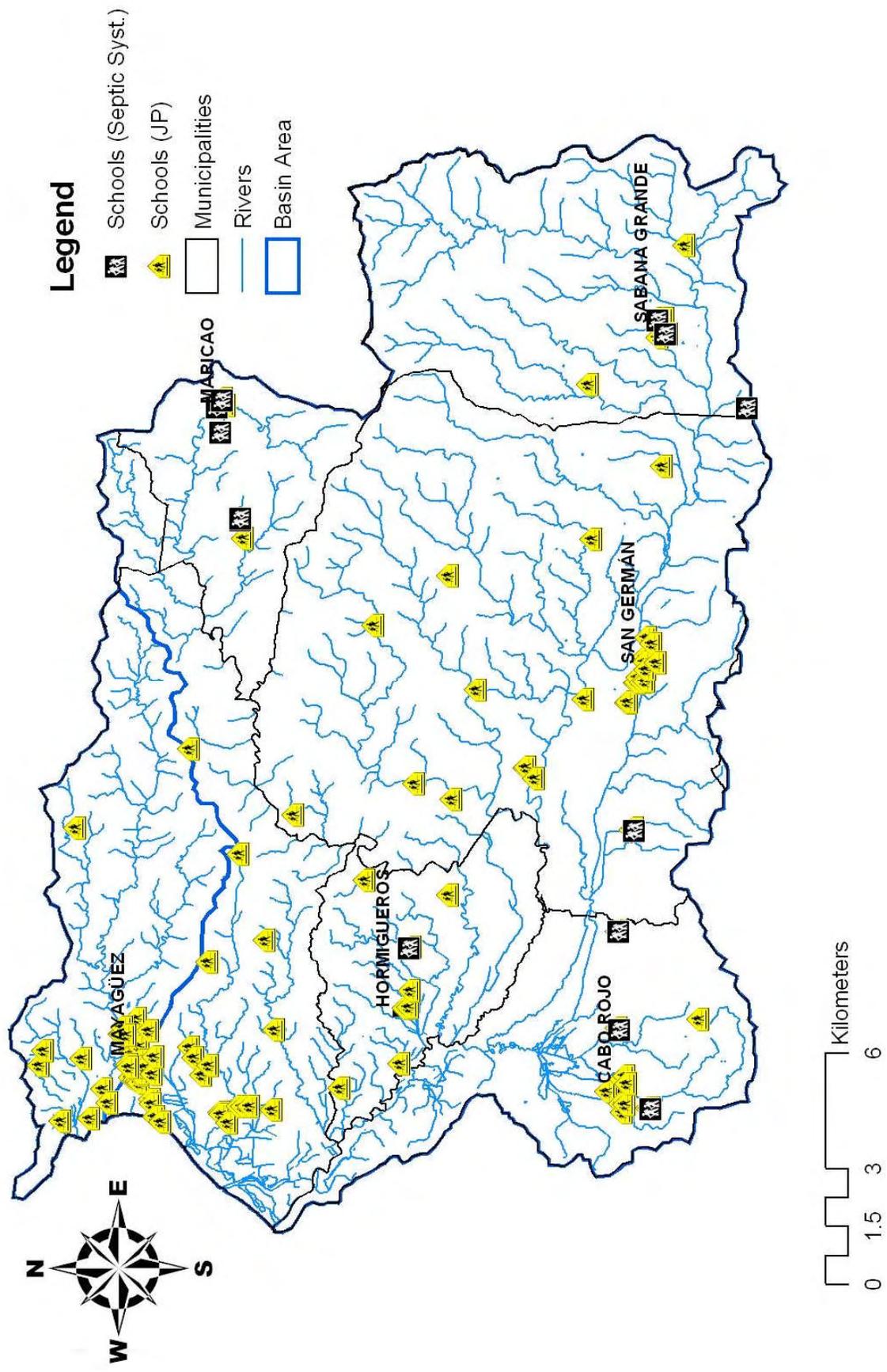


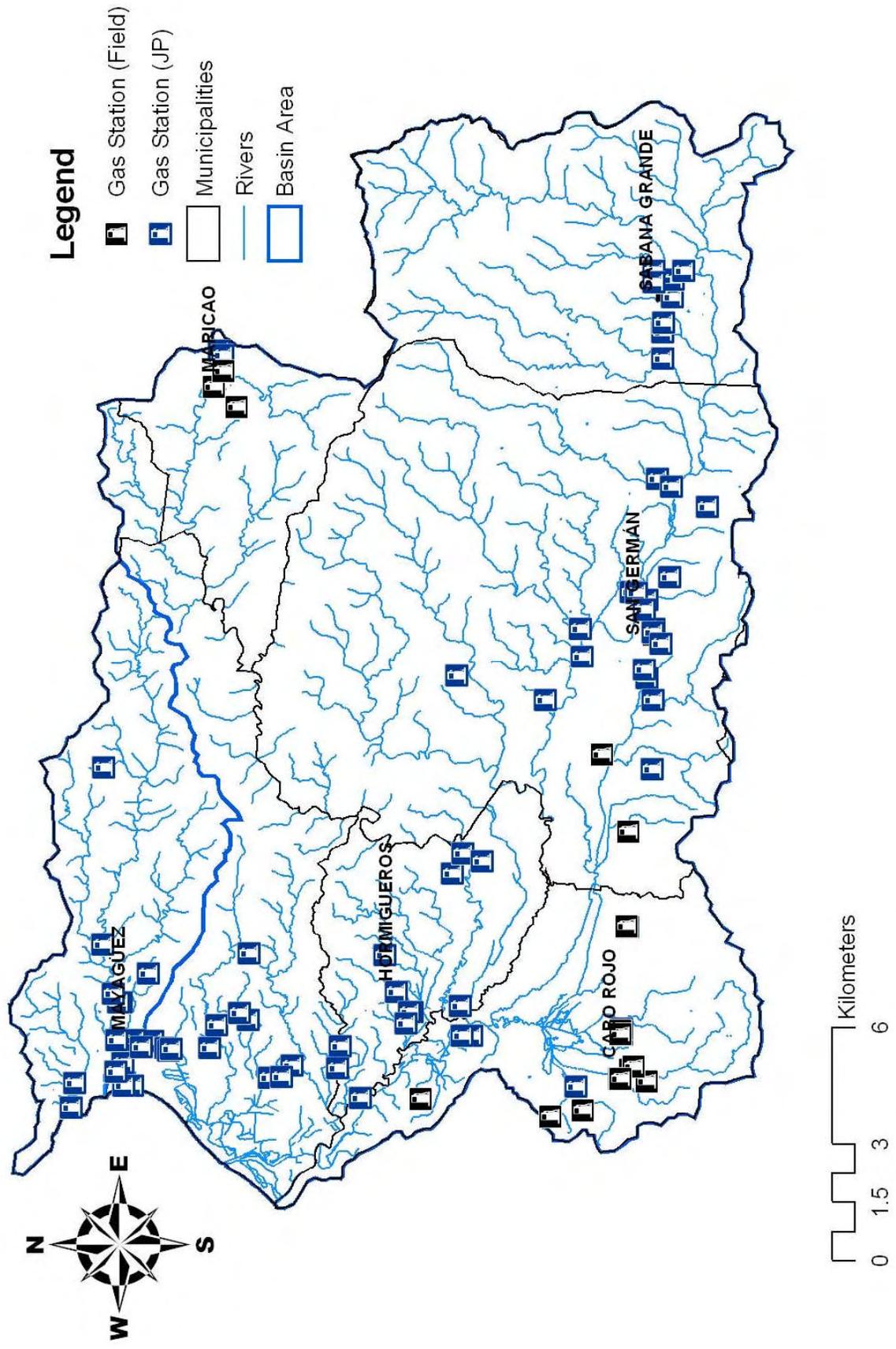


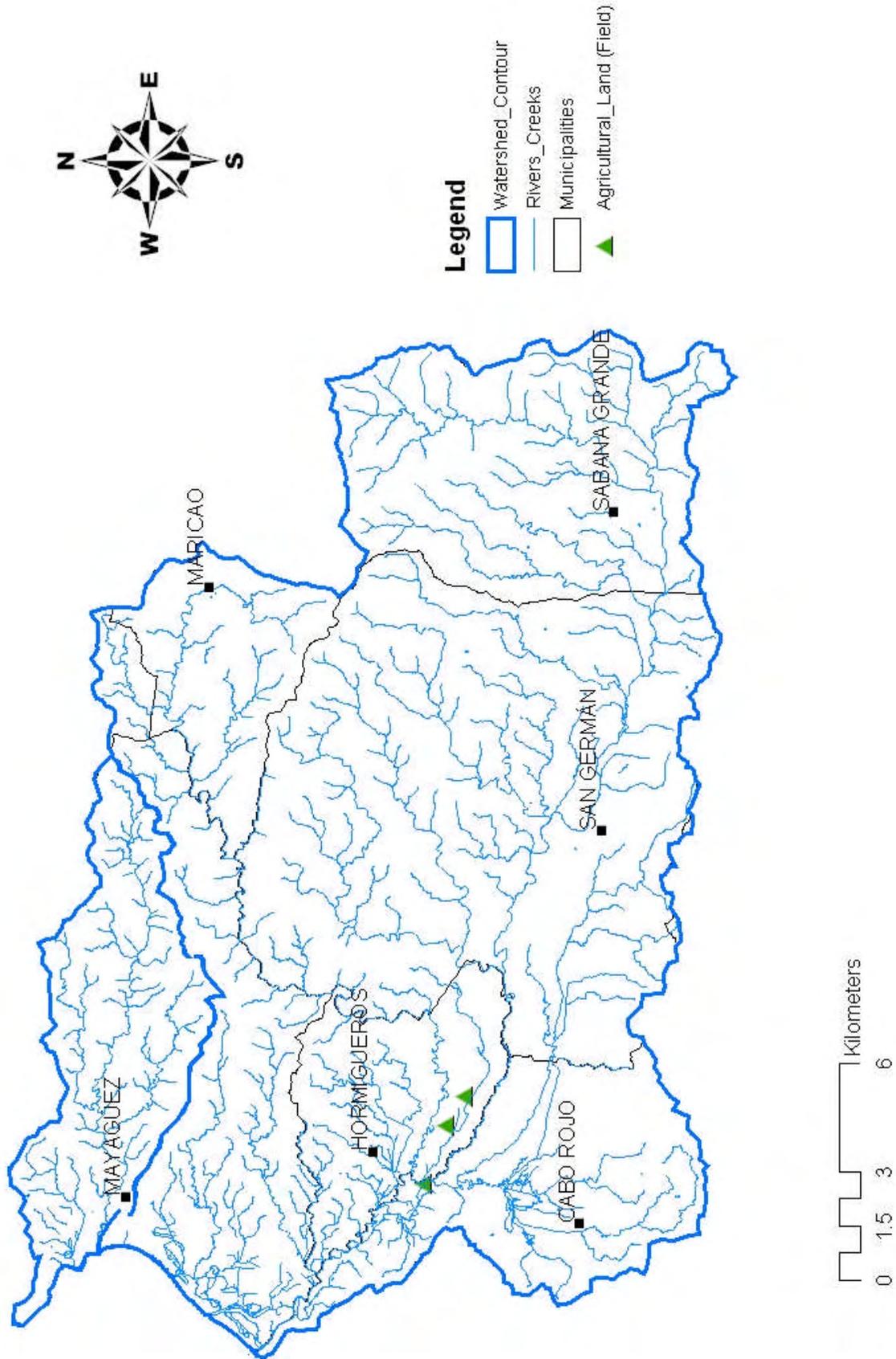


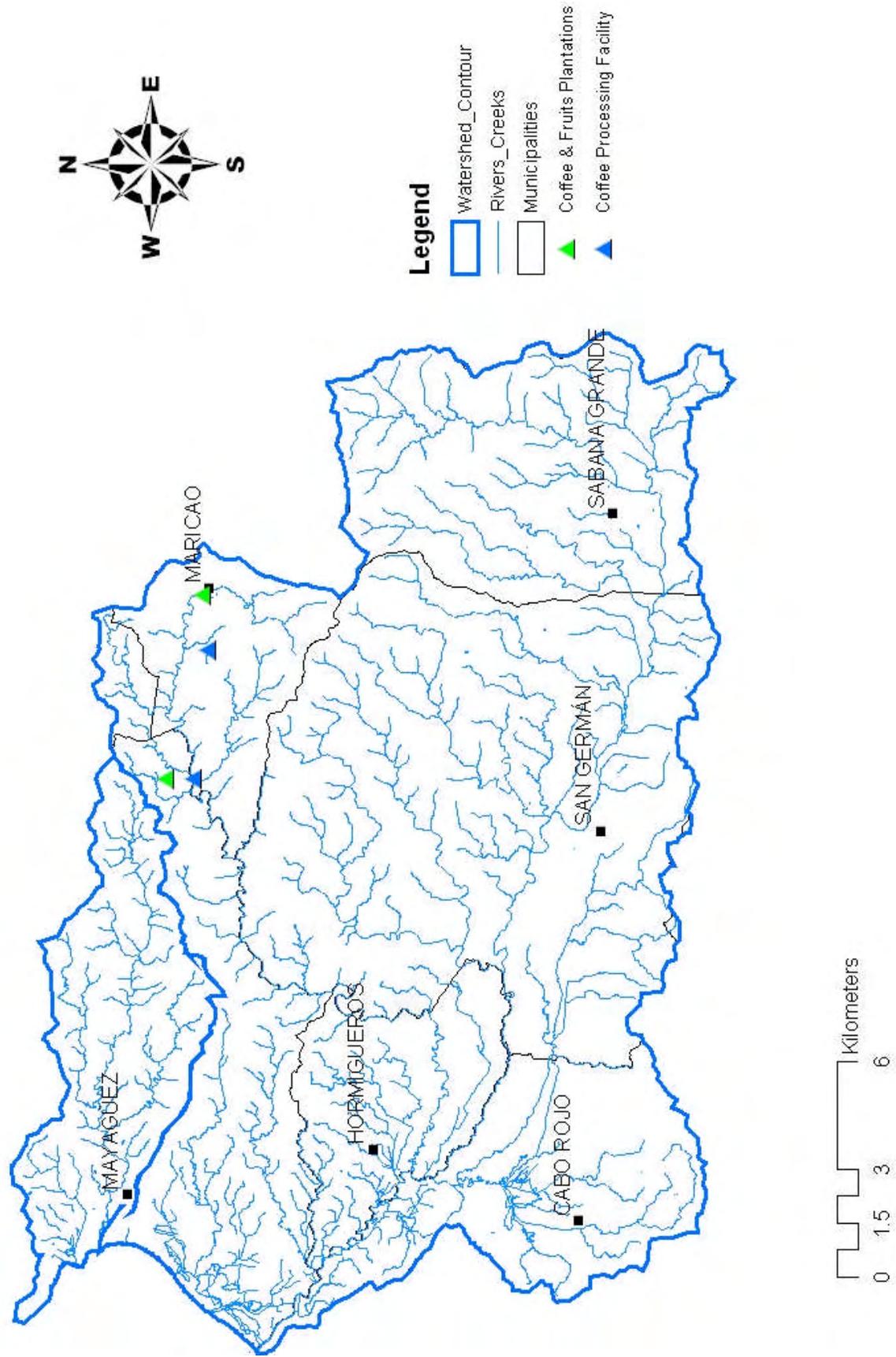


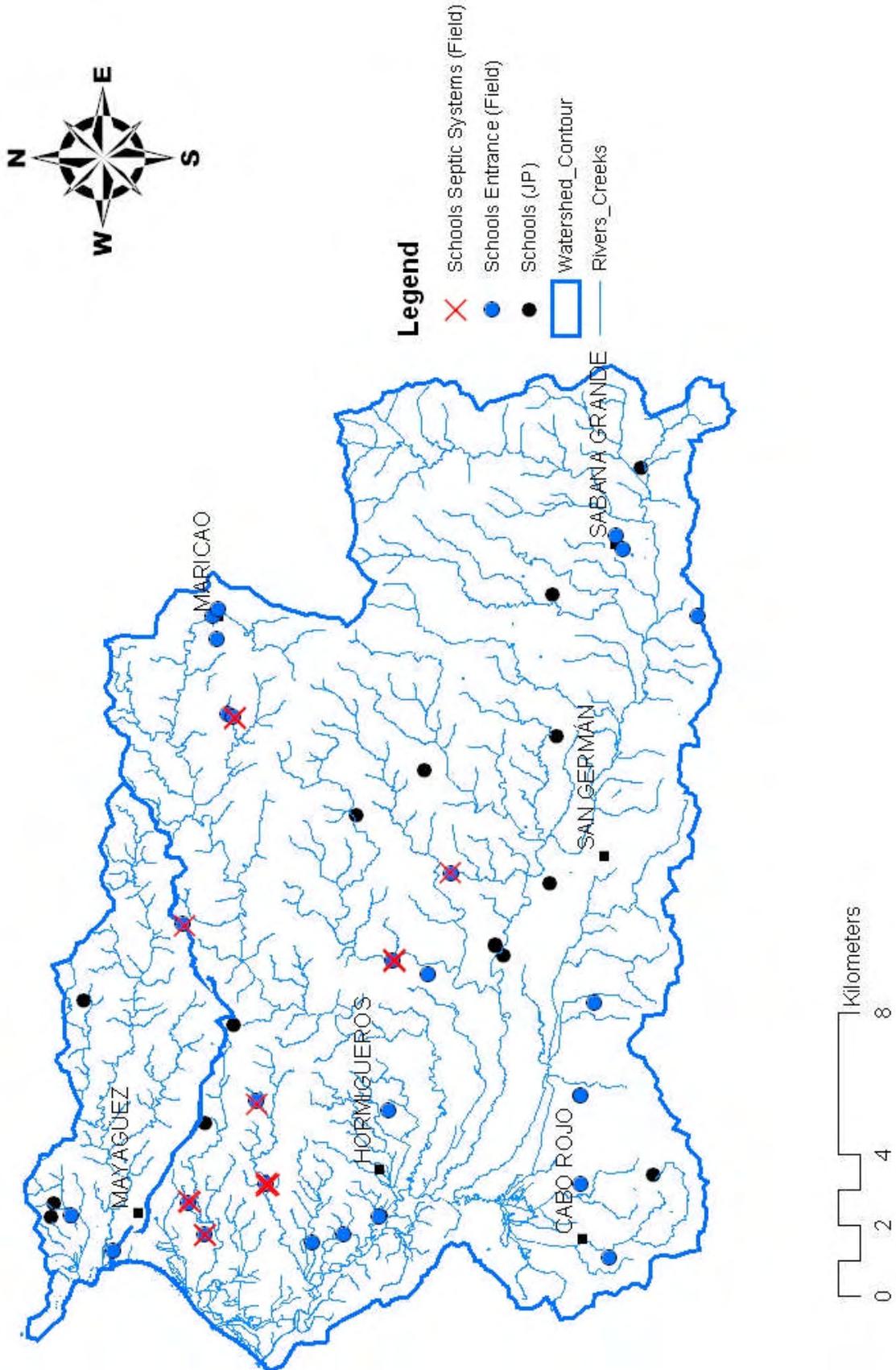


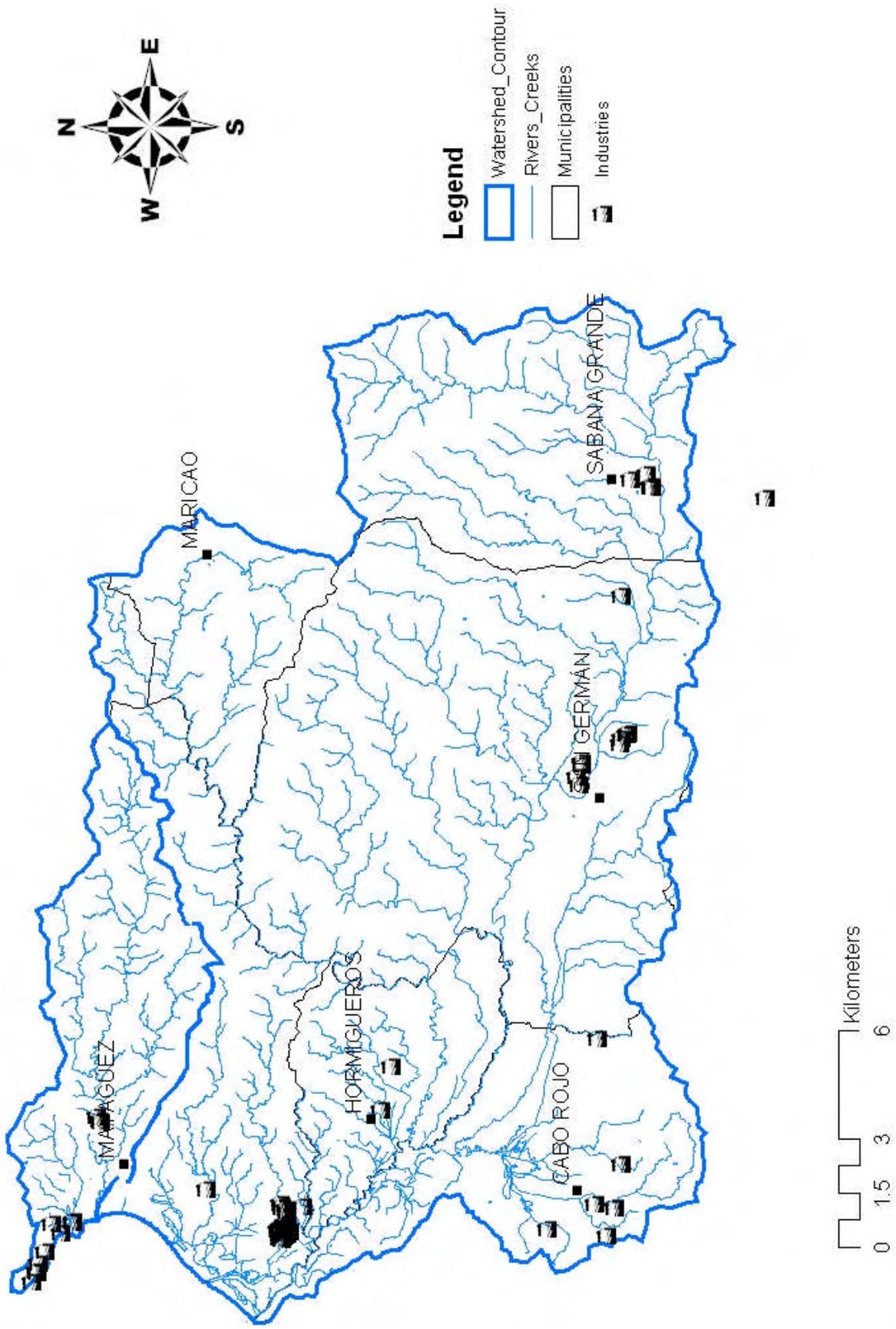


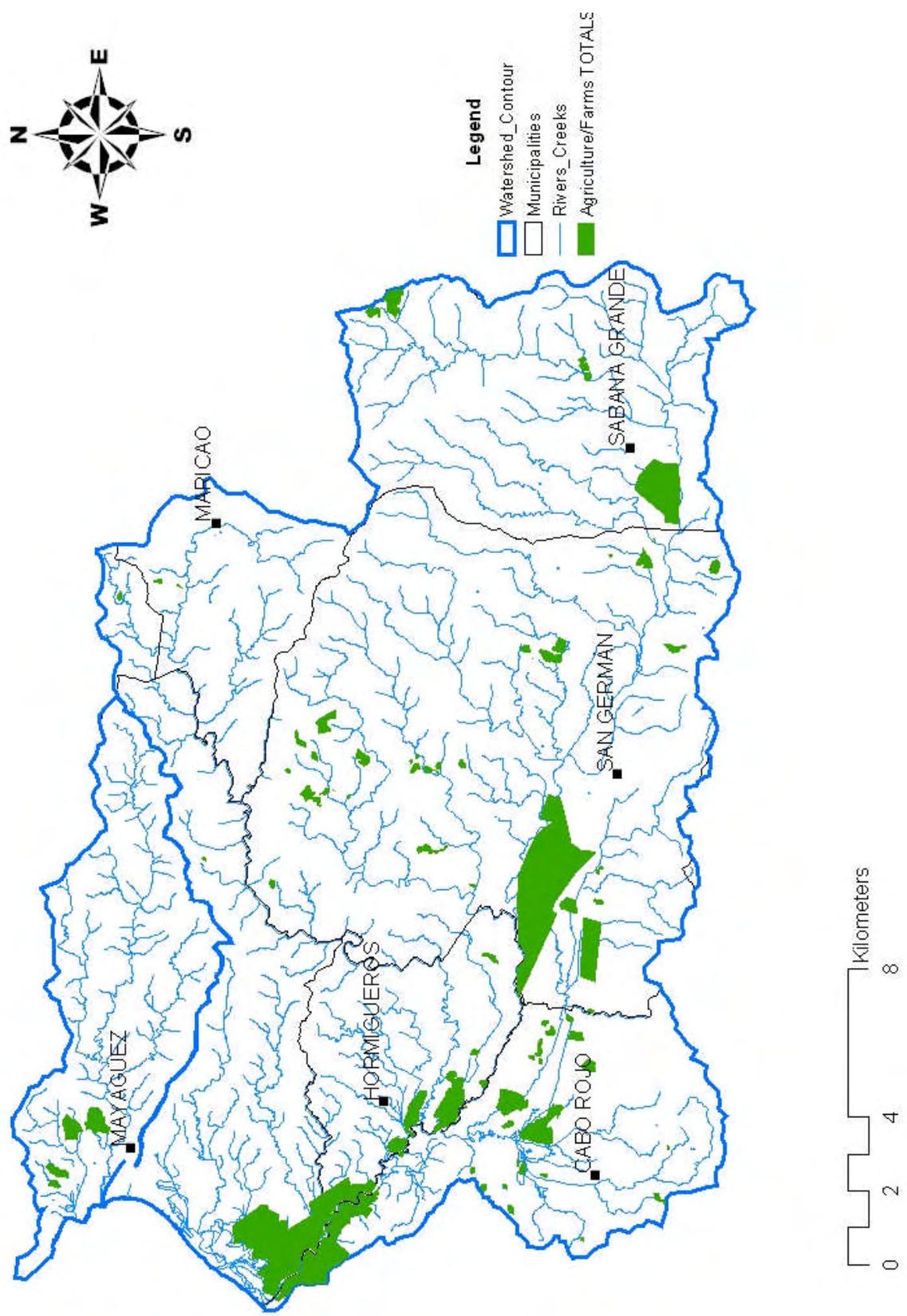












APPENDIX E

STATISTICAL ANALYSIS USING MINITAB 14

Descriptive Statistics: LOG_FCB, FCB

Variable	NAME	N	N*	Mean	SE Mean	StDev
LOG_FCB	CABO ROJO	322	0	9.034	0.269	4.819
	HORMIGUEROS	295	0	7.771	0.306	5.262
	LAS MARIAS	15	0	6.95	1.52	5.89
	MARICAO	96	0	7.995	0.558	5.465
	MAYAGUEZ	974	0	9.467	0.135	4.206
	SABANA GRANDE	321	0	9.464	0.256	4.589
	SAN GERMAN	735	0	8.499	0.195	5.276
FCB	CABO ROJO	322	0	1.23573E+12	1.67042E+11	2.99746E+12
	HORMIGUEROS	295	0	3.58089E+11	62053373037	1.06580E+12
	LAS MARIAS	15	0	6.00208E+11	4.00864E+11	1.55254E+12
	MARICAO	96	0	1.38544E+12	3.95960E+11	3.87960E+12
	MAYAGUEZ	974	0	5.71285E+11	62576415757	1.95295E+12
	SABANA GRANDE	321	0	1.36426E+12	1.93419E+11	3.46538E+12
	SAN GERMAN	735	0	1.43670E+12	1.29177E+11	3.50209E+12
Variable	NAME	Minimum	Q1	Median	Q3	
	LOG_FCB	CABO ROJO	0.000000000	10.278	11.182	11.886
	HORMIGUEROS	0.000000000	0.000000000	11.075	11.401	
	LAS MARIAS	0.000000000	0.000000000	11.17	11.39	
	MARICAO	0.000000000	0.000000000	11.172	12.027	
	MAYAGUEZ	0.000000000	10.585	11.123	11.556	
	SABANA GRANDE	0.000000000	10.799	11.299	11.968	
SAN GERMAN	0.000000000	0.000000000	11.292	12.047		
FCB	CABO ROJO	0.000000000	19222500000	1.52033E+11	7.69774E+11	
	HORMIGUEROS	0.000000000	0.000000000	1.18830E+11	2.51640E+11	
	LAS MARIAS	0.000000000	0.000000000	1.46790E+11	2.44650E+11	
	MARICAO	0.000000000	0.000000000	1.48538E+11	1.06423E+12	
VB	MAYAGUEZ	0.000000000	38445000000	1.32810E+11	3.59985E+11	
	SABANA GRANDE	0.000000000	62910000000	1.99215E+11	9.29670E+11	
	SAN GERMAN	0.000000000	0.000000000	1.95720E+11	1.11491E+12	
Variable	NAME	Maximum				
	LOG_FCB	CABO ROJO	13.406			
	HORMIGUEROS	12.973				
	LAS MARIAS	12.79				
	MARICAO	13.477				
	MAYAGUEZ	13.417				
	SABANA GRANDE	13.504				
SAN GERMAN	13.667					
FCB	CABO ROJO	2.54436E+13				
	HORMIGUEROS	9.39456E+12				
	LAS MARIAS	6.11625E+12				
	MARICAO	2.99941E+13				
	MAYAGUEZ	2.61286E+13				
	SABANA GRANDE	3.19024E+13				
	SAN GERMAN	4.64835E+13				

Grouping by 0's and 1's

Tabulated statistics: NOMBRE, C10

Rows: NOMBRE	Columns: C10		
	0	1	All
CABO ROJO	70 21.74	252 78.26	322 100.00
HORMIGUEROS	92 31.19	203 68.81	295 100.00
MAR/LM	36 32.43	75 67.57	111 100.00
MAYAGUEZ	158 16.22	816 83.78	974 100.00
SABANA GRANDE	60 18.69	261 81.31	321 100.00
SAN GERMAN	202 27.48	533 72.52	735 100.00
All	618 22.41	2140 77.59	2758 100.00

Cell Contents: Count
 % of Row

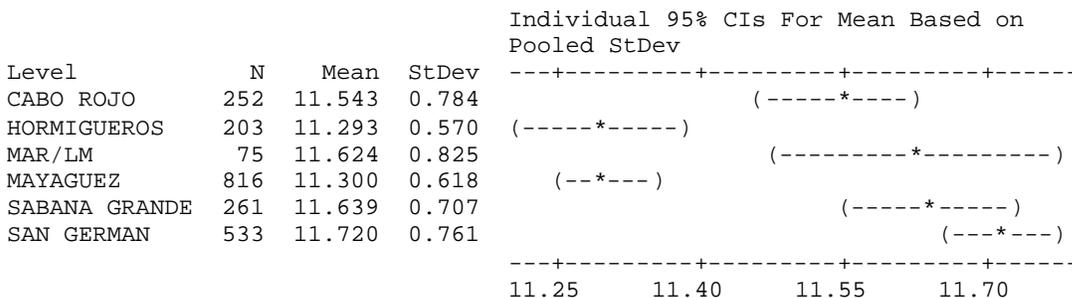
02/12/2005 13:21:40

Welcome to Minitab, press F1 for help.
Retrieving project from file: 'C:\Program Files\MINITAB
14\Data\FCB_INDEX1.MPJ'

One-way ANOVA: LOG_FCB versus NOMBRE

Source	DF	SS	MS	F	P
NOMBRE	5	73.159	14.632	30.63	0.000
Error	2134	1019.244	0.478		
Total	2139	1092.403			

S = 0.6911 R-Sq = 6.70% R-Sq(adj) = 6.48%



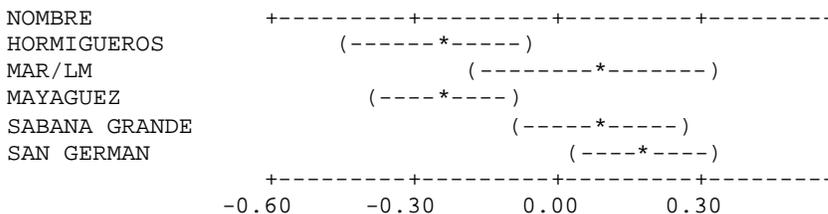
Pooled StDev = 0.691

Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of NOMBRE

Individual confidence level = 99.56%

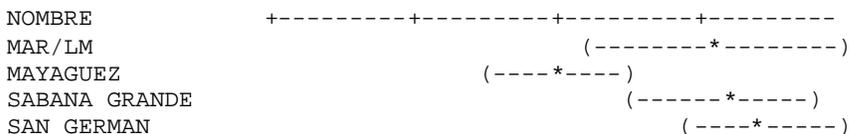
NOMBRE = CABO ROJO subtracted from:

NOMBRE	Lower	Center	Upper
HORMIGUEROS	-0.4360	-0.2502	-0.0645
MAR/LM	-0.1783	0.0808	0.3398
MAYAGUEZ	-0.3850	-0.2430	-0.1011
SABANA GRANDE	-0.0783	0.0956	0.2695
SAN GERMAN	0.0258	0.1763	0.3269



NOMBRE = HORMIGUEROS subtracted from:

NOMBRE	Lower	Center	Upper
MAR/LM	0.0649	0.3310	0.5971
MAYAGUEZ	-0.1472	0.0072	0.1617
SABANA GRANDE	0.1616	0.3459	0.5302
SAN GERMAN	0.2642	0.4266	0.5890



```

+-----+-----+-----+-----+
-0.60      -0.30      0.00      0.30

```

NOMBRE = MAR/LM subtracted from:

NOMBRE	Lower	Center	Upper
MAYAGUEZ	-0.5614	-0.3238	-0.0861
SABANA GRANDE	-0.2432	0.0149	0.2729
SAN GERMAN	-0.1473	0.0956	0.3385

```

NOMBRE          +-----+-----+-----+-----+
MAYAGUEZ        (-----*-----)
SABANA GRANDE   (-----*-----)
SAN GERMAN      (-----*-----)
+-----+-----+-----+-----+
-0.60      -0.30      0.00      0.30

```

NOMBRE = MAYAGUEZ subtracted from:

NOMBRE	Lower	Center	Upper
SABANA GRANDE	0.1986	0.3386	0.4787
SAN GERMAN	0.3097	0.4194	0.5290

```

NOMBRE          +-----+-----+-----+-----+
SABANA GRANDE   (---*---)
SAN GERMAN      (---*---)
+-----+-----+-----+-----+
-0.60      -0.30      0.00      0.30

```

NOMBRE = SABANA GRANDE subtracted from:

NOMBRE	Lower	Center	Upper
SAN GERMAN	-0.0681	0.0807	0.2295

```

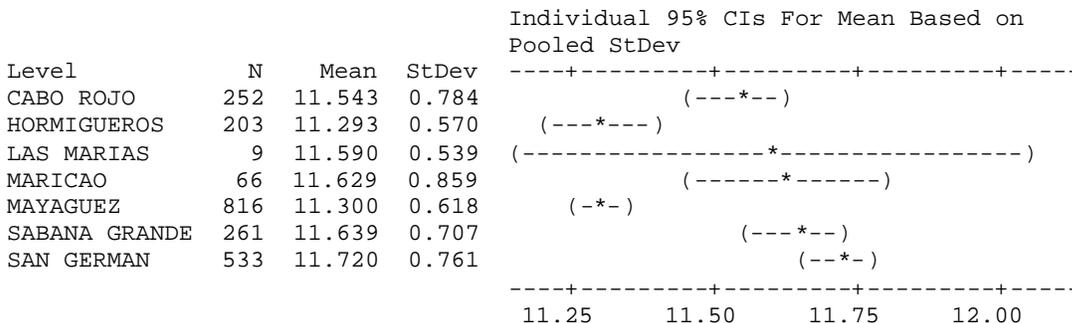
NOMBRE          +-----+-----+-----+-----+
SAN GERMAN      (----*----)
+-----+-----+-----+-----+
-0.60      -0.30      0.00      0.30

```

One-way ANOVA: LOG_FCB versus NAME

Source	DF	SS	MS	F	P
NAME	6	73.171	12.195	25.52	0.000
Error	2133	1019.232	0.478		
Total	2139	1092.403			

S = 0.6913 R-Sq = 6.70% R-Sq(adj) = 6.44%



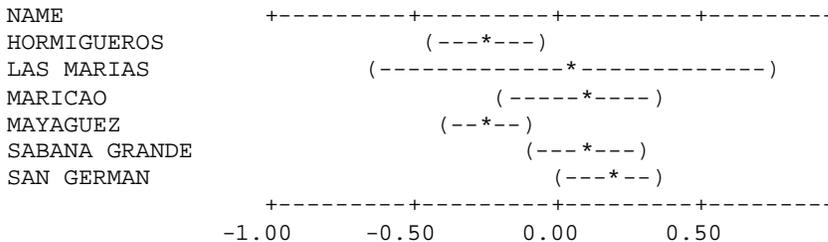
Pooled StDev = 0.691

Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of NAME

Individual confidence level = 99.68%

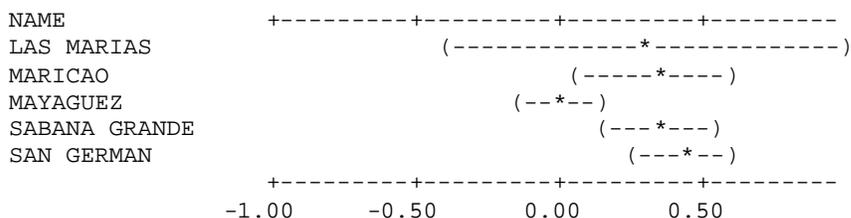
NAME = CABO ROJO subtracted from:

NAME	Lower	Center	Upper
HORMIGUEROS	-0.4425	-0.2502	-0.0580
LAS MARIAS	-0.6451	0.0463	0.7378
MARICAO	-0.1964	0.0854	0.3673
MAYAGUEZ	-0.3899	-0.2430	-0.0961
SABANA GRANDE	-0.0844	0.0956	0.2756
SAN GERMAN	0.0205	0.1763	0.3322



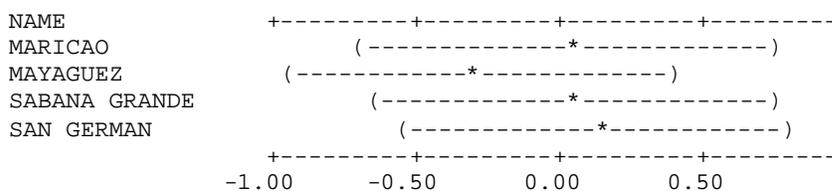
NAME = HORMIGUEROS subtracted from:

NAME	Lower	Center	Upper
LAS MARIAS	-0.3977	0.2966	0.9909
MARICAO	0.0469	0.3357	0.6245
MAYAGUEZ	-0.1526	0.0072	0.1671
SABANA GRANDE	0.1551	0.3459	0.5366
SAN GERMAN	0.2585	0.4266	0.5947



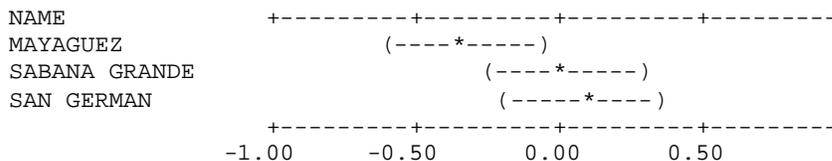
NAME = LAS MARIAS subtracted from:

NAME	Lower	Center	Upper
MARICAO	-0.6852	0.0391	0.7634
MAYAGUEZ	-0.9725	-0.2894	0.3938
SABANA GRANDE	-0.6418	0.0493	0.7403
SAN GERMAN	-0.5551	0.1300	0.8151



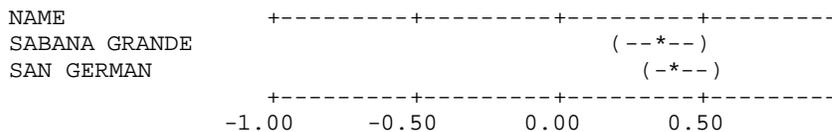
NAME = MARICAO subtracted from:

NAME	Lower	Center	Upper
MAYAGUEZ	-0.5893	-0.3285	-0.0676
SABANA GRANDE	-0.2707	0.0102	0.2910
SAN GERMAN	-0.1751	0.0909	0.3569



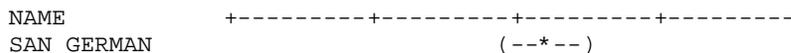
NAME = MAYAGUEZ subtracted from:

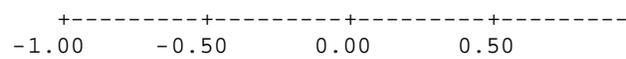
NAME	Lower	Center	Upper
SABANA GRANDE	0.1937	0.3386	0.4836
SAN GERMAN	0.3059	0.4194	0.5329



NAME = SABANA GRANDE subtracted from:

NAME	Lower	Center	Upper
SAN GERMAN	-0.0733	0.0807	0.2347

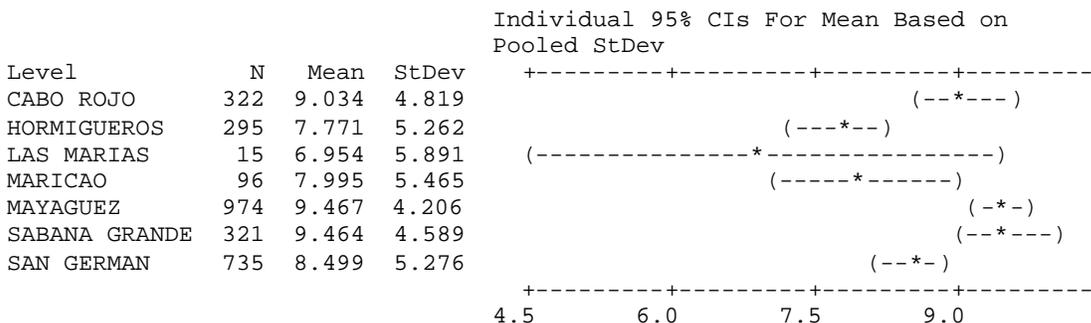




One-way ANOVA: LOG_FCB versus NAME

Source	DF	SS	MS	F	P
NAME	6	1050.4	175.1	7.61	0.000
Error	2751	63298.8	23.0		
Total	2757	64349.2			

S = 4.797 R-Sq = 1.63% R-Sq(adj) = 1.42%

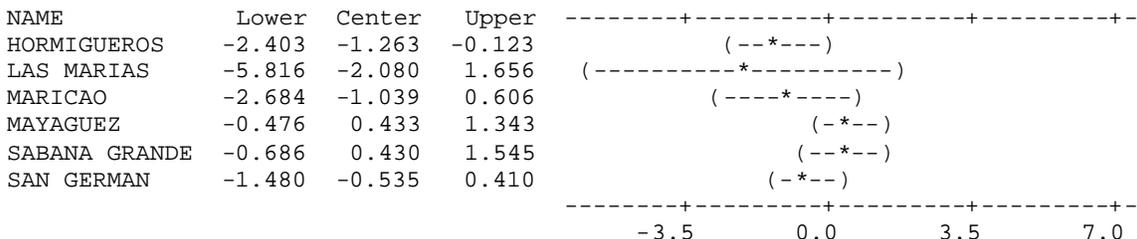


Pooled StDev = 4.797

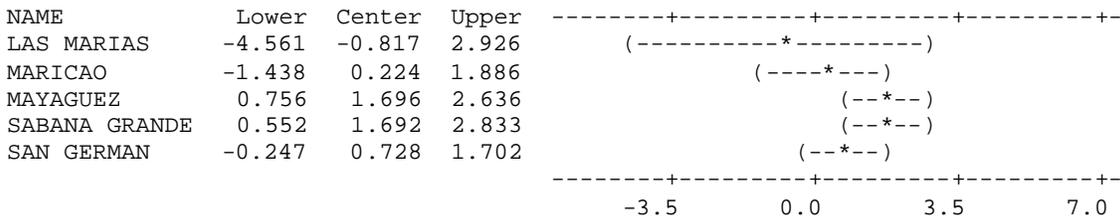
Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of NAME

Individual confidence level = 99.68%

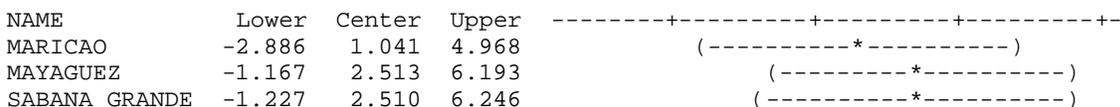
NAME = CABO ROJO subtracted from:



NAME = HORMIGUEROS subtracted from:



NAME = LAS MARIAS subtracted from:



SAN GERMAN	-2.144	1.545	5.234	(-----*-----)
				-----+-----+-----+-----+-----
				-3.5 0.0 3.5 7.0

NAME = MARICAO subtracted from:

NAME	Lower	Center	Upper	-----+-----+-----+-----+-----
MAYAGUEZ	-0.041	1.472	2.985	(---*---)
SABANA GRANDE	-0.177	1.469	3.114	(-----*-----)
SAN GERMAN	-1.031	0.504	2.039	(---*---)
				-----+-----+-----+-----+-----
				-3.5 0.0 3.5 7.0

NAME = MAYAGUEZ subtracted from:

NAME	Lower	Center	Upper	-----+-----+-----+-----+-----
SABANA GRANDE	-0.914	-0.004	0.907	(--*--)
SAN GERMAN	-1.660	-0.968	-0.277	(-*--)
				-----+-----+-----+-----+-----
				-3.5 0.0 3.5 7.0

NAME = SABANA GRANDE subtracted from:

NAME	Lower	Center	Upper	-----+-----+-----+-----+-----
SAN GERMAN	-1.911	-0.965	-0.018	(-*--)
				-----+-----+-----+-----+-----
				-3.5 0.0 3.5 7.0

Tally for Discrete Variables: LOG_FCB

LOG_FCB	Count
0.0000	618
9.5434	9
9.8445	20
10.0206	18
10.1455	18
10.2424	16
10.3216	14
10.3885	16
10.4465	16
10.4977	24
10.5434	18
10.5848	17
10.6226	19
10.6574	17
10.6896	27
10.7195	16
10.7476	19
10.7739	15
10.7987	20
10.8222	17
10.8445	19
10.8657	10
10.8859	13
10.9052	17
10.9237	22
10.9414	14
10.9584	17
10.9748	17
10.9906	39
11.0058	21
11.0206	20
11.0348	15
11.0486	13
11.0620	19
11.0749	23
11.0875	18
11.0997	16
11.1116	17
11.1232	9
11.1345	13
11.1455	16
11.1562	16
11.1667	34
11.1769	16
11.1869	10
11.1967	11
11.2062	16
11.2155	13
11.2247	16
11.2336	16
11.2424	10
11.2510	11
11.2595	16
11.2677	9
11.2758	6
11.2838	12
11.2916	34
11.2993	8
11.3069	7
11.3143	13

11.3216	11
11.3288	10
11.3358	8
11.3428	12
11.3496	8
11.3564	13
11.3630	10
11.3695	8
11.3760	4
11.3823	6
11.3885	28
11.3947	10
11.4008	6
11.4068	5
11.4127	6
11.4185	8
11.4243	1
11.4299	8
11.4355	3
11.4411	6
11.4465	2
11.4519	7
11.4573	7
11.4625	4
11.4677	13
11.4729	8
11.4779	7
11.4830	2
11.4879	7
11.4928	3
11.4977	4
11.5025	3
11.5072	6
11.5119	3
11.5166	5
11.5212	1
11.5257	3
11.5302	4
11.5347	17
11.5391	5
11.5434	8
11.5478	2
11.5520	1
11.5563	5
11.5605	4
11.5646	1
11.5688	3
11.5728	4
11.5769	3
11.5809	5
11.5848	4
11.5888	5
11.5927	28
11.5965	3
11.6004	6
11.6041	1
11.6079	4
11.6116	3
11.6153	4
11.6190	4
11.6226	2
11.6262	2
11.6298	2

11.6334	2
11.6369	2
11.6404	2
11.6438	17
11.6473	2
11.6507	1
11.6540	4
11.6574	2
11.6607	2
11.6640	2
11.6673	6
11.6738	1
11.6770	1
11.6802	1
11.6833	3
11.6865	2
11.6896	14
11.6988	2
11.7078	4
11.7108	1
11.7137	2
11.7166	2
11.7195	2
11.7224	2
11.7253	1
11.7310	10
11.7338	5
11.7366	1
11.7393	2
11.7421	2
11.7448	1
11.7476	1
11.7503	1
11.7530	2
11.7556	2
11.7583	3
11.7609	2
11.7662	1
11.7688	14
11.7739	1
11.7764	3
11.7790	1
11.7840	1
11.7865	4
11.7963	1
11.8011	1
11.8035	10
11.8059	1
11.8083	2
11.8106	3
11.8153	1
11.8199	2
11.8222	3
11.8267	1
11.8290	1
11.8312	1
11.8357	13
11.8401	1
11.8445	1
11.8488	1
11.8509	2
11.8531	1
11.8552	1

11.8594	1
11.8636	2
11.8657	14
11.8759	1
11.8779	1
11.8799	2
11.8819	3
11.8839	1
11.8859	1
11.8878	2
11.8898	1
11.8937	10
11.8976	1
11.9108	1
11.9145	1
11.9164	1
11.9200	7
11.9237	1
11.9344	1
11.9448	14
11.9500	2
11.9534	1
11.9551	2
11.9567	1
11.9601	1
11.9651	1
11.9683	10
11.9748	2
11.9796	1
11.9828	2
11.9844	1
11.9906	9
11.9952	2
12.0013	3
12.0028	1
12.0088	2
12.0118	6
12.0177	1
12.0206	1
12.0220	1
12.0249	1
12.0277	2
12.0320	10
12.0362	1
12.0390	1
12.0404	1
12.0418	2
12.0472	1
12.0513	5
12.0526	1
12.0567	1
12.0698	5
12.0736	1
12.0825	1
12.0838	1
12.0875	9
12.0973	1
12.1022	1
12.1045	6
12.1057	1
12.1093	1
12.1105	1
12.1140	1

12.1209	3
12.1232	1
12.1266	1
12.1289	1
12.1312	2
12.1323	1
12.1367	3
12.1520	3
12.1583	1
12.1625	1
12.1636	1
12.1667	11
12.1809	1
12.1869	1
12.1928	1
12.1947	7
12.2005	1
12.2015	1
12.2081	8
12.2090	1
12.2128	2
12.2155	1
12.2174	1
12.2211	3
12.2328	1
12.2336	3
12.2363	1
12.2389	1
12.2407	1
12.2459	4
12.2578	7
12.2611	1
12.2694	5
12.2774	1
12.2806	3
12.2862	1
12.2916	4
12.2940	1
12.3024	3
12.3099	1
12.3128	4
12.3136	1
12.3165	1
12.3194	1
12.3230	3
12.3281	1
12.3323	1
12.3330	2
12.3351	1
12.3428	5
12.3476	1
12.3523	4
12.3584	1
12.3617	7
12.3630	1
12.3708	9
12.3798	4
12.3885	2
12.3910	1
12.3971	1
12.4038	1
12.4056	2
12.4086	1

12.4139	3
12.4220	3
12.4243	1
12.4282	1
12.4299	2
12.4378	4
12.4455	3
12.4530	3
12.4604	6
12.4677	5
12.4688	1
12.4703	1
12.4739	1
12.4749	3
12.4764	1
12.4820	5
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12.4958	2
12.4991	1
12.5025	3
12.5091	3
12.5157	3
12.5221	3
12.5347	3
12.5378	1
12.5408	4
12.5469	3
12.5529	3
12.5588	4
12.5626	1
12.5646	1
12.5704	2
12.5761	1
12.5817	2
12.5927	1
12.5981	2
12.6034	2
12.6087	1
12.6124	1
12.6139	1
12.6190	3
12.6241	6
12.6341	4
12.6390	5
12.6438	2
12.6581	3
12.6591	1
12.6627	3
12.6666	1
12.6763	4
12.6808	2
12.6852	1
12.6939	5
12.7024	2
12.7149	1
12.7190	1
12.7230	1
12.7270	2
12.7310	1
12.7349	2
12.7363	1
12.7388	1

12.7427	3
12.7503	4
12.7540	1
12.7578	1
12.7615	2
12.7651	3
12.7688	1
12.7724	5
12.7759	2
12.7795	2
12.7865	2
12.7899	1
12.7968	3
12.8035	2
12.8199	1
12.8263	1
12.8295	1
12.8357	1
12.8388	2
12.8509	1
12.8522	1
12.8569	2
12.8598	2
12.8771	1
12.8799	2
12.8827	1
12.8855	1
12.8882	1
12.8910	1
12.8937	1
12.9044	1
12.9071	1
12.9149	2
12.9200	1
12.9251	2
12.9276	1
12.9326	2
12.9351	1
12.9375	1
12.9400	1
12.9448	1
12.9473	2
12.9496	3
12.9660	1
12.9729	1
12.9751	1
12.9774	2
12.9840	1
12.9862	1
12.9906	2
12.9971	1
13.0076	2
13.0097	1
13.0118	1
13.0320	1
13.0359	1
13.0437	1
13.0569	1
13.0716	2
13.0840	2
13.0875	1
13.0978	1
13.1145	1

13.1161	1
13.1209	1
13.1444	1
13.1459	1
13.1520	1
13.1535	1
13.1667	1
13.1681	1
13.1724	1
13.1823	1
13.1851	1
13.1893	1
13.2107	1
13.2554	1
13.2589	1
13.2728	1
13.2750	1
13.3055	1
13.3447	1
13.3495	1
13.3807	1
13.3911	1
13.4056	1
13.4171	1
13.4508	1
13.4770	1
13.4861	1
13.5038	1
13.5328	1
13.6673	1
N=	2758

APPENDIX F

INSTRUCTIONS ABOUT ACCESSING AND IMPORTING DATA FROM SSURGO

**Instructions about accessing and importing tabular data into a template
database from SSURGO**

1. Open the MS Access SSURGO template database in the version 2002 of MS Access.
2. Click the Reports tab of the Database Window. The Database Window may be behind a form titled "SSURGO Import" or "Soil Reports".
3. In the blank on the Import form, enter the fully qualified path name of the directory containing the soil tabular data ASCII delimited files whose contents are to be imported, (e.g. **C:\NRCS\SSURGO\LajasValleyUTM1983\soil_pr687\tabular**).
4. After the Report Viewer window is displayed, the Water Features and Map Unit Legend are exported to MS Excel Format to re-organize the data and finally match soil types with hydrological soils group classification to obtain the soils hydrological classification.