DEVELOPMENT OF A DECISION SUPPORT TOOL TO ENSURE SAFE DRINKING WATER IN NON-PRASA COMMUNITIES IN PUERTO RICO

by

Melissa Herrera Badel

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

MASTER OF SCIENCE
in

CIVIL ENGINEERING
(Environmental and Water Resources Engineering)

UNIVERSITY OF PUERTO RICO
MAYAGÜEZ CAMPUS
2009

Approved by:

______________________________ ____________________
Sangchul Hwang, PhD Date
President, Graduate Committee

____
Jorge Rivera Santos, PhD ____________________
Member, Graduate Committee Date

____
Ismael Pagán Trinidad, MSCE ____________________
Member, Graduate Committee Date

____
Ismael Pagán Trinidad, MSCE ____________________
Director, Department of Civil Engineering and Surveying Date

____
Jaime Benitez Rodriguez , PhD ____________________
Representative, Graduate Studies Date

ABSTRACT

One of the main goals of the Millennium Development Goals is to reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation. In 2007, 97% of the Puerto Rico's population used improved drinking water systems from the Puerto Rico Aqueduct and Sewer Authority (PRASA) and approximately 125,130 persons of the rural areas do not have access to improved drinking water systems. This situation has intensified the efforts for innovation or improved technologies for drinking water treatment, with effluents of better quality and particularly with technologies that conform to environmental, economic, and social conditions in rural communities.

This study contributes to the production of sustainable drinking water to rural communities of Puerto Rico, ensuring drinking water with low sanitary risk and water that meets drinking water bacteriological standards. This was done through the selection of communities with drinking water problems, the evaluation of Experimental Drum Sand Filtration (EDSF) system as a sustainable option to solve the drinking water problem based on the available data and information, and the development of a strategy to find the best location for EDSF system using Geographical Information Systems (GIS).

The identification and ranking of the communities based on the level of drinking water supply problems was done using an evaluation matrix method. The first step was to identify variables related to the drinking water problem, which received a quantitative value according to the positive or negative incidence with the problem. La Jurada community at Yauco, Puerto

Rico, obtained the highest score. This community has a water supply system without treatment where the water is taken from a small water source and then provided directly to the community and, according to the bacteriological records, the water quality does not comply with regulations.

The EDSF system is a good technological alternative for rural communities of Puerto Rico in terms of the physicochemical and bacteriological parameters, meeting regulatory biochemical water quality standards. However, it is necessary to improve the chlorine dosage to achieve the optimum residual chlorine concentration.

The MCDA was the tool used to find the best place where the Experimental Drum Sand Filtration (EDSF) system must be installed, provide it that works by gravity, to ensure the sustainability in terms of economy, society, and environment. This strategy was tested initially in Las Piedras community in San Germán and subsequently was adjusted and applied in La Jurada community in Yauco. The GIS tool was a good complementary tool to solve problems of location selection of small drinking water systems like EDSF system.

RESUMEN

Uno de los principales objetivos de las Metas de Desarrollo del Milenio es reducir a la mitad la proporción de población sin acceso sostenible a agua potable y saneamiento básico. En 2007, el 97% de la población de Puerto Rico utilizaba sistemas mejorados de agua potable a través de la Autoridad de Acueductos y Alcantarillados, mientras que 125,130 personas de la zona rural, no tenían acceso a sistemas mejorados de agua potable. Esta situación ha intensificado los esfuerzos para innovar o mejorar las tecnologías para el tratamiento de agua potable, con efluentes de mejor calidad y particularmente con tecnologías que se ajustan a las condiciones ambientales, económicas y sociales de las comunidades rurales.

Este estudio contribuye a la producción sostenible de agua potable en las comunidades rurales de Puerto Rico, asegurando agua potable con bajo riesgo sanitario la cual cumpla con la reglamentación bacteriológica vigente para este país, utilizando comunidades con problemas de agua potable. La evaluación del EDSF fue usada como una opción sostenible para resolver el problema de agua potable. Se desarrolló una estrategia para encontrar el mejor sitio donde localizar el sistema EDSF usando GIS.

La identificación y el ordenamiento de las comunidades, basados en los problemas de agua potable fue realizada usando el método de matriz de evaluación. El primer paso fue identificar las variables relacionadas con el problema de agua potable, las cuales reciben valores cuantitativos de acuerdo a la incidencia positiva o negativa con el problema. La comunidad Jurada en Yauco, Puerto Rico, fue la comunidad que obtuvo la calificación más alta basado en el

nivel de calificación. Esta comunidad tiene un sistema de abastecimiento de agua sin tratamiento donde el agua es tomada de una pequeña fuente de agua y suministrada a la comunidad y de acuerdo a la información bacteriológica, la calidad de agua no cumple con la regulación de agua potable.

El sistema EDSF es una buena alternativa tecnológica para comunidades rurales de Puerto Rico en términos de parámetros fisicoquímicos y bacteriológicos, ya que cumplen con la regulación. Sin embargo, es necesario mejorar la dosificación de cloro para alcanzar la concentración óptima de cloro residual.

El análisis de decisión multicriterios fue una herramienta usada para encontrar el mejor lugar donde el sistema EDSF puede ser instalado, dado que trabaja a gravedad, asegurando la sostenibilidad in términos económicos, sociales y ambientales. Esta estrategia fue probada inicialmente en la comunidad de Las Piedras en San Germán y posteriormente fue ajustada y aplicada en la comunidad de La Jurada en Yauco. Esta estrategia complementada con la herramienta de GIS fue un buen recurso para resolver problemas de selección de sitio para pequeños sistemas de agua como el EDSF, porque ayudó a encontrar las áreas donde el EDSF podría ser localizado.

"To my son Juan Martin, my mother Luz Marina,
my father Fernando, my sister Brenda and
my love Johnny, for their unconditional support,
guidance and infinity love"

ACKNOWLEDGMENTS

First of all, I want to thank God for his guidance and care. I also want to thank my advisor, Dr. Sangchul Hwang, for giving me the opportunity of completing this work, for his understanding, for his enthusiastic supervision, and his unconditional assistance, which contributed to my academic growth. Without his help, this thesis would not have been possible to make. I would also like to express my appreciation to the committee members, Professors Ismael Pagán Trinidad and Jorge Rivera Santos.

I greatly appreciate the economical and logistical support of University of Puerto Rico at Mayaguez the Chancellor's Office, the Department of Civil Engineering and Surveying, and the Environmental Protection Agency (EPA) through the Shaw Group, Inc..

I am very grateful to all my friends from Puerto Rico and Colombia who made my staying in Puerto Rico enjoyable: María de Lourdes and her family, Perla, Zalleris, Nelson, and especially my dear friends Imy and María Fernanda for listening to me, and for their unselfish friendship and help. I am also grateful to my friends Julián, Andrés, Viviana, and Paula, because and despite of the distance, our friendship is always alive. I would also like to thank my uncle Jorge, because he is an inspiring example to follow up.

I am forever indebted to my parents Luz Marina, Fernando, and my sister Brenda, for their continued support –emotional and moral-, faith in my capabilities, constant encouragement and

infinite love. I want to dedicate this work to my inspiration, Juan Martin, for his love, company, and patience.

Lastly, and most importantly, I wish to thank Johnny for his understanding, endless patience, help, motivation, unconditional love and encouragement when it was urgently needed. This is the starting point to fulfill our dreams.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

No. Title Page

LIST OF ABBREVIATIONS

ASCE	-	American Society of Civil Engineers
AWWA	-	American Water Works Association
EDFS	-	Experimental Drum Filtration System
EPA	-	Environmental Protection Agency
EQB	-	Environmental Quality Board
GIS	-	Geographic Information Systems
GPS	-	Global Position System
HPC	-	Heterotrophic Plate Count
IRC	-	International Water and Sanitation Center
IESWTR	-	Interim Enhanced Surface Water Treatment Rule
MCDA	-	Multi Criteria Decision Analysis
MCDM	-	Multi Criteria Decision Method
MDG	-	Millennium Development Goals
NPDWR	-	National Primary Drinking Water Regulation
PAHO	-	Pan American Health Organization
PRASA	-	Puerto Rico Aqueduct and Sewer Authority
RF	-	Rapid Filtration
SAW	-	Simple Additive Weighting
SDWA	-	Safe Drinking Water Act
SDWTR	-	Surface Drinking Water Treatment Rule
SSF	-	Slow Sand Filtration
TCR	-	Total Coliform Rule
THB	-	Total Heterotrophic Bacteria
UNICEF	-	The United Nations Children's Foundation
WHO	-	World Health Organization

1. INTRODUCTION

The main objective of Millennium Development Goals (MDG) is to eradicate the extreme poverty in its many dimensions: income poverty, hunger, disease, lack of adequate shelter, and exclusion, while promoting gender equality, education, and environmental sustainability. To achieve MDG, it is necessary not to lose sight of the basic human rights: the rights of each person on the planet to health, education, shelter, and security as pledged in the Universal Declaration of Human Rights and the UN Millennium Declaration (UN Millennium Project, 2005).

Through MDG the World has pledged to reduce by half the proportion of people without sustainable access to safe drinking water and basic sanitation in order to fulfill the seventh goal: "To half, by 2015, the proportion of people without sustainable access to safe drinking-water and basic sanitation". Achieving the MDG drinking water and sanitation target poses two major challenges: a rapid pace of urbanization, which requires a major effort even to keep up the current coverage levels, and huge backlog of rural people unserved with safe drinking water and sanitation, which calls for an intensive mobilization of resources to reduce the vast coverage gap between urban and rural populations (WHO/UNICEF, 2006).

For this reason, the investigations have been intensified towards innovation or improvement technologies for drinking water treatment, with effluents of better quality and particularly in technologies that conform to environmental, economic and social conditions in rural communities.

1.1 *Justification*

Access to safe drinking-water is essential to health, a basic human right and a component of effective policy for health protection. Nearly 1.8 million people die every year due to diarrheal diseases (including cholera) in developing countries, 90% of which are children under five years old. Approximately 88% of these diseases are attributed to unsafe water supply, inadequate sanitation and poor hygiene practices. In fact, about 1.1 billion of the world population does not use drinking water from improved sources; 84% of the population without access to an improved source of drinking water lives in rural areas, while 2.6 billion people lack basic sanitation (WHO/UNICEF, 2006). An estimated 94% of the diarrheal burden of disease is attributable to the environment, and associated with risk factors such as unsafe drinking water, lack of sanitation and poor hygiene (Prüss-Üstün and Corvalán, 2006). With improved water supply the diarrhea morbidity rate is reduced by 6% and with improved sanitation by 32% (WHO/UNICEF, 2006).

In 2007, 97% and 55% of the Puerto Rico's population used improved drinking water and adequate sanitation of PR Aqueduct and Sewer Authority (PRASA), respectively. 5.6% of Puerto Rico's population lives in rural areas (U.S. CENSUS BUREAU, 2000), of which 125,130 people do not have access to improved drinking water and adequate sanitation. Moreover, there are others who have improved drinking water who still do not have an adequate sanitation system. In rural areas of Puerto Rico, 94.2% of the population has on-site sanitation systems, but only 5.8% have access to improved sanitation facilities (PAHO/WHO, 2001).

One of the major problems of the supply systems in rural communities is that during the rainy season the river and stream levels rise of turbidity and other parameters, which makes that water quality deteriorate and increases the risk of diseases associated with water supply in rural communities. This risk is even more dangerous when many of these communities do not have treatment systems and water collected goes directly to their homes.

These data shows that some small communities, especially in rural areas of Puerto Rico, require further attention in terms of water supply and sanitation. In this regard, a huge effort is required to link water supply and sanitation planning and intervention with sustainable technical solutions in order to control and avoid diseases related to unsafe drinking water and inadequate sanitation.

This study contributes to the production of sustainable drinking water to rural communities of Puerto Rico, ensuring drinking water with low sanitary risk and water that meets drinking water bacteriological standards, through the selection of communities with drinking water problems, the evaluation of Experimental Drum Sand Filtration (EDSF) system, and the development of strategy to find the best location for EDSF system using Geographical Information Systems (GIS).

1.2 Objectives

This study was conducted to develop a decision support tool to improve drinking water quality and supply in Non-PRASA rural communities in Puerto Rico. Initially, the communities with drinking water problems were identified, the feasibility of implementation of the EDSF system was tested, and a strategy was developed to select the location of the EDSF system identified in communities.

The specific objectives were to:

- Identify the rural communities with urgent need of improved water quality and supply using Geographic Information System (GIS);

- Assess the performance of the EDSF at a field site in a Non-PRASA community as a candidate engineering technology which can help to solve the issues of water quality and supply; and

- Develop a strategy by mean of a GIS tool to find the optimum places, where the EDFS can be installed in rural communities of Puerto Rico.

2. LITERATURE REVIEW

This study aims to provide a decision support tool to ensure water quality and supply in rural areas of Puerto Rico, accompanied by the development of a strategy to select the communities with water quality problems and to find the optimum place where the EDSF system can be installed, using GIS techniques. The following presents the literature review that supports this research.

2.1 Status of water supply and sanitation (Global, Caribbean, and Puerto Rico)

The need to provide adequate water supply and sanitation to communities mainly in rural areas and developing countries for minimizing unsafe drinking water and inadequate sanitation related diseases is among the MGD. The seventh goal of MGD was proposed to reduce by half the proportion of people without sustainable access to safe drinking water and sanitation (WHO/UNICEF, 2006).

According to the report of Joint Monitoring Programme for Water Supply and Sanitation, in 2004 (WHO/UNICEF, 2006) over 1.1 billion of the World's population do not use drinking water from improved source (Figure 1), 84% of the population without access to an improved source of drinking water live in rural areas. Near 181 million people, between 1990 and 2004, were connected to improved drinking water systems, however, it is necessary for approximately 275 million people to be connected to improved drinking water systems to achieve the goals.

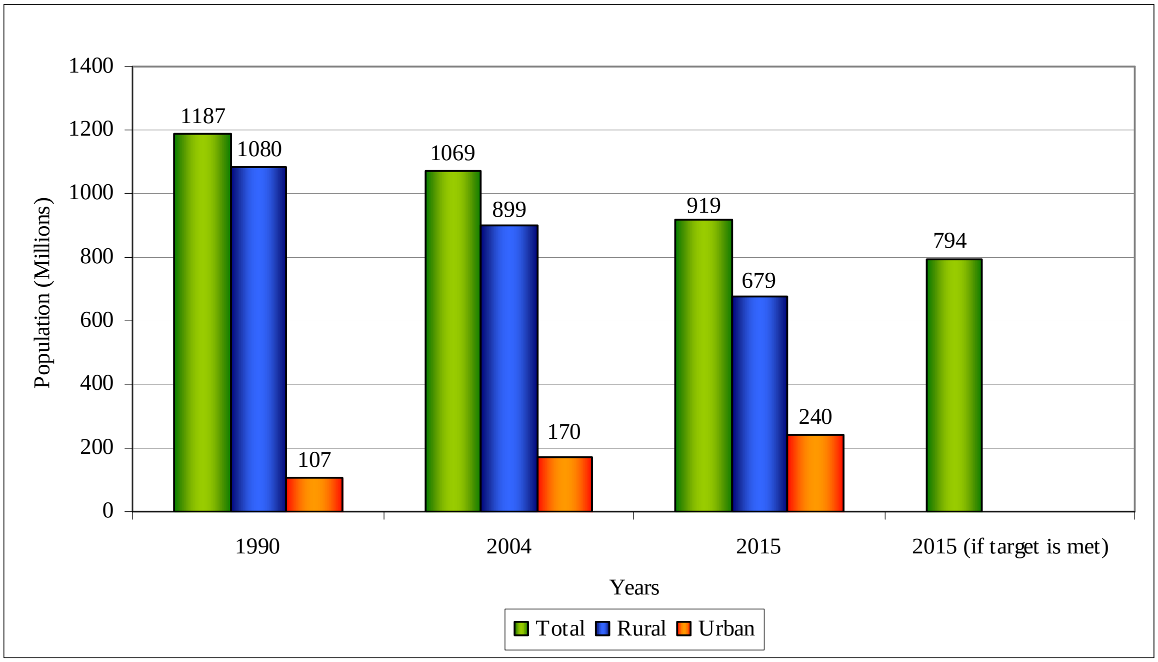

Figure 1. World Population Without An Improved Drinking Water Source.
(Source: WHO/UNICEF, 2006)

The access to improved water sources is significantly higher in urban than in rural areas (Figure 1). In rural areas the coverage of improved source remains unacceptably low. Urban drinking water coverage remained the same from 1990 to 2004 at 95%, whereas in rural areas coverage increased to 73% in 2004 from 64% in 1990. In 27 developing countries, less than 50% of the rural populations have access to improved drinking water (WHO/UNICEF, 2006).

The global coverage rate of 59% reached in 2004 for sanitation means that 611 million people in urban areas, and a staggering 2 billion in rural areas do not have access to improved sanitation. In rural areas, coverage with improved sanitation facilities rose from 26% in 1990 to just 39% in 2004. If that trend continues, coverage will rise to only 49% by 2015. In other words, about a half of the rural population will still be without basic sanitation in 2015 (Figure 2).

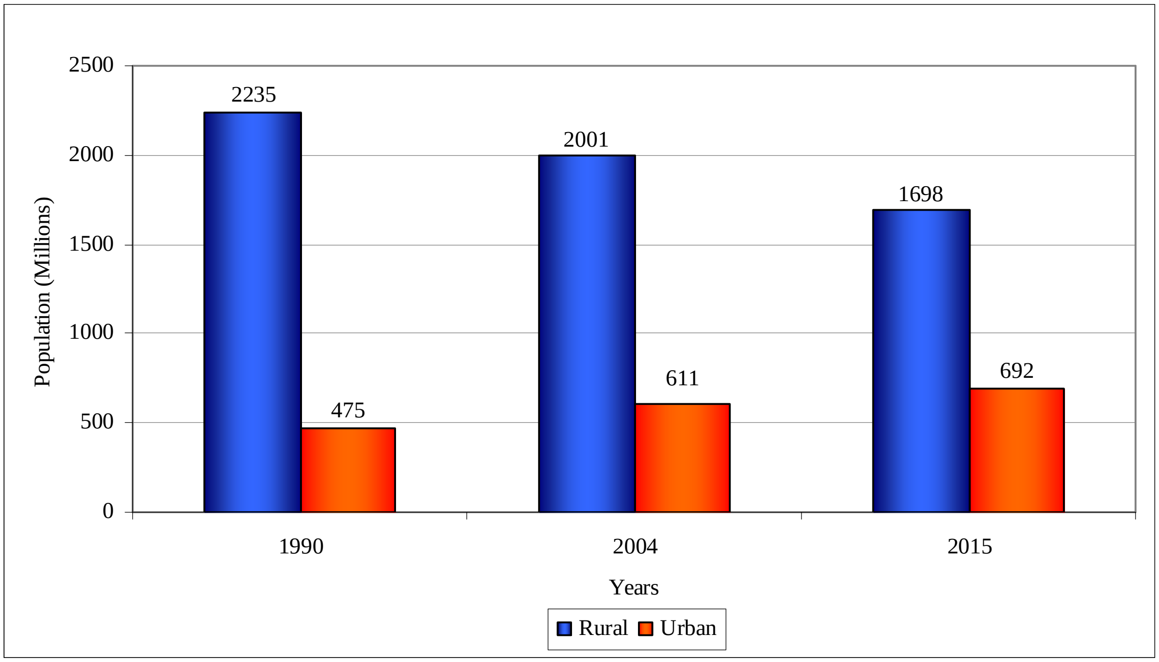

Figure 2. World Population Without To An Improved Sanitation.
(Source: WHO/UNICEF, 2006)

In the Caribbean, 77% and 37% of urban and rural populations, respectively, had access to improved drinking water, whereas 20% of the urban and 44% of the rural population did not have access to basic sanitation (WHO/UNICEF, 2006).

In the urban areas of the Caribbean in 2004, 77% of people were served with conventional aqueduct or improved drinking water, but only 36% in rural areas were served. 39% of people in rural areas were served with no conventional drinking water systems resulting a large number of these people did not have improved drinking water systems (Figure 3) (PAHO, 2001).

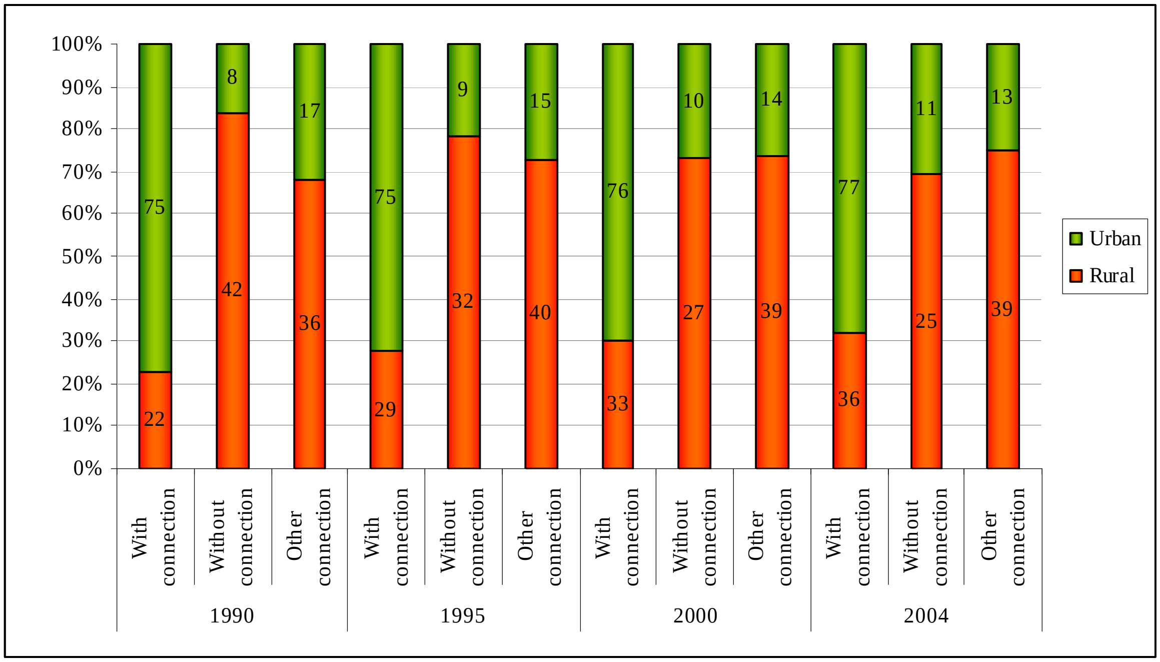

Figure 3. Coverage Of Improved Drinking Water Systems In Caribbean.
(Source: PAHO, 2001)

As shown in the Figure 4, the status of the sanitation in the Caribbean rural communities is very different from that in the urban areas. In 2004, the population without connection reaches 44% (in rural communities), whereas the percentage of population that lives in urban areas without connection to sanitation is 13% (PAHO, 2001).

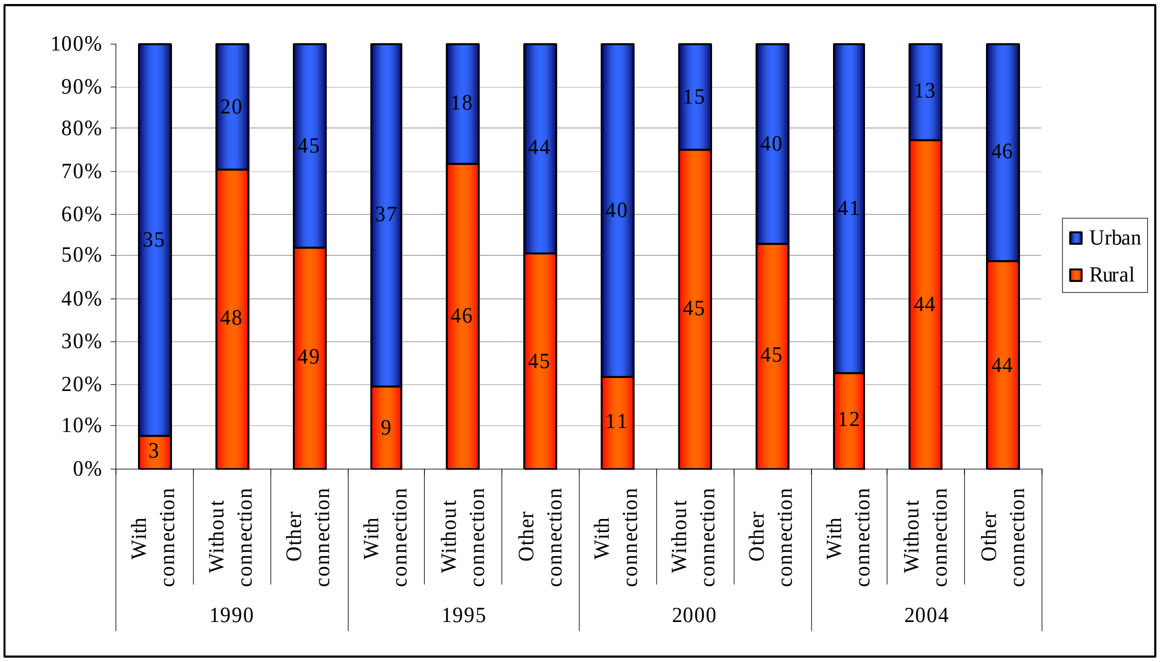

Figure 4. Coverage Of Improved Sanitation In Caribbean.
(Source: PAHO, 2001)

In Puerto Rico, all urban households are connected to PRASA. However, 3% of the population does not have safe drinking water supply (Torres, 2008). Non-PRASA systems are the community drinking water systems that are not connected to the Puerto Rico Aqueduct and Sewer Authority (PRASA). There are 286 Non-PRASA drinking water systems (Figure 5). The majority of Non-PRASA systems (59.1%) are located in the center of the Island (PRASA, 2007). 61.2% of Non-PRASA systems are supplied by groundwater and 38.8% by surface water (PRASA, 2007). Approximately 96% of these systems do not use filtration (Torres, 2008), but 78% have disinfection treatment; however, near of 95% of them do not meet the potable water bacteriological standards (Sodeberg, 2008).

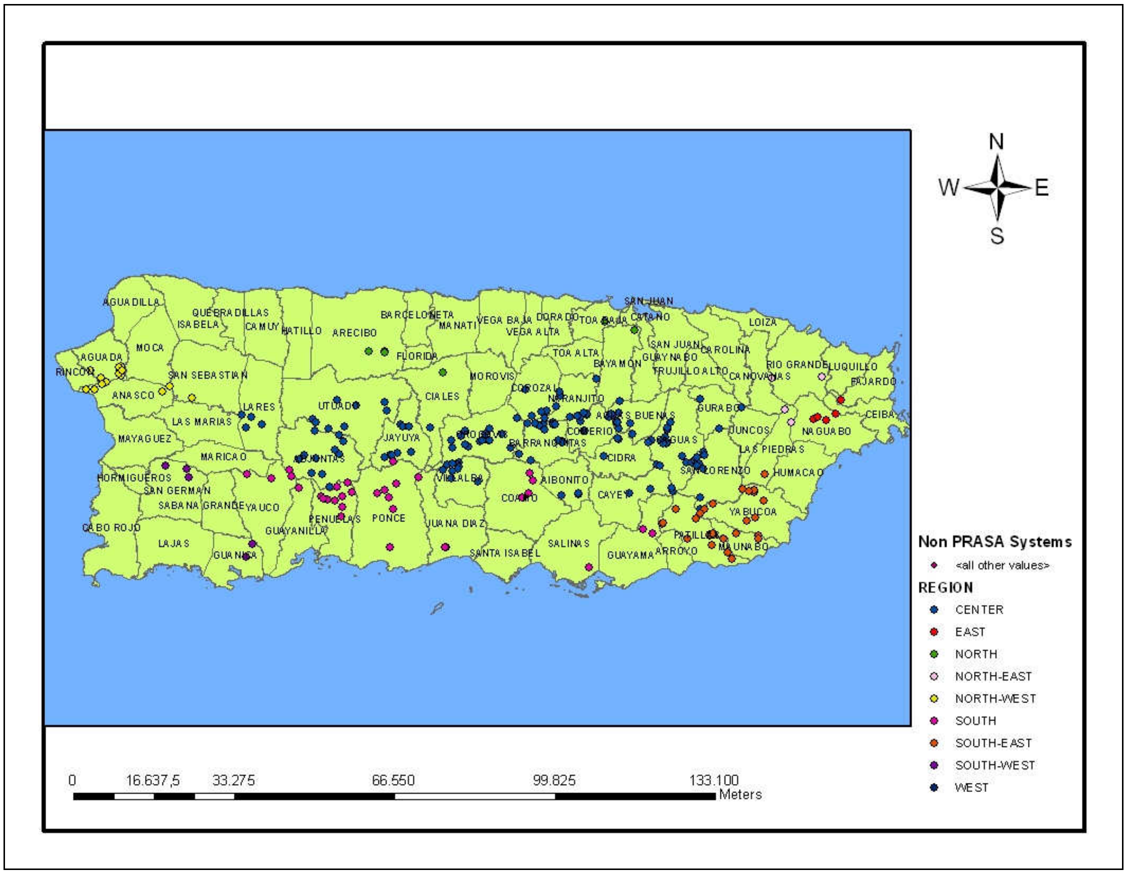

Figure 5. Location Of Non-PRASA Systems.
(Source: PRASA, 2007)

In 2000 (Figure 6), 100% of the population living in urban areas had access to any type of sanitation facility; 59.8% was served by sewer systems, while 40.2% used on site sanitation. Although 94.2% of rural community populations had on-site sanitation, only 5.8% had improved sanitation facilities (PAHO/WHO, 2001). It is important to point out that on-site sanitation without improved sanitation facilities are potential sources of surface and groundwater pollution through surface and groundwater transport mechanism. Considering the intense rainfall patterns in Puerto Rico, this constitute are major health threat.

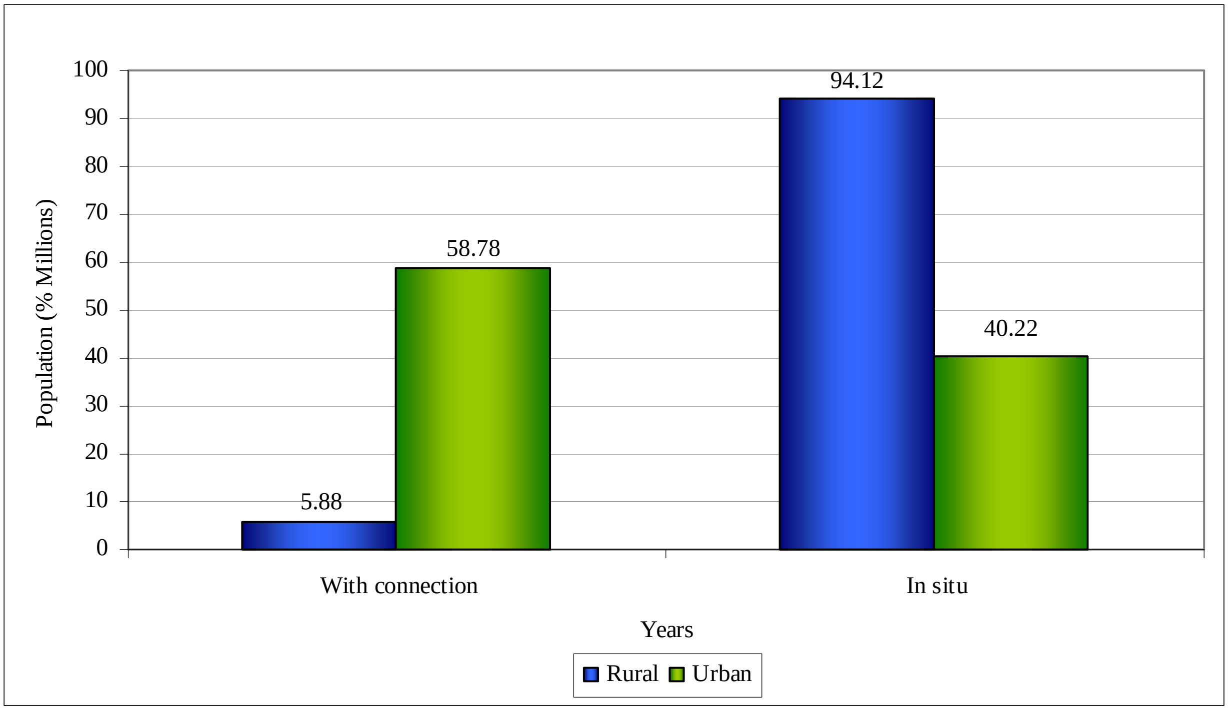

Figure 6. Coverage Of Basic Sanitation In Puerto Rico.
Source: PAHO, 2001

2.2 *Impacts of poor water quality on health and safety*

EPA defined safe water as water that does not contain harmful bacteria, toxic materials or chemicals. Water may have taste and odor problems, color and certain mineral problems, but it still be considered safe for drinking. They also defined potable water as the water satisfactory for drinking, cooking, and other uses. Improved drinking water sources are defined by WHO in terms of the types of technology and levels of services that are more likely to provide safe water than unimproved technologies.

Health hazards and risk factors related to water, sanitation and hygiene are of a composite nature (Table 1). Various determining aspects may need to be taken into consideration, including (Fewtrell, 2007):

Table 1. Diseases Related To Unsafe Water, Sanitation And Hygiene.

DISEASE OR RISK	FRACTION [a]	TRANSMISSIONS ROUTES
Diarrhea	>25%	Transmissions routes are fecal-oral with food or water contaminated.
Intestinal nematode infection	>25%	Transmission occurs when infective eggs are ingested. The eggs may be found in uncooked food products contaminated with soil, faeces or wastewater
Trachoma	>25%	The disease is strongly related to lack of face washing, poor access to water supplies and lack of latrines.
Schistosomiasis	>25%	Transmission occurs through human contact with water containing free-swimming larval forms, penetrating skin.
Lymphatic Filariasis	>25%	This disease is caused by worms that live in the lymphatic system and whose larvae are transmitted by the bite of an infected mosquito.
Perianatal conditions	>5%	The exposures to environmental hazards such as unsafe water and inadequate sanitation constitute important risks to infant health, increasing the mortality rate for low-birth-weight and preterm infants
Malnutrition	>25%	Several infectious diseases associated with malnutrition, including diarrhoea and other diseases caused by intestinal parasites, are related to poor water, sanitation, hygiene and food safety.
Cancer	>5%	Stomach cancer is associated with Helicobacter pyloris infection and transmission may be facilitated by poor sanitation and crowding. Other risk factors for cancer include asbestos in drinking water.
Cardiovascular diseases	>5%	The low mineral content in drinking-water are suspected of being associated with cardiovascular diseases, but evidence is still being developed and debating.

[a]Fraction attributable to the environment
(Source: Prüss-Üstün and Corvalán, 2006)

- drinking-water is a medium that can transmit pathogens and toxic chemicals;
- the lack of services to provide access to safe drinking-water and adequate sanitation, and the lack of solid waste management services increases the risk of several diseases;
- the failure to apply integrated water resources management principles in the planning, design and operation of dams, irrigation schemes and other hydraulic projects may result in changes in water ecologies that lead to the proliferation of vectors of certain diseases (e.g. malaria, schistosomiasis, lymphatic filariasis, arbovirus infections);
- water-associated behaviors including, for example, personal and domestic hygiene, water contact patterns and unsafe use of built environments; and
- the management of aquatic ecosystems, which may increase or decrease disease risks.

Diarrheal diseases kill an estimated 1.8 million people each year (WHO, 2005). Among children under five years old in developing countries, diarrhea accounts for 17% of all deaths (United Nations, 2006). Oral rehydration therapy has dramatically decreased the mortality associated with diarrhea, but has had little effect on morbidity estimated to be approximately 4 billion cases per year (Kosek, 2003). With continued high attack rates, diarrheal disease is also an enormous economic burden, resulting in significant direct costs to the health sector and patients for treatment as well as in lost time at school, work and other productive activities (Mulligan, 2005).

An estimated 94% of the diarrheal burden of disease is attributable to environment and associated with risk factors such as unsafe drinking-water and poor sanitation and hygiene. Diarrheal diseases associated with a lack of access to safe drinking-water and inadequate sanitation result in nearly 1.7 million deaths annually. A large proportion of diarrheal diseases is caused by fecal-oral pathogens. In the case of infectious diarrhea, transmission routes are affected by interactions between physical infrastructure and human behaviors. Faecal pathogens are frequently transferred to the waterborne sewage system through flushing toilets, septic tanks or latrines, and these may subsequently contaminate surface waters and groundwater. Through these pathways, drinking-water, recreational water or food may be contaminated and cause diarrheal disease following ingestion (Prüss-Üstün and Corvalán, 2006). Improvements in drinking-water quality through household water treatment, such as chlorination at point of use, can lead to a reduction of diarrhea episodes by between 35% and 39% (WHO, 2004). Some interventions and effects on diseases related unsafe water are shown in Table 2.

Table 2. Relation Between Water And Sanitation Interventions And Diseases Control.

DISEASES	INTERVENTIONS				
	Water Quality	**Water Quantity**	**Personal and Domestic Hygiene**	**Wastewater Disposal**	**Excreta Disposal**
Diarrhea					
Viral	Medium	High	High	Negligible	Medium
Bacterial	High	High	High	Negligible	Medium
Protozoal	Low	High	High	Negligible	Medium
Poliomelitis and hepatitis A	Low	High	High	Negligible	Medium
Worm infections					
Ascariasis, trichuris	Low	Low	Low	Low	High
Hookworm	Low	Low	Low	Negligible	High
Pinworm, dwarf	Negligible	High	High	Negligible	High
tapeworm	Negligible	Low	Low	Negligible	High
Other tapeworms	Low	Low	Negligible	Low	High
Schistosomiasis	High	Negligible	Negligible	Negligible	Negligible
Guinea worm					
Other worms with aquatic hosts	Negligible	Negligible	Negligible	Negligible	Medium
Skin infections	Negligible	High	High	Negligible	Negligible
Eye infections	Low	High	High	Low	Low
Insect-transmitted diseases					
Malaria	Negligible	Negligible	Negligible	Low	Negligible
Urban yellow fever, dengue	Negligible	Negligible	Low	Medium	Negligible
Bancroftian filariasis	Negligible	Negligible	Negligible	High	High
Onchocerciasis	Negligible	Negligible	Negligible	Negligible	Negligible

(Source: AWWA, 1991)

The water supply and sanitation situation at the global, Caribbean, and local levels aforementioned, has contributed to the increasing numbers of studies related to low cost water treatment technologies for rural areas. In deciding how best to reduce the burden of diarrheal diseases (both in developed and developing countries), one of the key needs is to make a quantitative assessment of the health impact of promoting household water treatment and safe storage relative to the impact of providing improved community water sources (Natch et al., 2006).

2.3 *Technologies for drinking water treatment*

When the objective of water treatment is to provide safe drinking water, then we need to select technologies that are not only the best available, but those that will meet local and national quality standards. The primary goals of a water treatment plant for over a century have remained practically the same: namely, to produce water that is biologically and chemically safe, appealing to the consumer, and noncorrosive and nonscaling.

Water treatment concepts underlying those used today were developed in Europe during the 1700s (Hutchins, 2004). Many older plants in the United States were equipped with slow sand filters. In the mid 1890s, the Louisville Water Company introduced the technologies of coagulation with rapid sand filtration. The first application of chlorine in potable water was introduced in the 1830s for taste and odor control. At that time diseases were thought to be spread by odors. Chlorination was first introduced on a practical scale in 1908 and then became a common practice (Cheremisinoff, 2002).

The contaminants in water are removed by physical, chemical, and biological means. The individual methods usually are classified as physical, chemical, and biological unit process. Although these operations and processes occur in a variety of combinations in treatment systems, it has been found advantageous to study their scientific basis separately because the principles involved do not change (Tchobanoglous, 2002).

The physical units operations are treatment methods in which the application of physical forces predominate. Because most of these methods evolved directly from man's first observations of nature, they were the first to be used for water and wastewater treatment; screening, mixing, flocculation, sedimentation, flotation, filtration and gas transfer. The chemical unit processes are treatment methods in which the removal or conversion of contaminants is brought about by the addition of chemicals or by other chemical reactions. Coagulation, precipitation, adsorption, and disinfection are the most common examples used in water and wastewater treatment. The biological unit processes are treatment methods in which the removal of contaminants is brought about by biological activity (Tchobanoglous, 2002). A summary of most common drinking water treatment processes is shown in Table 3.

Table 3. Most Common Drinking Water Treatment Processes.

WATER QUALITY PARAMETER	PROCESS COMPONENT
Turbidity – particulate reduction	Filtration ▪ Rapid sand – conventional Coagulation Flocculation ▪ Clarification Plain settling Plate settlers Solids contact Dissolved air flotation Filtration ▪ Rapid sand – direct mode Coagulation/flocculation Filtration Slow sand filtration ▪ Diatomaceous earth filtration ▪ Membrane filtration Ultrafiltration Nanofiltration Reverse osmosis
Bacteria, viruses, cyst removal	Partial reduction – filtration (above) Inactivation – disinfection

Table 3. Continued

WATER QUALITY PARAMETER	PROCESS COMPONENT
Bacteria, viruses, cyst removal	▪ Chlorine ▪ Chloramine ▪ Chlorine dioxide ▪ Ozone ▪ UV
Color	Coagulation/rapid sand filtration Adsorption ▪ Granular activated carbon (GAC) media ▪ Powdered activated carbon (PAC) addition ▪ Synthetic resins (ion exchange) Oxidation ▪ Ozone ▪ Chlorine ▪ Potassium permanganate ▪ Chlorine dioxide Nanofiltration
Taste and color control	Oxidation ▪ Ozone ▪ Chlorine ▪ Chlorine dioxide ▪ Potassium permanganate BAC adsorption
Volatile organic reduction	Air stripping ▪ GAC adsorption ▪ Combination of the above
Disinfection product by control	Precursor reduction ▪ Enhanced coagulation ▪ GAC adsorption ▪ Biologically activated carbon (BAC) media – preozonation ▪ Nanofiltration Product by removal ▪ GAC adsorption ▪ Air stripping (partial)
Iron, manganese reduction/sequestering	Filtration of precipitators formed by preoxidation ▪ Sand and/or anthracite media ▪ Green sand media ▪ Proprietary media Polyphosphate sequestering agent
Hardness reduction	Lime softening ▪ Ion exchange ▪ Nanofiltration

Table 3. Continued

WATER QUALITY PARAMETER	PROCESS COMPONENT
Inorganic, organic chemical reduction	Ion exchange Biologically activated carbon media Adsorption Reverse osmosis
Corrosion control	Post-treatment ▪ pH adjustment ▪ Inhibitors

(Source: AWWA/ASCE, 2005)

Selection of potential sites for a new water treatment plant must take into consideration a number of factors. Some of the principal ones are:

- Proximity of plant site to the source of water and to customers being served.
- Consideration of water transmission requirements to interconnect the plant to the source water and the water distribution system.
- Proximity of plant site to ultimate treatment waste disposal location.
- Environmental and land use concerns.
- Subsurface and geotechnical considerations.
- Land availability, cost, and zoning.
- Storage requirements at plant site for raw water supply.
- Compatibility with surrounding existing and planned developments.
- Potential for flooding and stormwater handling requirements.
- Availability of utilities (power, natural gas, sewer, telephone).
- Site topography and accessibility.
- Vulnerability to security risks and natural disasters (AWWA/ASCE, 2005).

2.4 *Filtration*

Filtration is the removal of particulates and thus some contaminants by water flowing through a porous media. Filtration is considered to be the most likely and practical treatment process or technology to be used for removing suspended particles and turbidity from a drinking water supply. Federal and state laws require all surface water systems and systems under the influence of surface water to filter their water.

As far as it is known, the first instance of filtration as a means of water treatment dated from 1804, when John Gibb designed and built an experimental slow sand filter for his bleachery in Paisley, Scotland, and sold the surplus treated water to the public at a half penny per gallon. He and others improved on the practical details and in 1829 the method was first adopted for a public supply when James Simpson constructed an installation to treat the water supplied by the Chelsea Water Company in London. In 1885 the first mechanical filters were installed in the USA, and in 1899 automatic pressure filters were first patented in England. The most convincing proof of the effectiveness of water filtration was provided in 1892 by the experience gained in two neighboring cities, Hamburg and Altona (Huisman et al., 1974).

Filtration methods include slow sand filtration (SSF) and rapid filtration (RF), diatomaceous earth filtration, direct filtration, membrane filtration, bag filtration, and cartridge filtration. The filtration methods typically use natural filtration media (e.g., granulated media particles, such as carbon, garnet, or sand, alone or in combination) (EPA, 2003). Filters also may be divided into two types: pressure and gravity. Pressure filters consist of closed vessels (usually steed shells) containing beds of sand or of other granular material through which water is forced under pressure. A gravity filter consists essentially of an open-top box, usually made of concrete, drained at the bottom, and partly filled with a filtering medium (Huisman et al., 1974).

There are typical operational differences between SSF and RF units. Filtration rates are around 50 to 150 times lower for SSF. Flow retention periods are about 30 to 90 times longer for SSF. The surface of the SSF units is usually scraped at the end of the filter runs, whereas RF units are cleaned by backwashing. These differences are originated from the most relevant and distinctive feature of SSF: its biological life. The water treatment in SSF is the result of a combination of physicochemical and biological mechanisms that interact in a complex way (Galvis, 1999).

Slow sand filtration is a method of passing water slowly through a bed of media (normally native sand) allowing physical, chemical, and biological treatment processes to clean the water. During its passage the particulate impurities are brought into contact with the surface sand grains and held position there (Huisman et al., 1974). According to the Surface Water Treatment Rule under the Safe Drinking Water Act (SDWA), many small systems could meet their regulatory filtration obligations with the simple slow sand filters. Because slow sand filters with disinfection have not been used extensively, they are classified as “new” technology in the current literature. Slow sand filters are most attractive for smaller systems with high quality raw water, specifically, water which comes from a protected surface water supply, has previously received only chlorination as a treatment, contains less than 10 NTU, and has no color problems. Although their operational simplicity makes them very suitable for small plants, slow sand filters are also applicable for medium to large plants (EPA, 1991).

The removal of suspended particles within a filter is considered to involve at least two separate and distinct steps: First, the transport of suspended particles to the immediate vicinity of the solid-liquid interface presented by the filter: and second, the attachment of particles to this surface (Yao et al., 1971). On the surface of the sand there is a thin slimy mat of material, largely organic in origin, known as the *Schumtzdecke,* which can also provides some removal. (AWWA, 1991). When a suspended particle following a streamline of the flow may come in contact with the collector by virtue of its own size; this transport process is interception. The second process consists of the path of the particle influenced by the combined effects of the buoyant weight of the particle and the fluid drag on the particle, this transport process is called sedimentation. Finally, a particle in suspension is subject to random bombardment by molecules of the suspending medium, resulting in the well-known Brownian movement of the particle. The term diffusion is used to describe mass transport by this process. The transport model assumes that a single spherical particle of the filter media is unaffected by its neighbors and is fixed in space in the flowing suspension (Figure 7) (Yao et al., 1971). The general design criteria for slow sand filters include criteria such as design period, period of operation, filtration rate, filter bed units, depth and sand media specification, as shown in Table 4.

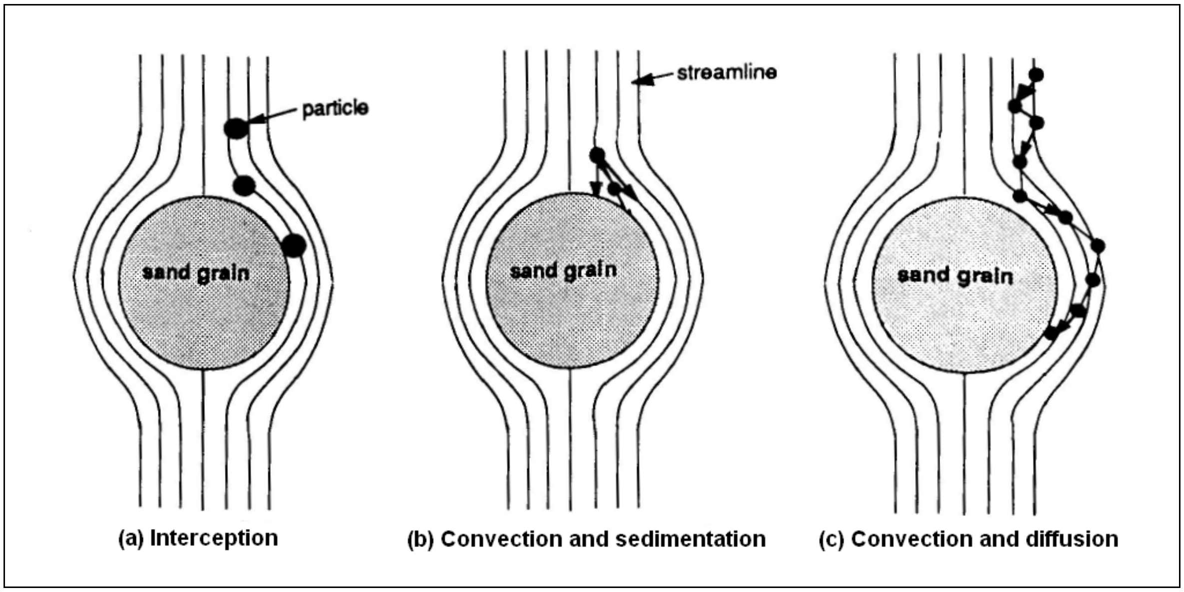

Figure 7. Basic Transports Mechanisms In Water Filtration.
(Source: AWWA, 1991)

Table 4. General Design Criteria For Slow Sand Filters.

CRITERIA	TEN STATE STANDARS (TSS)	IRC* MANUAL
Design Period	---	10 – 15 years
Period of Operation	---	24 hr/d
Filtration Rate	0.08 – 0.24 m/hr (0.03 to 0.10 gpm/ft^2)	0.1 to 0.2 m/hr (0.04 to 0.08 gpm/ft^2)
Filter Bed Units	2 minimun	2 minimun
Filter Bed Depth	≥ 80 cm (30 in)	50-90 cm (18-35 in)
Sand Media Specification Effective Size Uniformity Coefficient	 0.30 – 0.45 mm ≤ 2.5	 0.15 - 0.30 mm < 3 – 5

(Source: Fox et al., 1994)
*IRC: International Water and Sanitation Center.

The rapid sand filter, which is similar in some ways to slow sand filter, is one of the most widely used filtration units. The major difference is in the principle of operation is the speed or rate at which water passes through the media. Some significant differences exist in construction, control, and operation between slow sand filters and rapid sand filters. Because of the construction and operation of the rapid sand filtration with its higher filtration, the land area needed to filter the same quantity of water is reduced. Usually 2 to 3 ft deep, the filter media is supported by approximately 1 ft of gravel. The media may be fine sand or a combination of sand, anthracite coal, and coal (dual-multimedia filter). Water is applied to a rapid sand filter at a rate of 1.5 to gal/min/ft2 of filter media surface. Generally, raw water turbidity is not that high. However, even if raw water turbidity values exceed 1000 TU, properly operated rapid sand filters can produce filtered water with turbidity well under 0.5 TU. The time the filter is in operation between cleanings (filter runs) usually lasts from 12 to 72 h, depending on the quality of the raw water. To clean the filter media, it is necessary to carry out a backwashing of the rapid sand filter. The backwashing consists of passing treated water backwards (upwards) through the filter media and agitating the top of the media (Spellman, 2008).

2.5 *Regulatory Overview*

In 1974, the U.S. Congress passed the SDWA to protect public health by regulating the nation's public drinking water supply. Before this date each state ran its own drinking water program and set standards that had be met at the local level. It also determined the authority that establishes acceptable or "safe" levels for known or suspected drinking water contaminants and that designs a national drinking water protection program (EPA, 2003).

EPA has set uniform nationwide minimum standards for drinking water by promulgating the National Primary Drinking Water Regulations (NPDWR) and Secondary Drinking Water Regulations (SDWR). NPDWR are legally enforceable standards that apply to public water systems. A summary of NPDWR relevant to the current study is shown in Table 5. These protect public health by limiting the levels of contaminants in drinking water. SDWR is a non-enforceable guideline regarding contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. EPA recommends secondary standards for water systems but does not require systems to comply.

Tabla 5. Summary EPA Primary Drinking Water Standards Relevant To The Current Study.

CONTAMINANT	MCL or TT (mg/L)	Potential health effects from exposure above MCL	Public health goal
pH	6.5 – 8.5		-
Turbidity	At no time can turbidity (cloudiness of water) go above 5 NTU; systems that filter must ensure that the turbidity go no higher than 1 NTU (0.5 NTU for conventional or direct filtration) in at least 95% of the daily samples in any month.	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (e.g., whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing micro-organisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	
Chlorine (as Cl_2)	Maximum Residual Disinfectant Level = 4.0	Eye/nose irritation; stomach discomfort	
Chlorine dioxide (as ClO_2)	Maximum Residual Disinfectant Level = 0.8	Anemia; infants & young children: nervous system effects	
DO	Concentration above 5 mg/L support aquatic life		
Heterotrophic Plate Count (HPC)	No more than 500 bacterial colonies per milliliter.		n/a

Tabla 5. Continued

CONTAMINANT	MCL or TT (mg/L)	Potential health effects from exposure above MCL	Public health goal
Total Coliforms (including fecal coliform and E. Coli)	No more than 5.0% samples total coliform-positive in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform- positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or *E. coli* if two consecutive TC-positive samples, and one is also positive for *E. Coli* fecal coliforms, system has an acute MCL violation.	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present.	Zero

(Source: EPA, 2001)

In 1989, under the SDWA, the Surface Water Treatment Rule (SWTR) and the Total Coliform Rule (TCR) were established. Combined, these two rules were intended to control pathogens in general. Puerto Rico is under the Surface Water Treatment Rules being a Commonwealth that belongs to the EPA Region II.

Water quality standards in Puerto Rico were promulgated in 1974. These standards assign the water usages for which the Puerto Rico's water resources quality must be maintained and preserved. A summary of Puerto Rico's drinking water quality standards is shown in Table 6.

Tabla 6. Water Quality Standards For Surface Water Allocated To Supply Clean Water.

CONTAMINANT	Standard Value
DO	>5.0 mg/L
Coliforms	The water's geometric average of a range representative of sample (at least 5 samples) taken sequentially, shall not exceed 10,000 colonies/100 mL of total coliforms or 200 colonies/mL of fecal coliforms. Less of 20% of the samples shall not exceed 4,000 colonies/100 mL of total coliforms.
pH	6.0 – 9.0
Turbidity	<50 NTU

(Source: EQB, 2003)

2.6 *Microbial Water Quality*

Securing the microbial safety of drinking-water supplies is based on the use of multiple barriers, from catchment to consumer, to prevent the contamination of drinking-water or to reduce contamination to levels not dangerous to health. In general terms, the greatest microbial risks are associated with ingestion of water that is contaminated with human or animal (including birds) faeces. Faeces can be a source of pathogenic bacteria, viruses, protozoa and coliforms (WHO, 2006). Drinking water of bacteriological quality is primarily determined by using "indicator organisms", whose presence indicates faecal contamination. The presence of the indicators is often a key in assessing potential public health risks due to pathogens and is used in drinking water quality regulations and guidelines in many countries (Wang et al., 2008).

The coliform group consists of several general bacteria belonging to the family Enterobacteriaceae. Traditionally, these bacteria included Escherichia, Citrobacter, Enterobacter and Klebsiella. However, using more modern taxonomical criteria, the group is heterogeneous and includes non-faecal lactose fermenting bacteria as well as other species which are rarely found in faeces but are capable of multiplication in water (WHO, 2006). Historically, the definition of the coliform group has been based on methods used for its detection rather than on the tenets of systematic bacteriology (APHA, 1991). An estimated removal of the coliforms when are passed through several barriers is shown in Figure 8.

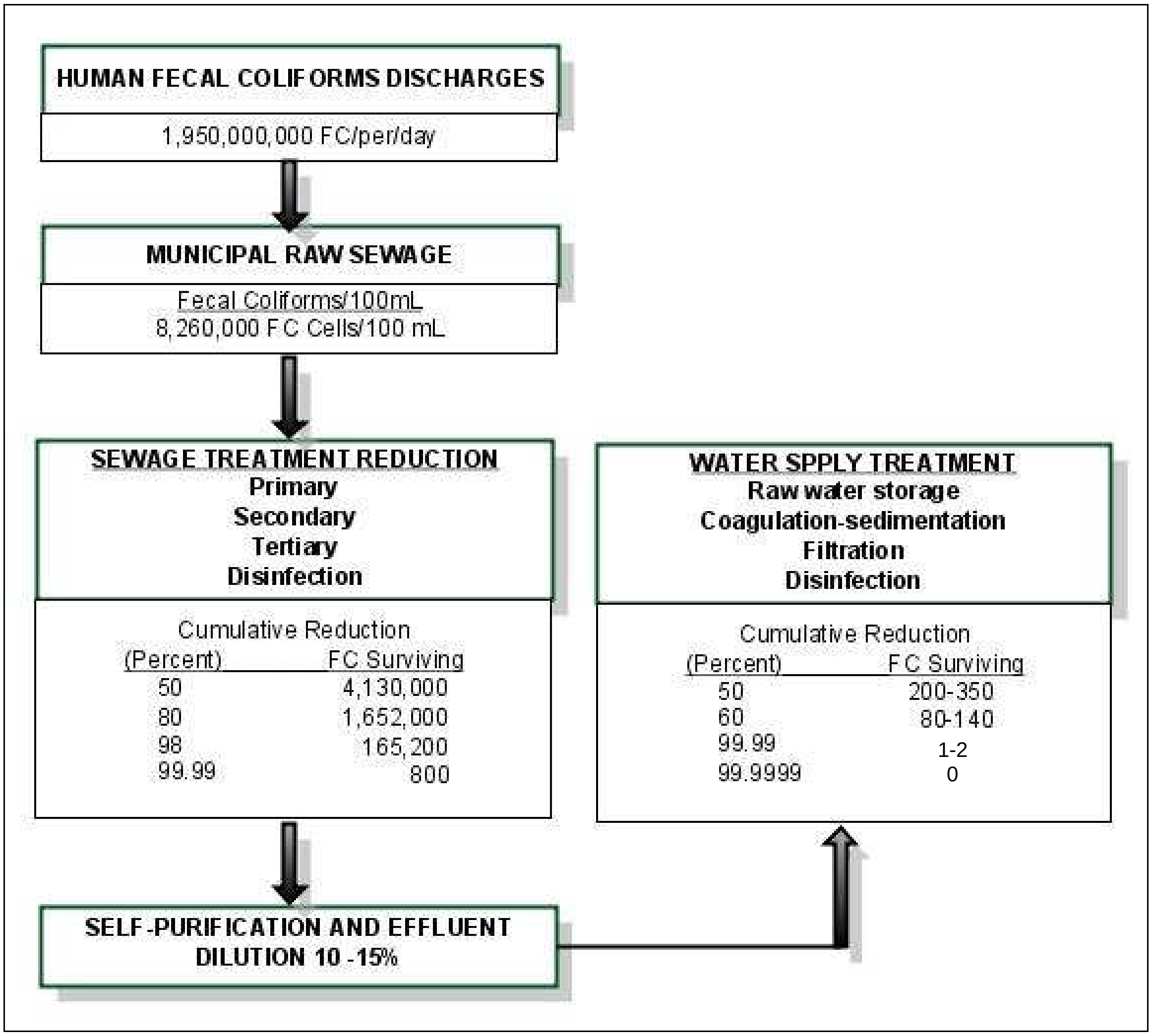

Figure 8. Fecal Coliforms Reduction by Unit Processes.
(Source: Wang et al., 2008)

Total coliforms include organisms that can survive and grow in water. As a disinfection indicator, the test for total coliforms is far slower and less reliable than direct measurement of disinfectant residual. In addition, total coliforms are far more sensitive to disinfection than are enteric viruses and protozoa (WHO, 2006).

In the EU Drinking Water Directive the term "faecal coliform" is used specifically to indicate coliforms of faecal origin, which it defines as those that are thermotolerant, i.e. capable of growth at 44°C. As not all thermotolerant coliforms are faecal in origin, they must be regarded as presumptive faecal coliforms. Therefore, the presence of E. coli, which is known to be exclusively faecal in origin, is usually also determined. Escherichia coli consist of up to 95% of the enterobacteria found in faeces (Gleson et al., 1997).

Heterotrophic bacteria present in a water supply can be a useful indicator of changes, such as increased microbial growth potential, increased biofilm activity, extended retention times or stagnation and a breakdown of integrity of the system. The numbers of heterotrophic bacteria present in a water supply may reflect the presence of large contact surfaces within the treatment system such as in-line filters. Heterotrophic plate count (HPC) measurement detects a wide spectrum of heterotrophic microorganisms, including bacteria and fungi (WHO, 2006).

Despite slight variations in the microbiological parameters used by different countries, similar plating procedures, most probable number methods (MPN), and membrane filtration (MF) techniques have been applied worldwide for coliform measurements (Gleson et al., 1997).

2.7 General GIS concepts and components

A Geographic Information System (GIS) is defined as "an organized collection of computer hardware, software, and geographic data designed to efficiently capture, store, update, manipulate, analyze, and display all forms of geographically referenced information" (EPA, 2000). A GIS provides a powerful analytical tool that can be used to create and link spatial and descriptive data for problem solving, spatial modeling, and to present the results in tables or maps.

The three main components of GIS are data, software, and hardware. The GIS structure is shown in the Figure 9.

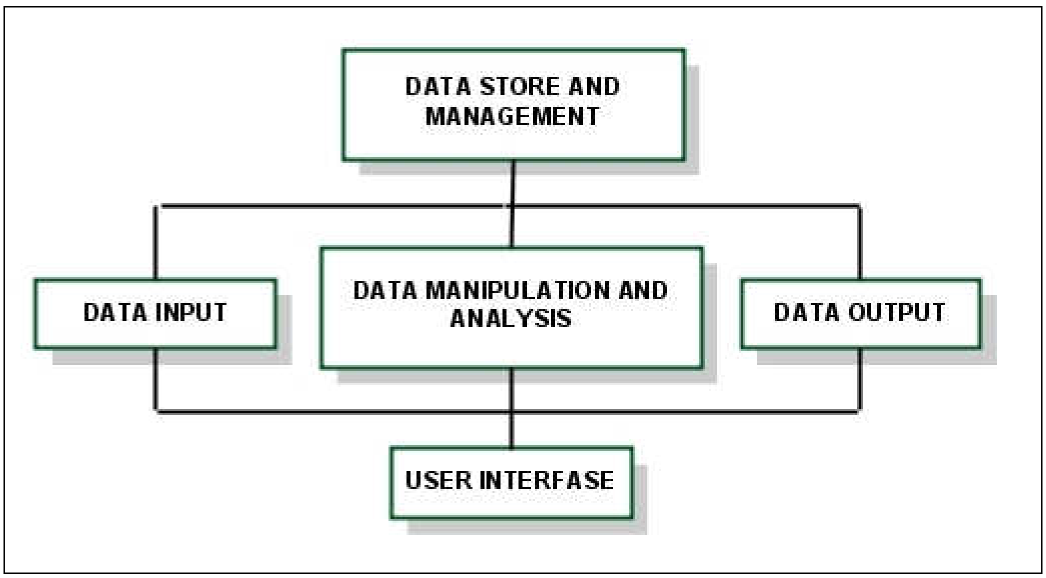

Figure 9. Structure Of GIS.
(Source: Malczewski, 1999)

Software: Software is a combination of computer programs, routines and symbolic languages that control and operate computer hardware, or manipulate data (EPA, 2000).

Hardware: Computer hardware used to support GIS is a highly variable part of the overall system. A fully functional GIS must contain hardware to support data input, output, storage, retrieval, display, and analysis. A typical GIS unit is composed of a computer workstation, printer, plotter, and digitizing table (EPA, 2000).

Data: There are two types of GIS data: input and output. Data input refers to the process of identifying and gathering the data required for a specific application. The process involves acquisition, reformatting, georeferencing, compiling, and documenting the data. The data input component converts data from their raw or existing form into one that can be used by a GIS. The data output component of GIS provides a way to see the data or information in the form of maps, tables, diagrams, and so on. The output subsystem displays to users the results of GIS data processing and analysis (Malczewski, 1999). GIS data are stored in two complementary forms: geographic and descriptive. Geographic data include the geometry of physical features. Descriptive data are typically stored in tabular forms and contain information about physical features and their relationships. The typical data sources are global positioning systems (GPS) data and remote-sensing data (EPA, 2000).

2.8 Use of multi-criteria decision analysis and GIS

Multi Criteria Decision Analysis (MCDA) have been developed to assist decision makers in either ranking a known set of alternatives for a problem or making a choice among this set while considering the conflicting criteria. This method uses information based on how the alternatives perform relative to each criterion and comparison of the criteria to assign ranks to the alternatives. In recent years, the integration of MCDA techniques with GIS has considerably advanced the map overlay approaches to site suitability analysis.

A GIS-based MCDA integrates, transform spatial data into a decision tools. It involves the utilization of geographical data, the decision maker's and the manipulation of data, and preferences to arrive at uni-dimensional values of alternatives. The data are processed during the decision-making process to obtain information about the decision situation. Decision problems that involve geographical data are referred to as geographical or spatial decision problems (Malczewski, 1999).

The basic strategy is to divide the decision problem into small, understandable parts; analyze each part; and integrate the parts in a logical manner to produce a meaningful solution. Much of the focus in developing the field of decision analysis has been in the area of operations research and management science, in which the decision-making process is of key importance for functions such as investment, logistics, and allocation of resources (Malczewski, 1999). The majority of the MCDA are integrated for six main components:

1. A goal or a set of clear goals.
2. A decision maker with their clear preferences with respect to the evaluation criteria.
3. A set of evaluation criteria.
4. The set of decision alternatives.
5. The set of uncontrollable variables identified (decision environment).
6. The outcomes associated with each alternative or decision criteria.

With MCDA techniques it is possible to identify a single most preferred option or to rank options. It can also identify a limited list with a number of options that subsequently will be evaluated, or to distinguish acceptable from unacceptable possibilities.

Any spatial decision problem can be structured into three major phases: intelligence, which examines the existence of a problem or the opportunity for change; design, which determines the alternatives and choice which decides the best alternative (Simon, 1960). The major elements (Figure 10) involved in spatial decision making process are discussed below.

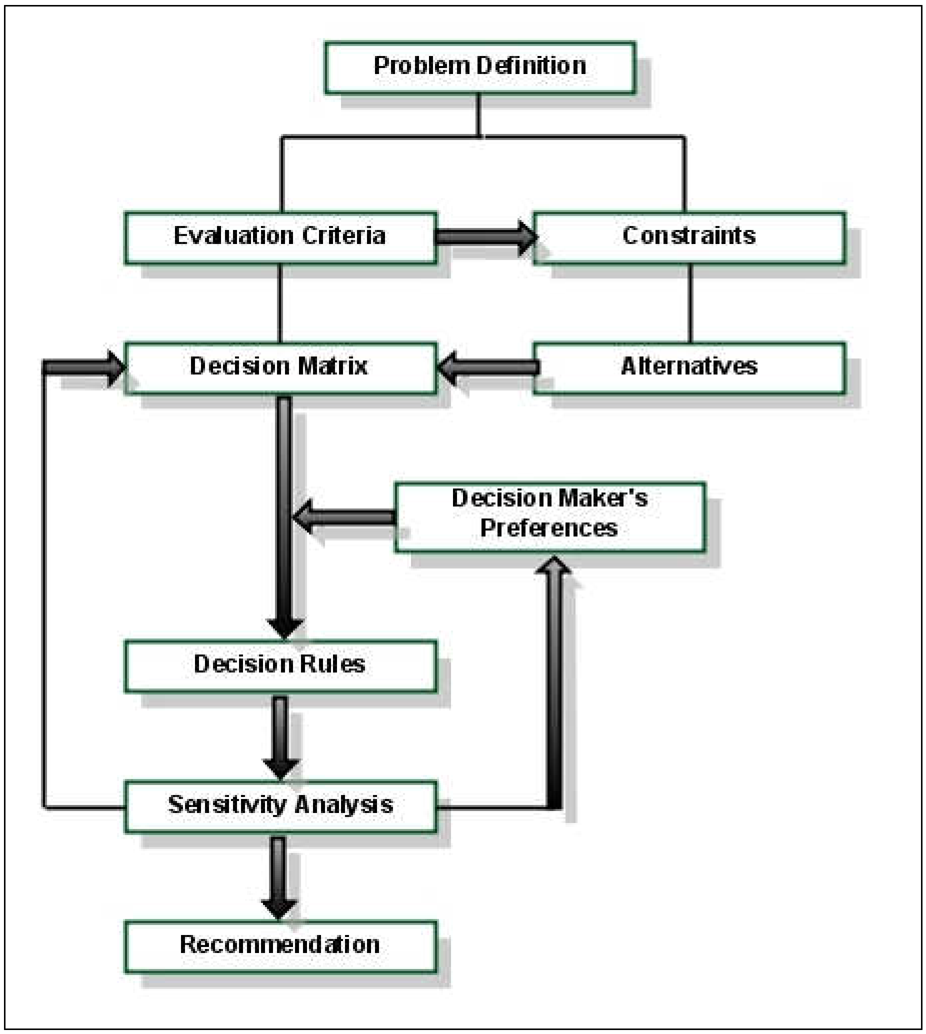

Figure 10. Main Steps Of The Spatial Multicriteria Decision Analysis.
(Source: Malczewski, 1999)

Problem definition: Any decision making process begins with the recognition and the definition of the problem. A decision problem is the difference between the desired and existing state of the real world. In this step the GIS capabilities for storage, management, manipulation, and analysis are used (Malczewski, 1999).

Evaluation criteria: This stage involves specifying a comprehensive set of objectives that reflects all concerns relevant to the decision problem and measures for achieving those objectives which are defined as attributes. Because the evaluation criteria are related to geographical entities and the relationships between them, they can be represented in the form of maps (Malczewski, 1999).

Criterion weights: A weight can be defined as a value assigned to an evaluation criterion which indicates its importance relative to other criteria under consideration. There are four different techniques when assigning the weights: Ranking, Pairwise Comparison, and Trade of Analysis Methods.

- *Ranking*: The method requires the decision maker to estimate weights on the basis of a predetermined scale. One of the simplest rating methods is based on allocating points ranging from 0 to 100, where 100 is assigned to the most important criterion and proportionally smaller weights are given to criteria lower in the order.

- *Pairwise comparison method:* The method involves pairwise comparisons to create a ratio matrix. It takes pairwise comparisons as input and produces relative weights as output.

- *Trade-off analysis method:* Trade-offs define unique set of weights that will allow all of the equally preferred alternatives in the trade-offs to get the same overall value/utility (Malczewski, 1999).

Decision Rules: The decision rule provides an ordering of all alternatives according to their performance with respect to the set of evaluation criteria and the decision problem depends on the selection of best outcome. There are different decision rules, which are shown below.

- *Simple Additive Weighting (SAW)*: The method is based on the weighted average. An evaluation score is calculated for each alternative by multiplying the scaled value given to the alternative of that attribute with the weights of relative importance directly assigned by the decision maker followed by the summing of the products for all criteria.

- *Analytical Hierarchy Process (AHP)*: The AHP developed by Saaty (1980) is a technique for analyzing and supporting decisions in which multiple and competing objectives are involved and multiple alternatives are available. The method is based on three principles: decomposition, comparative judgment and synthesis of priorities.

- *The value/utility function methods:* The method is based on multiattribute utility theory (Keeney et al, 1976).

- *Ideal point methods:* In the ideal point method the alternatives are ranked according to their separation from an ideal point. The ideal point is defined as the most desirable, weighted, hypothetical alternative (decision outcome).

- *Outranking methods:* This method is based on a pairwise comparison of alternatives.

- *Ordered Weight Average (OWA):* OWA is a weighted sum with ordered evaluation criteria. Thus, in addition to the criterion weights which are assigned to evaluation criteria to indicate their relative importance, order weights are used. The order weights are associated with the criterion values on the location by location basis.

- *Goal Programming:* It is a form of linear programming for multiple goals (evaluation criteria). Linear programming identifies the set of feasible solutions the point which optimizes a single objective, whereas goal programming determines the point that best satisfies the set of goals in the decision problem which aims to minimize the deviations from the goals.

- *Compromise Programming:* It is a method based on the displaced ideal concept which assumes that the choice among alternatives depends on the point that is used as a reference (Zeleny, 1982).

Sensitivity Analysis: Sensitivity analysis aims to identify the effects of changes in the inputs which are geographical data and the decision maker's preferences on the outputs, in other words, on the ranking of alternatives (Malczewski, 1999).

3. METHODOLOGY

The methodology implemented to accomplish the objectives of this research was divided into two phases. The first phase included 1) the identification of the Non-PRASA communities suffering from water quality problems in their water supply systems and consequently requiring urgent technical interventions, and 2) the development of a multi criteria analysis in order to identify the most suitable place for installing the EDSF system, using GIS. The second phase was devoted to the evaluation of the EDSF system in terms of its efficiency and practicability.

For the second phase, the experimental work was carried out in Rio Piedras community in San Germán and analyses were conducted both on-site and at the Environmental Engineering Laboratory at the University of Puerto Rico, Mayagüez. The laboratory is equipped with materials and equipment necessary to conduct the bacteriological analysis.

3.1 Identification of Non-PRASA communities with drinking water problems

The identification of the communities with drinking water supply problems that require an immediate intervention was carried out by defining the criteria that allow its classification from information consolidated through GIS. This classification will provide a ranking of priorities for those communities in which the EDFS system could be used as an alternative for drinking water treatment.

3.1.1 Identification of necessary data

In order to establish the current situation of the rural drinking water supply in Puerto Rico, it was necessary to collect reliable data and generate a database that contributes to describe this topic. Data included information on population, municipal boundaries, rivers and water streams, drinking water supply and wastewater treatment systems, Non-PRASA systems, topography, the incidence of health diseases and educational levels of the population.

3.1.2 Collection of data

The data was collected from several sources including public and private institutions (PR Department of Health, EPA, USGS, PRASA, and other sources). The some data were collected in a shapefile format, if the data was numeric, these were converted to a shapefile format. The very recent data collected from the First Rural (Non-PRASA) Community Water Supply and Sanitation Workshop, which our research groups hosted as the first step for the project. The main topics discussed in the workshop were (1) Perspective of rural (Non-PRASA) community water supply and sanitation, (2) Status of rural water supply and sanitation systems and (3) Public policies and best management practices. The data collected in the workshop were mainly to update the Non-PRASA inventory.

3.1.3 Creation of digital database

Once the aforementioned information had been collected, it was necessary to create a digital database using the software ArcMap as a tool for graphical representation and data analysis. The software ArcMap is a very useful tool and is able help generate the following types of maps: (1) the general water supply situation in Puerto Rico; (2) the general sanitation situation (3) the representation of the existing Non-PRASA systems and the rural areas (4) the selection criteria for localities with drinking water problems; and (5) the location selected for the implementation of a drinking water supply system for a specific case study.

3.1.4 Definition of study area

The area of interest under the current research is limited to the western part of Puerto Rico, including the following municipalities: Aguadilla, Isabela, Quebradillas, Camuy, Aguada, Moca, San Sebastián, Lares, Añasco, Rincón, Las Marías, Mayagüez, Maricao, Hormigueros, San Germán, Sabana Grande, Yauco, Cabo Rojo, Lajas, and Guánica. This area was selected because it is the second place around the country with most number of Non-PRASA systems, additionally, there is enough information available and its proximity to Mayagüez allowed us to verify the data at the field.

3.1.5 Selection of non- PRASA communities

After creating a digital database, selection of five communities with significant drinking water problems was carried out through an evaluation matrix method. The first step was identifying variables related to the problem, which received a quantitative weight value (between 1-10) according to the positive or negative incidence over water supply. The criteria were:

- *Population Density:* This criterion is useful for delineating the areas in Puerto Rico that can be classified as rural or urban according to the current population density defined by the Puerto Rico Planning Board. This institution indicates that the population density in a rural area must be lower than 2,500 hab/km^2 whereas the urban area has a population density that ranges between 2,500 and 3,000 hab/km^2. The Non-PRASA systems located in rural areas obtained the highest score according to the rank, which was 10 points, because this research was directed to rural zones of Puerto Rico that still have populations without access to water supply.

- *Type of Treatment:* PRASA carried out the diagnosis of each Non-PRASA system in Puerto Rico, in which information on the different components of each community system was collected. This criterion has been sub-divided into three types of treatment, which corresponds to the typical treatment systems that exist in Non-PRASA communities, such as: only disinfection, filtration and disinfection (with treatment) or without treatment. Due to the fact that the main objective of this stage of this research was to identify communities with serious problems of water supply, the highest score was allocated to those communities without access to any treatments. The variables and scores for each category include:
  - Without treatment = 10
  - Only disinfection = 5
  - Filtration and disinfection = 1

- *Status of system:* Within the diagnosis carried out by PRASA, it was included an analysis of the system's status, which refers to its functionality and physical condition. The variables and scores include:
  - Bad = 10
  - Average = 5
  - Good = 1

As it was proposed in the aforementioned criteria, the highest score was allocated to communities with water systems that were deteriorated and required an upgrade.

- *Bacteriological Quality:* The Health Department of Puerto Rico performs a periodical monitoring of the Non-PRASA systems in order to determine whether they are complying with their regulations. The information about compliance of the standards was included within the diagnosis reports prepared by PRASA. Variables and scores for this criteria are shown below:
  - Does not meet standard = 10
  - Meet standard = 1

  Those systems that do not meet the bacteriological standards received the highest score because they produced water of very low quality which would probably increase the incidence of water borne diseases in the population served. This indicates clearly that the water supply system must be upgraded.

- *Infant Mortality:* There is evidence that some components of the clean water can be the main cause of infant mortality. One example of this is the research conducted by Hafeman et al. (2007), in which there was a clear correlation between levels of arsenic contained in the clean water and the infant mortality rate in India. The lack of access to safe drinking water decreased the chances of infants and children survival by exposing them to waterborne diseases. Waterborne diseases such as diarrhea, cholera and typhoid take a heavy toll on the lives of infants and children in a developing country. It is, therefore, hypothesized that the higher the proportion of population of a district lacking access to safe drinking water, the higher the infant mortality in that district (Chaudhury et al., 2006). The aforementioned information is the main reason of why this research has included mortality rate as a meaningful criterion. Data on the infant mortality rate were provided by the Health Department of Puerto Rico and then digitalized in maps using GIS. The highest score was allocated to the municipality with a higher number of infant mortality events. Scores and variables for this criteria are as follows:

- More 16.5% (per 1000 infants) = 10
- Between 9.1% to 16.5% (per 1000 infants) = 5
- Less 9.1% (per 1000 infants) = 1

- *Cancer Rate Incidence:* Malignant neoplasm at several sites of the body have been associated with exposures to occupational and environmental risk factors. There are different risks factors that increase the incidence of various types of cancer, such as smoking, air pollution, exposure to carcinogenic chemicals, excessive exposure to UV rays, etc. However, one of the main factors related to water is the level of asbestos in it, because there has been found a clear relationship between this compound and different types of cancer (Prüss-Üstün and Corvalán, 2006). For this reason, it was necessary to include this criterion, using the statistical data provided by the Health Department of Puerto Rico. The scores and variables included are the following:
    - 0-200.5=1
    - 200.6-226.5=2
    - 226.6-243.7=3
    - 246.8-259.2=4
    - 258.3-298.9=5

The units of these data correspond to the number of new cases of all types of cancers for each 100,000 people. In the scoring it can be observed that the range have changed to 1 to 5, instead of 1 to 10 due to the data on the incidence of cancer have an important bias. This is because many people who suffer from cancer can probably migrate to another place in order to receive a better diagnosis and treatment at a better hospital. For this reason, the cancer figures of the municipalities where the illness was developed were weighted to a lesson extent.

- *Educational level:* The educational level of the population can have an impact on the sustainability of the drinking water supply systems because a higher educational level might increase people´s skills to run those treatment systems. The ranges shown below represent the percentage of people with a complete higher educational level (undergraduate). For this reason, scores were included as shown below:
  - 0.0-8.9 = 10
  - 9.0-10.8 = 8
  - 10.9–12.2 = 6
  - 12.3-14.8 = 4
  - 14.9-22.9 = 2

The final step in the identification of Non-PRASA communities with drinking water problems was to sum up the individual values in order to obtain a final ranking. Communities with high values were the ones which required an urgent intervention. Those with low values had the lowest priority, although all had called for proper attentions.

3.2 *Description of EDSF system*

The Experimental Drum Sand Filtration (EDSF) system consists of three 55-gallon steel drums with three different effective sizes of sand media (0.18mm, 0.55 mm and 1.10 mm), a pre-chlorinator installed at the inlet of the water operating with liquid chlorine, a tablet post-chlorinator assembled at the outlet of the drums and a 10 W solar panel was installed to power the electric panel programmed to actuate the valves in accordance to the electric logic (Figure 11) (Hwang, 2008). Table 7 shows the control logic for the actuated valves.

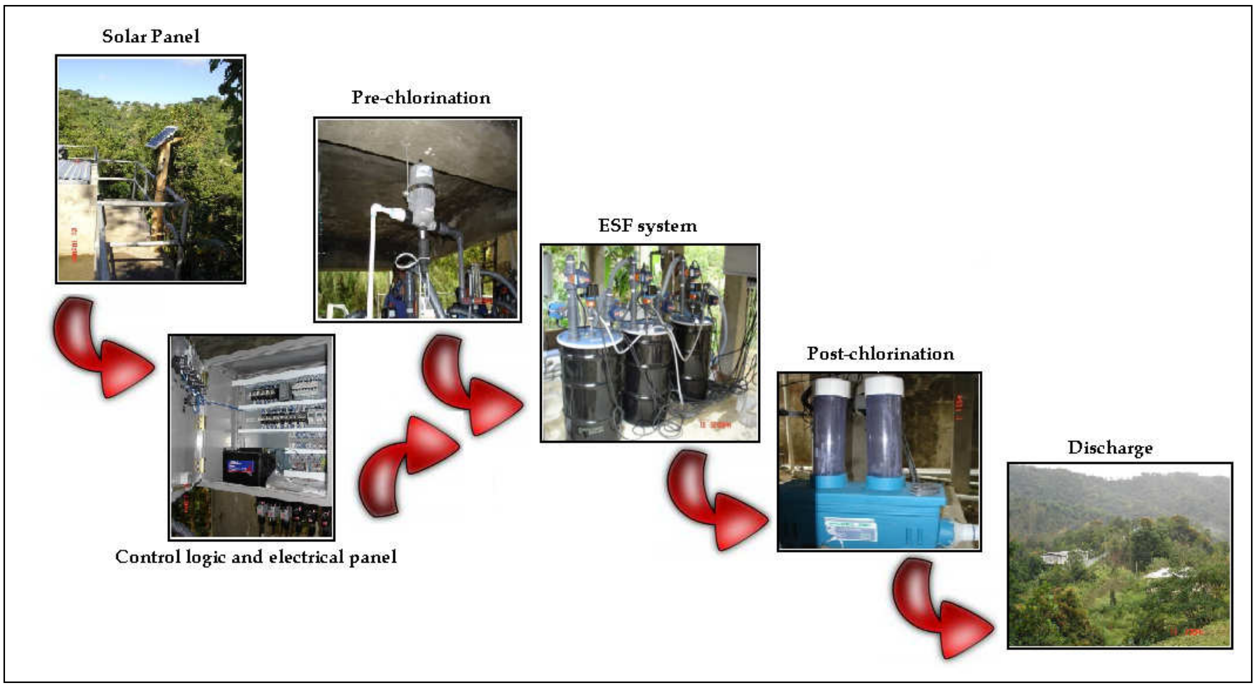

Figure 11. Main Components Of EDSF System.

Tabla 7. Control Logic Sequence Of The Valves.

Overall Control Logic

Valve Sequence	A1 3-way	A2 3-way	A3 BV	A4 BV	B1 3-way	B2 3-way	B3 BV	B4 BV	C1 3-way	C2 3-way	C3 BV	C4 BV	Time
A/B - on, C - BW	A	A	off	off	B	B	off	off	off	off	on	on	0000 Sun - 0006 Sun
A/B - on, C - off	A	A	off	off	B	B	off	off	off	off	off	off	0006 Sun - 0800 Tue
B/C - on, A - BW	off	off	on	on	A	A	off	off	B	B	off	off	0800 Tue - 0806 Tue
B/C - on, A - off	off	off	off	off	A	A	off	off	B	B	off	off	0806 Tue - 1600 Thur
C/A - on, B - BW	B	B	off	off	off	off	on	on	A	A	off	off	1600 Thur - 1606 Thur
C/A - on, B - off	B	B	off	off	off	off	off	off	A	A	off	off	1606 Thur - 0000 Sun

Filtering (1/2" 3-Way Valves) Control Logic

Valve Sequence	A1	A2	B1	B2	C1	C2	Time
A/B - on, C - off	A	A	B	B	off	off	0000 Sun - 0800 Tue
B/C - on, A - off	off	off	A	A	B	B	0800 Tue - 1600 Thur
C/A - on, B - off	B	B	off	off	A	A	1600 Thur - 0000 Sun

This system was developed by The Shaw Group, Inc, as contractors of the Environmental Protection Agency (EPA), to serve as a model to provide a practical solution to mitigate water quality problems faced by many rural communities in tropical environments. Initially, the EDSF system was tested at the EPA Test & Evaluation (T&E) Facility in Cincinnati, Ohio. Then the units were disassembled, and shipped to Puerto Rico to assess feasibility of using it as drinking water purification units for Non-PRASA communities in PR (Hwang, 2008).

The research activities with EDSF system were developed at the existing community-based water treatment facility in Las Piedras community, San Germán, PR, which receives raw water of the Caín River. This existing system is composed of a horizontal flow gravel filter and slow sand filter. The Department of Civil Engineering and Surveying of the University of Puerto Rico at Mayagüez designed, built, and started the operations of a water treatment plant in the rural community of Río Piedras, Caín Alto ward, in San Germán in 1997 (Cardona, 2001). This community was found to be one of the communities having a problem of chronic fecal contamination in their drinking water. Fecal contamination in the community's drinking water was confirmed through field studies (Conesa, 1991). The treatment plant constructed at the Rio Piedras Community, Caín Alto Ward, in San Germán (Figure 12), was one of the first efforts to introduce a small slow sand filtration technology in the Island.

Figure 12. EDSF System Location.

The assembly and installation of EDSF system was done on January 2008. The system was operating with a combination of two drums in series for 2 days. A backwashing activity was set to last 6 minutes controlled through valves programmed in accordance to electric logic and with a water production rate of 1 gpm. The EDSF system was fed with the effluent from a gravel filter which was one of the system components of the existing filtration system and the effluent from the EDSF units is discharged through a drain line.

3.3 *Physicochemical and Bacteriological Analyses*

Physicochemical and bacteriological samples were analyzed using methods typical of water treatment systems which are shown in Section 3.3.2 and analytical techniques used conformed to established procedures as defined by Standard Methods (AWWA/WEF, 1992). The sampling points, frequency, procedure and materials used are shown below.

3.3.1 Sampling and frequency

The present research was divided in two main sampling periods. Two week-long sampling and analysis events were performed to collect representative data encompassing the sequences of all three drum filters and backwashing event. In the first sampling week, the EDSF system was performed from May 17 to May 23, 2008, the volume of water to be treated was set at 1 gallon per minutes (gpm), and the drum filter operation was backwashed for 6 min and then stayed in stand-by mode, while other two filters ran in series for 2 days and 8 hours (Table 8). For the disinfection was used Dosmatic A30-4 mL injector , this equipment applied 0.1% sodium hypochlorite (NaOCl) solution at an injection ratio of 1:250 to the incoming raw water.

In the second sampling period was between December 14 and 21, 2009. The volume of water to be treated was changed to 1.5 gpm, and the sequences were changed also, especially for the backwashing events and the duration of drum usage was slightly modified. For this case, the drums (A and B), (B and C), and (C and A) were in operation for 1 day 23 hr, 2 days 2 hrs, and 2 days and 11 hours respectively (Table 8). After finding low residual chlorine concentrations at the sampling port No.2 during the previous week sampling, NaOCl concentration was doubled to 0.2 % and applied at the same 1:250 feeding ratio to the incoming

1.5 gpm raw water. It should be noted that NaOCl solution was made with a commercial 5.25% NaOCl solution by diluting it with the sand-filtered effluent from the existing facility.

Tabla 8. Operation Sequence Of EDSF Units During Sampling Periods.

Sampling Periods		Drums		
1 gmp	**1.5 gmp**	**A**	**B**	**C**
00:00 Sun - 00:06 Sun	15:00 Sun - 15:06 Sun	On	On	Backwash
00:06 Sun - 08:00 Tue	15:06 Sun - 14:00 Tue	On	On	Stand-by
08:00 Tue - 08:06 Tue	14:00 Tue - 14:06 Tue	Backwash	On	On
08:06 Tue - 16:00 Thu	14:06 Tue - 16:00 Thu	Stand-by	On	On
16:00 Thu - 16:06 Thu	16:00 Thu - 16:06 Thu	On	Backwash	On
16:06 Thu - 00:00 Sun	16:06 Thu - 15:00 Sun	On	Stand-by	On

During two periods, physicochemical parameters such as dissolved oxygen (DO), turbidity, pH, free and total chlorine concentration, and bacteriological parameters as fecal coliforms and heterotrophic bacteria were measured. Sampling points in the filtration system are identified in Figure 13. Also, samples in the source (river) and the pre-filter were collected and physicochemical and bacteriological parameters were measured.

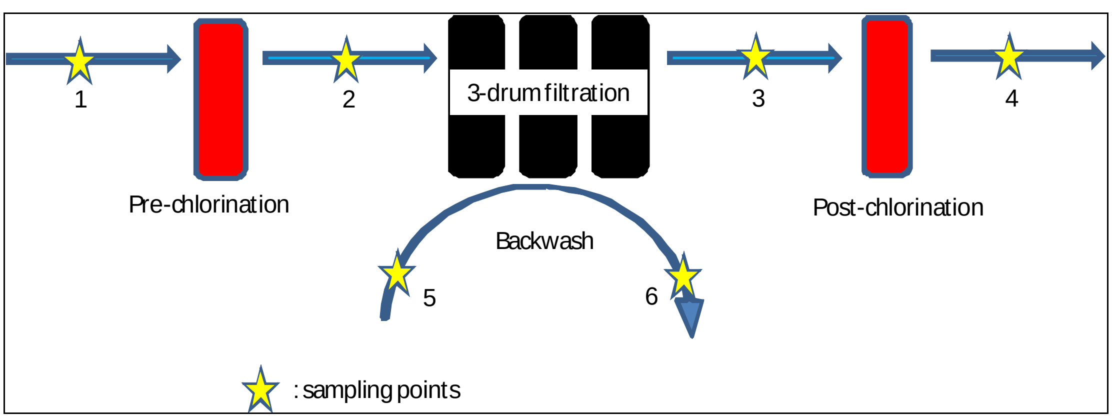

Figure 13. EDSF System Sampling Points.

Bacteriological samples were transported in container with ice at 1-4°C to the laboratory. The analysis was carried out within 24 hours of sample collection. To calculate the number of colonies to fecal coliforms and HPC, the following equation was used:

$$Colonies/100mL = \frac{number\ of\ colonies}{Volume\ of\ sample\ filtered\ (mL)} \qquad \text{(Eqn. 1)}$$

3.3.2 Procedure and materials

Physicochemical parameters were measured on-site with laboratory equipments that were brought to the site. The equipments used in the analysis were calibrated in the laboratory prior to the field measurements.

- *Physicochemical Parameters:* Residual chlorine concentrations were monitored with a HACH calorimetric method. The value of pH and dissolved oxygen concentration were monitored with Oakton pH/DO Meter 300 series and turbidity was measured with LaMotte 2020 Turbidometer. The equipment calibration was performed according to the manufacturer's specification for pH/DO meter and tubidometer.

- *Bacteriological Parameters:* Fecal coliform and HPC analysis were performed using the Standard Membrane Filter Procedure 9222 of Standard Methods for the Examination of Water and Wastewater (AWWA/WEF, 1992).

The method consisted basically of filtering a measured volume of water through a membrane composed of cellulose esters. A membrane was used to retain microorganisms on or near the surface of the membrane. The membrane was then aseptically transferred either to a differential solid agar selective for the organism sought or to an absorbent pad saturated with a suitable liquid medium. On incubation at a specific temperature for a specific time, growth occurred. It is assumed that the organisms retained by the membrane will form colonies with characteristic morphology and color depending on the medium used. These colonies can then be counted and also the number of organisms per 100 mL calculated (Wang et al., 2008). The incubation period for fecal coliform analysis was 24 hours to 45°C and HPC analysis was 72 hours to 35°C and the general procedure is shown in the Figure 14.

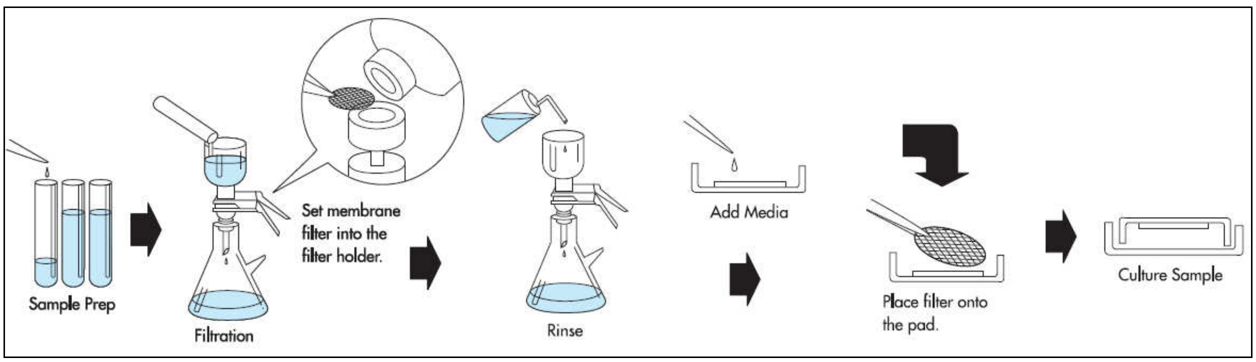

Figure 14. Filter Membrane Procedure.

The materials used were:

- *Glassware:* All glassware, working solution bottles, sample plastic bags, graduated cylinders, culture dishes, a filter membrane and filtration funnels were sterilized prior to use.

- *Filter membranes:* A Filter membrane used was mixed cellulose esters Gelman ® GN-6 Metricel ® Sterile Filter Membrane of 47 mm x 0.45µm. It is the most accepted filter media for microbiological analysis, and provides maximum recovery of organisms.

- *Filtration apparatus:* The filtration apparatus consisted of a seamless funnel fastened to a base by a locking device or held in place by a magnetic force or gravity. Prior to use, the funnel and base were wrapped separately and autoclaved.

- *Absorbent pads*: If absorbent pads are to be used, they should have at least the same diameter as the membrane, and be approximately 1 mm thick. They should be of high quality, be uniformly absorbent and be free from toxic substances which may prove inhibitory to bacterial growth. Prior to use, absorbent pads should be sterilized. In this research, pre-sterilized polystyrene dishes (50 x 11 mm) with absorbent cellulose pad of 47 mm were used.

- *Media:* Standard Methods (APHA, 1992) recommends that due to the need for uniformity, only dehydrated media should be used. Tryptic soy broth of Sigma-Aldrich Laboratory and Difco FC Broth Base of Becton, Laboratory were used for HPC and fecal Coliforms analyses, respectively.

3.4 *Implementation of MCDA for selection of the Drum Filtration Systems Location*

In most countries, the provision of potable water and the disposal of sewage products are undertaken by utility companies that are either publicly-or privately-owned. For operational reasons, they tend to enjoy a monopoly of service provision over country's region. The planning task of a typical water company can be viewed as the integration of three different areas:

- Hydrology –understanding the mechanisms by which the raw material is generated and modified;
- Engineering –the control and transformation of the raw material so as to meet demand by consumers;
- Economics –the costs associated with maintaining a supply to the consumer of acceptable quality, and the subsequent pricing of that supply to those consumers.

Although the water projects between rural and urban communities differ in their dimensions, their planning is similar. Each of the areas mentioned above are directly related to the system treatment and its location, meaning that the site's selection step by treatment system is fundamental. Any project of drinking water supply must have its goals clear for a good planning framework. The first element of planning must be the articulation of these objectives or goals, which will underpin the organization of policy or strategy.

In this research, the problem to be solved through MCDA methodology was to find the best place where the EDSF system could be installed to ensure the sustainability of water environment in Non-PRASA communities in Puerto Rico.

Initially, the methodology developed for selecting the location of the EDSF System was applied in the Las Piedras community, where the strategy was tested. Afterwards, the strategy was adjusted and applied to the Jurada community. The decision rule used in this study was Simple Additive Weighting (SAW) because if was compatible with weight methodology and provided the better solutions. Below are described each of the steps to be applied towards achieving the target, using methodologies MCDA and the GIS tool.

3.4.1 Collection of the geographical and spatial information

To start with the implementation of the methodology, it was necessary to have all the geographic information of the study site. First, all information was collected in a map format: hydrology, topography, land use, boundaries, and other related information. Subsequently, the coordinates of the source, the storage water tank and the households that integrate the community were taken using the GPS.

3.4.2 Identification of evaluation criteria

For selecting the system location, the criteria were as follow:

- *Topography:* For the location of a drinking water treatment, the topography plays a major role in minimizing the costs of the project, since there are significant differences between the provision of water by gravity and pumping. In this case, the water supply by gravity minimizes operational costs of the system. To delineate the topographical area that meets the objective of water supply by gravity, the houses located in the highest and lowest elevation were identified. With this information, the area that contained the sites with elevations enabling the provision of water by gravity was focused.

- *Proximity to rivers and streams:* The closeness of the drinking water systems to water sources may improve the effectiveness of the operation, because if there are quality problems in the intake which affect the operation of the system, they can be easily and quickly accessed for problem-solving.

- *Proximity to community:* The drinking water systems near communities improve the access to the installations facilitating the operation and maintenance activities.

- *Proximity to flood areas:* Locating the drinking water system away from flood areas will protect the system from catastrophic damage and degradation. The data of flood areas were obtained from FEMA.

- *Proximity to land slid areas:* Same as flood areas, the drinking water system must be located away from these areas. The delineation of land slid areas was carried out using FEMA information.

The criteria proximity to flood and land slide areas were restrictions, for this reason, if a specific alternative met the criteria topography and proximity to rivers or streams but was inside of flood or land slide areas, the alternative was rejected.

3.4.3 Assigning weight to evaluation criteria

To select the location of the EDSF System, the criterion used to assign weights or values was the rating method, since it is a simple method that integrates each of the criteria parameters. The points were assigned to each evaluation criteria in a range of 0 to 4, and were distributed as follows:

- *Topography:* the areas that meet the goal of providing water by gravity were assigned a score of 4.

- *Proximity to rivers and streams:* the areas near to the rivers and streams were assigned a score of 4.

- *Proximity to community:* the treatment systems near to the communities will facilitate operation and maintenance activities, since the access is easier. Scores were up to 4.

- *Proximity to flood areas:* the areas that are not within the flood area were assigned a score of 4.

- *Proximity to land slide areas:* in this evaluation criterion the scores were distributed as follows: area of highest susceptibility to landsliding (1), area of high susceptibility to landsliding (2), area of moderate susceptibility to landsliding (3) and area of low susceptibility to landsliding (4).

4. RESULTS AND DISCUSSION

The following part of this document presents the results of this study and then the discussion of each phase established in the methodology, which are aimed to meet the objectives defined for this research. First, the results of the selection matrix with the ranking of the main communities with drinking water problems are presented; second, the results of MCDA methodology for the identification of the EDSF system to the potential site are shown, and finally, assessment of EDSF system is presented.

4.1 Ranking of Non-PRASA communities with drinking water problems

Each variable described in the methodology was represented in the maps that allow visualizing them both individually and in groups. Figure 15 shows the delineation of the researched area (in purple), the urban settlements (in orange) and the Non-PRASA systems labeled with a ditched line in red color. One Non-PRASA system, out of 21 that were identified, was located within an urban area which was part of the study. Nearly 10,500 people have water served from Non-PRASA systems in the west part of Puerto Rico, that of which 31.3% are located in Aguada, 17.7% in Yauco, 16.9% in Añasco and 16.4% in San Germán.

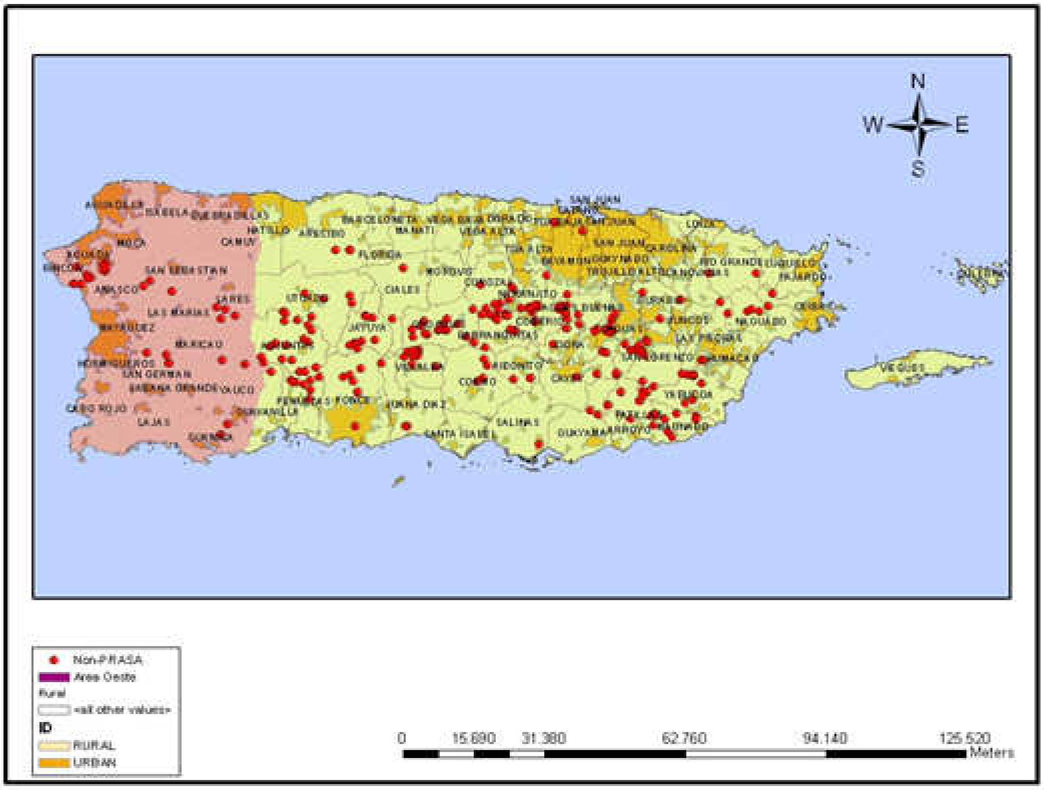

Figure 15. Location Of Non-PRASA Systems And Delineation Of Study, Rural and Urban Areas.

In relation to the bacteriological quality of each Non-PRASA system, Figure 16 shows the systems, in blue triangles, that did not comply with this regulation and the systems with disinfection, in red circles, did not comply with bacteriological standards. Approximately, 48% of the Non-PRASA systems that were part of the area under analysis did not comply with regulation. Among them, 22% did not have any type of treatment while 11% were in bad shape. It was also identified that 15% of the systems even with a treatment facility did not comply with the bacteriological water quality regulation.

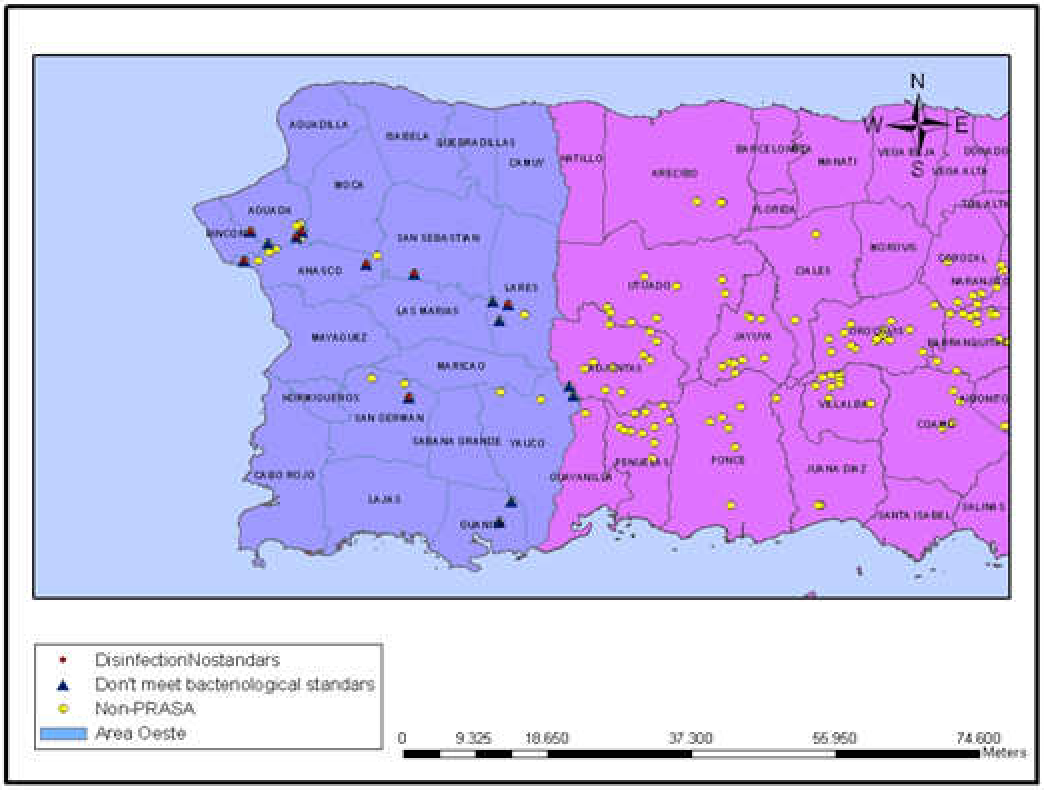

Figure 16. Bacteriological Quality And Type Of Treatment Of Non-PRASA Systems.

48% of the Non-PRASA systems of the researched area belonged to a group of municipalities with a very low incidence of child mortality, whereas 33% of them were part of the localities with the highest incidence of child mortality (Figure 17). Although the literature was clear regarding the relationship between mortality by diarrheal diseases and unsafe water quality, the variable infant mortality was not linked to the data of water quality problems in the rural areas of Puerto Rico.

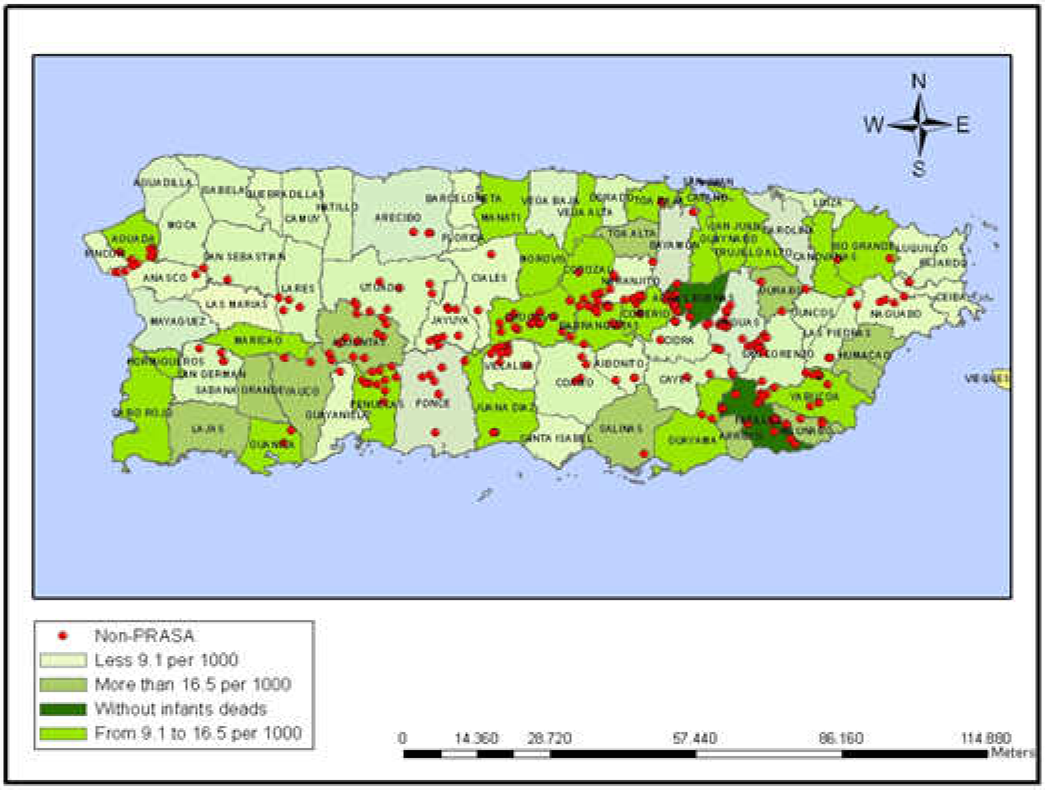

Figure 17. Infant Mortality In Puerto Rico.

When the rate of cancer incidence in Puerto Rico was analyzed, it could be concluded that municipalities with the higher rate corresponded to the main urban centers where the best health care institutions were located. In the area under the research, 52% of the Non-PRASA systems were located within municipalities where the rate of cancer incidence was part of the lowest rank (160.8 – 200.5) (Figure 18).

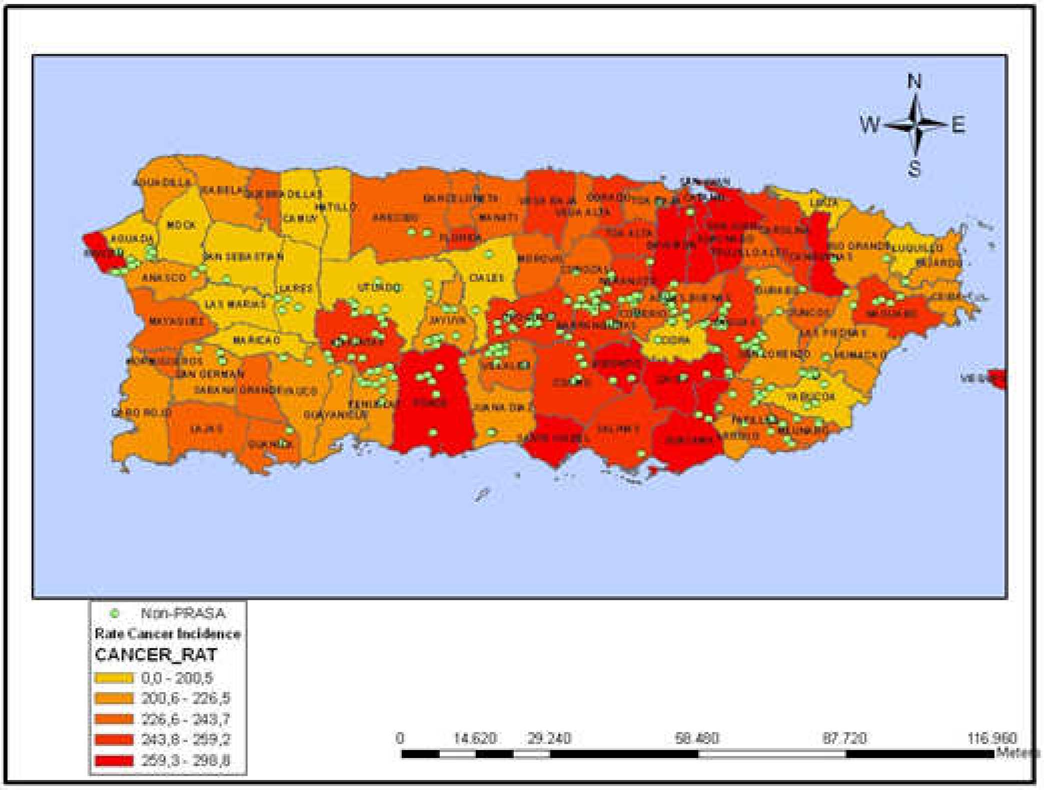

Figure 18. Rate Of Cancer Incidence In Puerto Rico.

48% of the Non-PRASA systems were located within municipalities where the range of people with higher education (undergraduate degree) varied between 9.0 and 10.8; only 19% of them were part of the municipalities with the highest rate of people that had completed undergraduate studies.

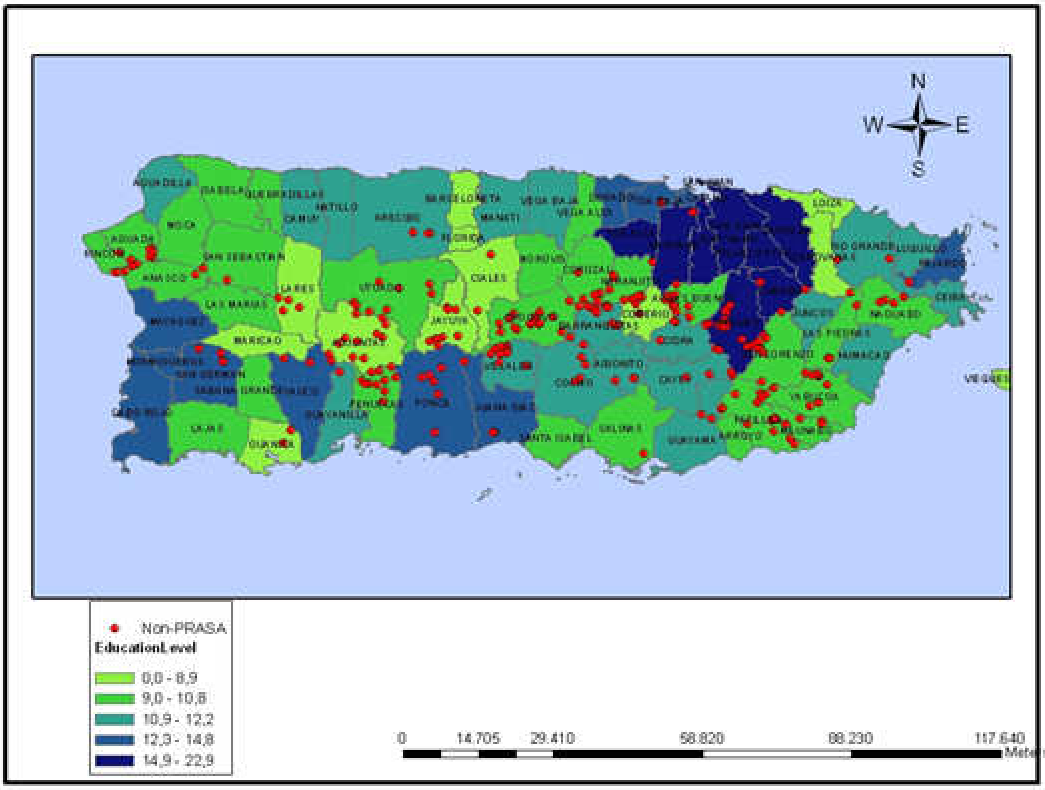

Figure 19. Education Level In Puerto Rico.

The selection matrix was fed up with each Non-PRASA system information and its variables and scores as shown in Table 8. The results of adding up the scores given were then ordered from the higher to the lower as shown in Table 9 and in this manner the systems were ranked according to the priority of intervention which was defined by its urgency.

Table 9. Non-PRASA Communities Selection Matrix.

AGUADA	RURAL	EDUCATION	CANCER	INFANT MORTALITY	TYPE OF TREAT.	THE SYST.	BACTERIOLOGICAL QUALITY	QUALIFICATION
Jaguey Chiquito	1	8	1	5	5	5	10	35
Cerro Gordo Arriba II	10	8	1	5	5	1	10	40
Cerro Gordo	1	8	1	5	5	5	1	26
Comunidad Aislada Desarrollo	10	8	1	5	5	5	10	44
Comunidad Cerro Gordo El Parque	10	8	1	5	5	0	10	39
Quebrada Larga	10	8	1	5	5	1	1	31
Proyecto Aguas	10	8	1	5	5	1	1	31
ANASCO								
Caguabo	10	8	2	1	5	5	10	41
Comunidad Hatillo	10	8	2	1	5	5	1	32
Pinales Arriba	10	8	2	1	5	5	1	32
Corcobada	10	8	2	1	5	5	10	41
SAN SEBASTIAN								
Sonador II	10	8	1	1	5	1	1	27
Acueducto Rural Guacio Inc	10	8	1	1	5	1	10	36
LARES								
Vega Acevedo	10	10	1	1	5	1	10	38
Com. Las Cuarenta	10	10	1	1	5	5	1	33
Lucas Lugo	10	10	1	1	10	5	10	47
SAN GERMAN								
Rosario Penon	10	4	2	1	5	5	1	28
Comunidad Mendez	10	4	2	1	10	5	1	33
Periche	10	4	2	1	5	5	10	37
Comunidad RioPiedras	10	4	2	1	1	1	10	29
YAUCO								
B. Rubias	10	4	2	10	5	5	1	37
Guaraguao	10	4	2	10	1	1	1	29
La Montana	10	4	2	10	1	10	10	47
La Jurada	10	4	2	10	10	10	10	56
Mongote	10	4	2	10	10	0	1	37
MARICAO								
Aceitunas	10	10	1	5	10	5	1	42
Llanadas	10	10	1	5	10	10	1	47

Table 10. Non-PRASA Systems Ranked According To Priority Of Intervention.

No.	NON-PRASA SYSTEM	MUNICIPALITY	RANK
1	La Jurada	Yauco	1
2	Lucas Lugo	Lares	2
3	Llanadas	Maricao	2
4	La Montana	Yauco	2
5	Comunidad Aislada Desarrollo	Aguada	5
6	Aceitunas	Maricao	6
7	Corcobada	Añasco	7
8	Caguabo	Añasco	7
9	Cerro Gordo Arriba II	Aguada	9
10	Comunidad Cerro Gordo El Parque	Aguada	10
11	Vega Acevedo	Lares	11
12	B. Rubias	Yauco	12
13	Periche	San Germán	12
14	Mongote	Yauco	12
15	Acueducto Rural Guacio Inc	San Sebastian	15
16	Jaguey Chiquito	Aguada	16
17	Comunidad Mendez	San Germán	17
18	Com. Las Cuarenta	Lares	17
19	Comunidad Hatillo	Añasco	19
20	Pinales Arriba	Añasco	19
21	Quebrada Larga	Aguada	21
22	Proyecto Aguas	Aguada	21
23	Guaraguao	Yauco	23
24	Comunidad RioPiedras	San Germán	23
25	Rosario Penon	San Germán	25
26	Sonador II	San Sebastian	26
27	Cerro Gordo	Aguada	27

La Jurada, Yauco was the community that obtained the highest score. This community has a water supply system without treatment where the water was taken from a small water resource and then provided directly to the community. According to the bacteriological records, the water quality did not comply with regulations. Additionally, La Jurada reported high rates of infant mortality.

The strategy of prioritizing interventions in the Non-PRASA systems, which required an urgent technical intervention, could be used by decision makers to mandate the upgrading of systems and/or their investment plans. However, this strategy could be improved or complemented by adding up important variables that were not considered in this study due to the lack of information. It was especially true for the case of the statistics on diarrhea, a variable which frequently is highly related to water quality (Prüss-Üstün and Corvalán, 2006). Another variable to be included must be the water quality at the catchment level. This should be done in order to determine the efficiency of the systems and the potential risks to diseases according to nonpoint- and point- source contaminations.

4.2 *Results of physicochemical and bacteriological analysis of the EDSF system*

The experimental water treatment studies are valuable in developing changes in an existing water treatment process to improve performance and/or reduce costs. The evaluation of experimental water treatment enables the identification the advantages and disadvantages of the process, of the operation and/or maintenance of each component of the system. The EDSF system was evaluated by analyzing the physicochemical and bacteriological parameters to verify the compliance of the standards.

When the assembly and installation of the EDSF system was completed, a test run was carried out to identify any miss-connections or defects and no problems were found. However, a problem was found with the electrical logic sequence of the valves attributed to the lack of power provided by the solar panel. The problem was resolved with appropriate settings and the EDSF systems started operation in March 2008. First, the behavior of EDSF system operated with 1.0 gpm (first period) will be presented and subsequently the analysis results when the EDSF operated with 1.5 gpm (second period) will be shown.

4.3.1 Results of first sampling period

In the first period the dissolved oxygen values were in the range of 5.59 to 8.2 mg/L for the samples taken in the ports 1, 2, 3, and 4, with a constant trend of dissolved oxygen concentration of approximately 7 mg/L (Figure 20). These dissolved oxygen levels indicate that there was a good aeration in the each component of the EDSF system, and met with the NPDWR and Puerto Rico Standards.

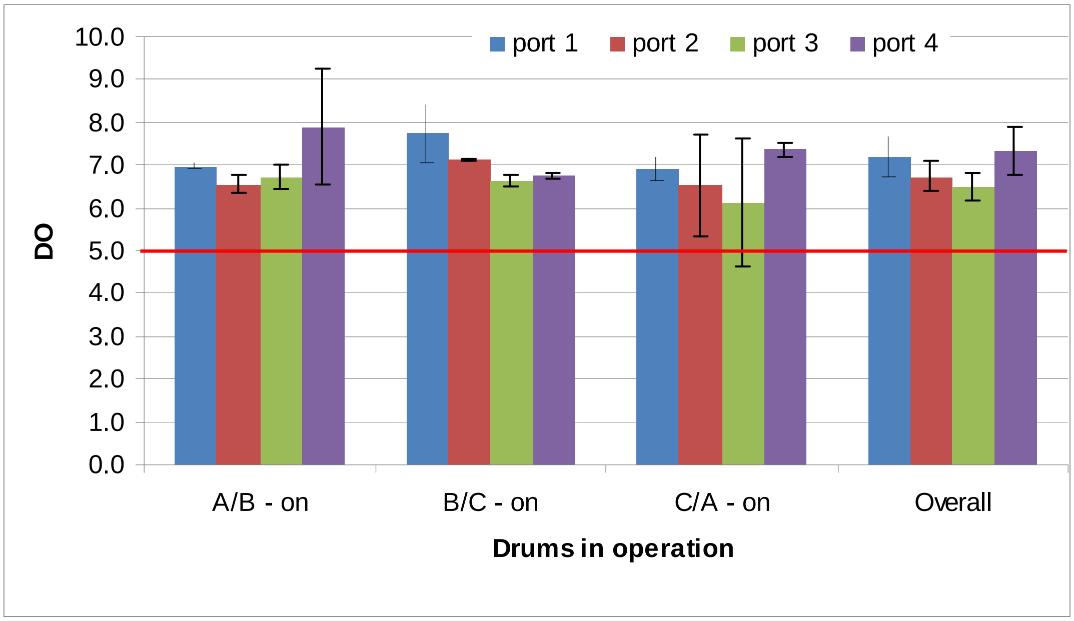

Figure 20. Performance Of Dissolved Oxygen In First Sampling Period.

Note: The horizontal line indicates a PDWSR for DO.

The turbidity trend for the four ports measured was similar (Figure 21). A peak of turbidity was identified at the sampling port No. 3 when the drums (B/C) were operated. This could be attributed to small particles escaping from the drums. However, in general the turbidity parameter met with NPDWR and the Puerto Rican standards.

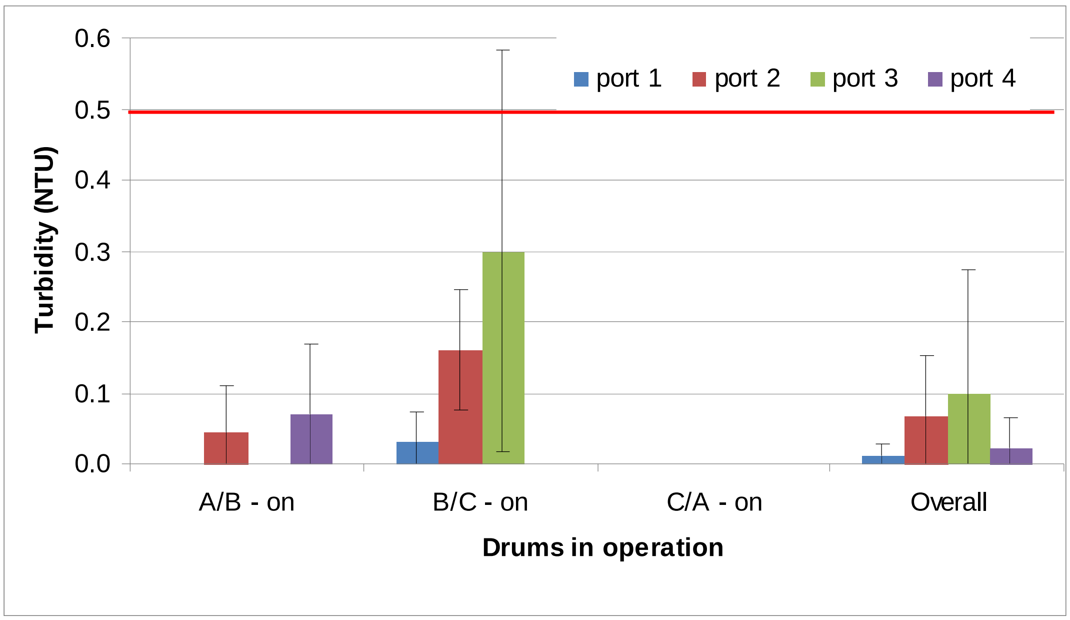

Figure 21. Performance Of Turbidity In First Sampling Period.
Note: The horizontal line indicates a PDWSR for turbidity for conventional or direct filtration.

Total chlorine concentration behavior was similar and corresponded to the expected values, concentration values vary between 0.03 and 0.3, and however, the highest value was found in port 4 when the post-chlorination occurs (Figure 22). According to the on-site chlorine measurement and the results from the microbial analysis, chlorine dosage had been adjusted in order to both meet the target residual chlorine concentrations in the effluent (0.2 to 4 mg/L) and produce appropriate germicidal effects. This resulted in an increase of total residual chlorine concentration in the effluent. In accordance with NPDWR the maximum residual disinfectant level cannot exceed 4.0 mg/L, hence the results show that the EDSF system did meet the regulation. It is important to mention that adjusting the final chlorine concentration has been a difficult task with the post-chlorination, since the current chlorination equipment didn't allow the chlorine concentration to be accurately controlled due mainly to the physical size of the equipment.

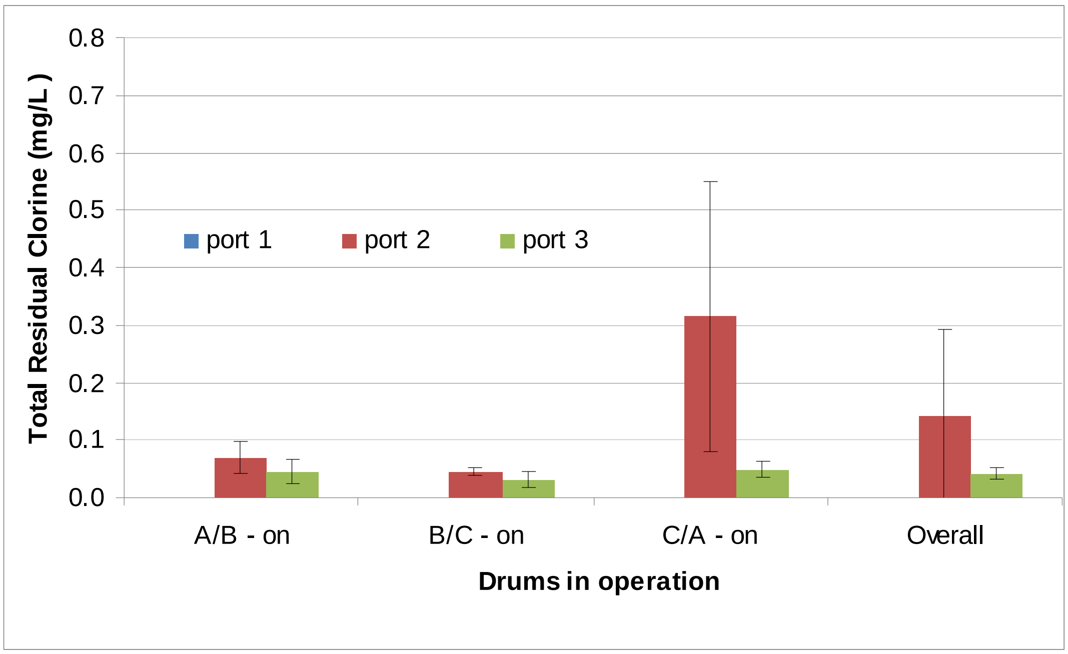

Figure 22. Performance Of Total Residual Chlorine Concentration in First Sampling Period. Note: The maximum residual chlorine concentration must not exceed to 4.0 mg/L according PDWSR.

Fecal coliforms analyses were not detected in the samples collected from the inlet to the EDSF system (Port 1) during study. Hence, no further analysis was done with respect to fecal coliforms. In general, the behavior of HPC did not follow a trend in relation to all the points. Rather, it showed an irregular behavior (Figure 23) regarding with THB, the results met the

EPA drinking water standards because there were no less than 500 colonies/100 mL or more in the effluent of the EDSF system.

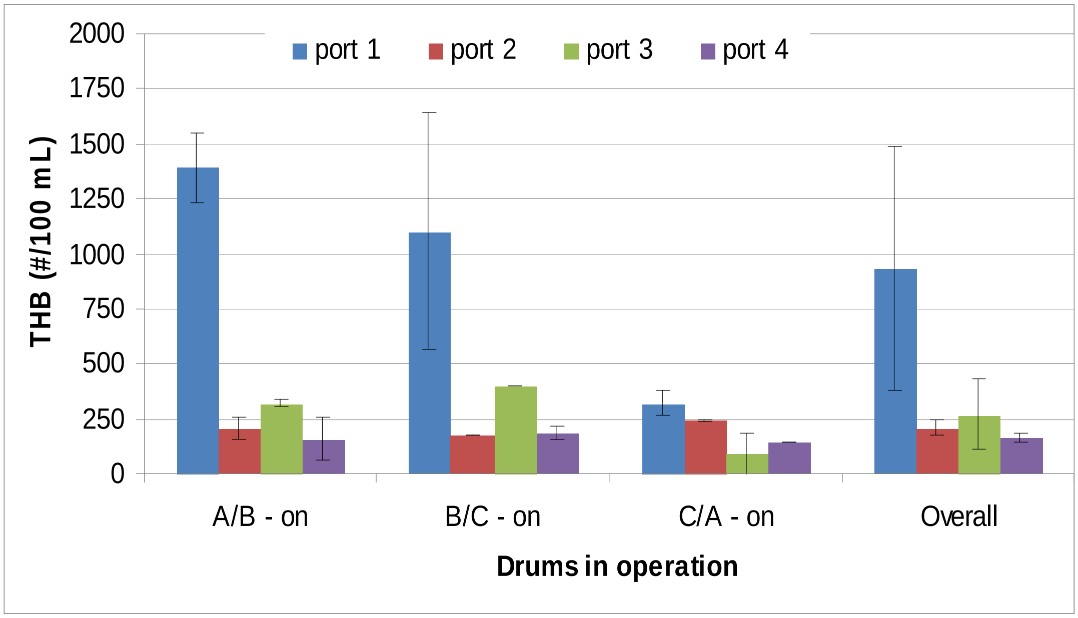

Figure 23. Performance Of THB In First Sampling Period.
Note: The HPC must not exceed 500 bacterial colonies per mL according PDWSR.

4.3.2 Results of second sampling period

The turbidity in the four ports to each sequence was near to zero and the behavior was similar to the first period. On the other hand, total chlorine concentration values vary between 1.29 and 1.92 (Figure 24) despite much efforts of regulating its concentration. TRC concentration at the sampling port 4 (after post-chlorination) was still high in the range 4.7 and 13.2 mg/L with an average of 8.7 mg/L, where 90% the THB reduction was achieved. Except for the case of the sampling port No. 4, TRC parameter met the current regulation contrary to ports 1 and 4.

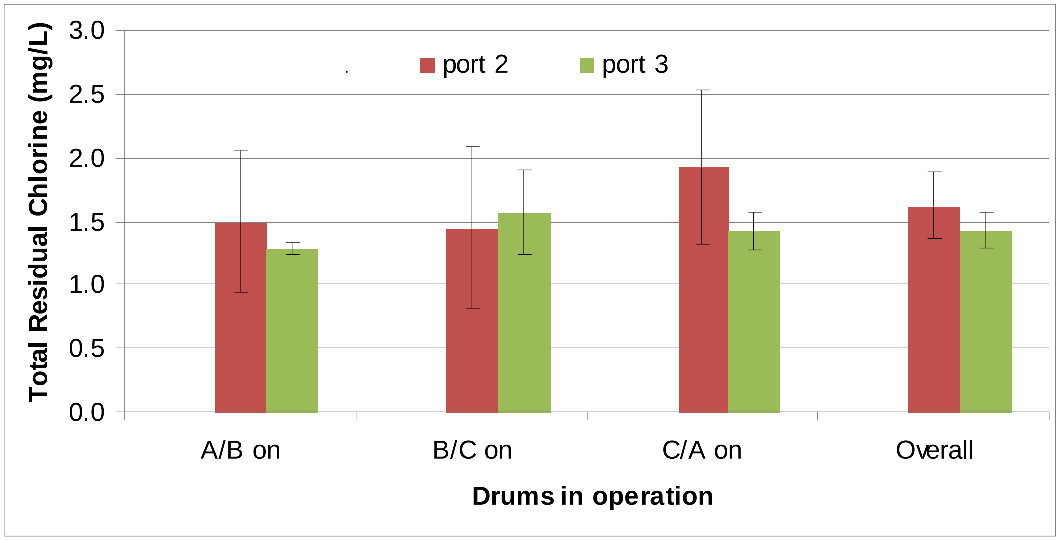

Figure 24. Performance Of Total Residual Chlorine In Second Sampling Period.
Note: The maximum residual chlorine concentration must not exceed to 4.0 mg/L according PDWSR.

As shown in Figure 25 despite great numbers of THB's in the influent (sampling port No. 1), a 50% reduction was achieved with the pre-chlorination. Overall, a 90% of THB reduction was achieved (i.e., influent vs. effluent).

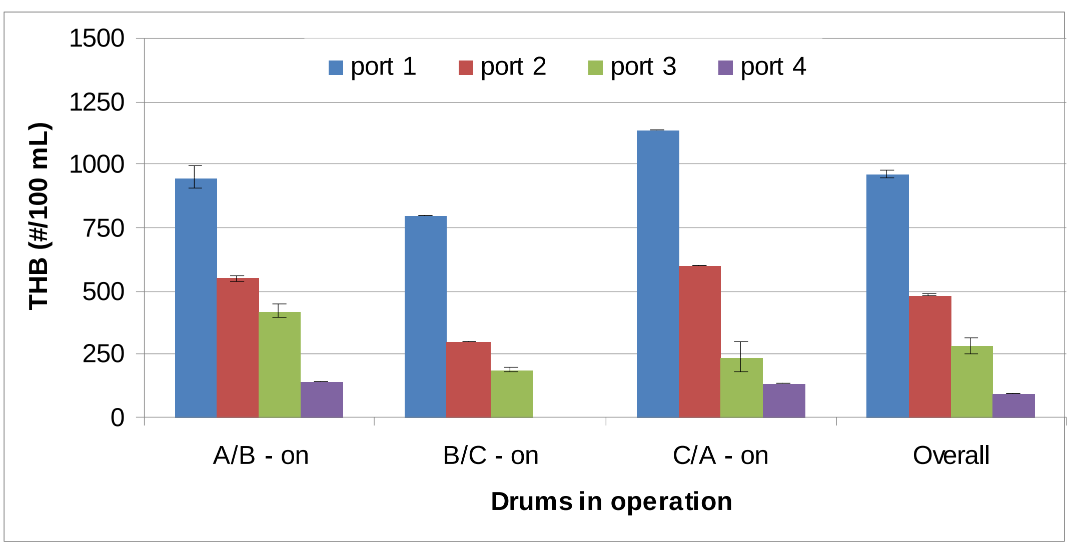

Figure 25. Performance Of THB In Second Sampling Period
Note: The HPC must not exceed 500 bacterial colonies per mL according PDWSR.

4.3 *Selection of the Drum Filtration Systems location*

For the identification of the EDSF system to the potential sites, an MCDA methodology involving the following major steps was applied: (i) collection of the geographical and spatial information, (ii) identification of evaluation criteria and (iii) assigning weight to evaluation criteria.

Initially, the methodology was proven in Las Piedras community where the first step was to take the data with GPS (households, water inlet, gravel filter, and EDSF system). These data plus criteria selection of the site are represented in the following map (Figure 26).

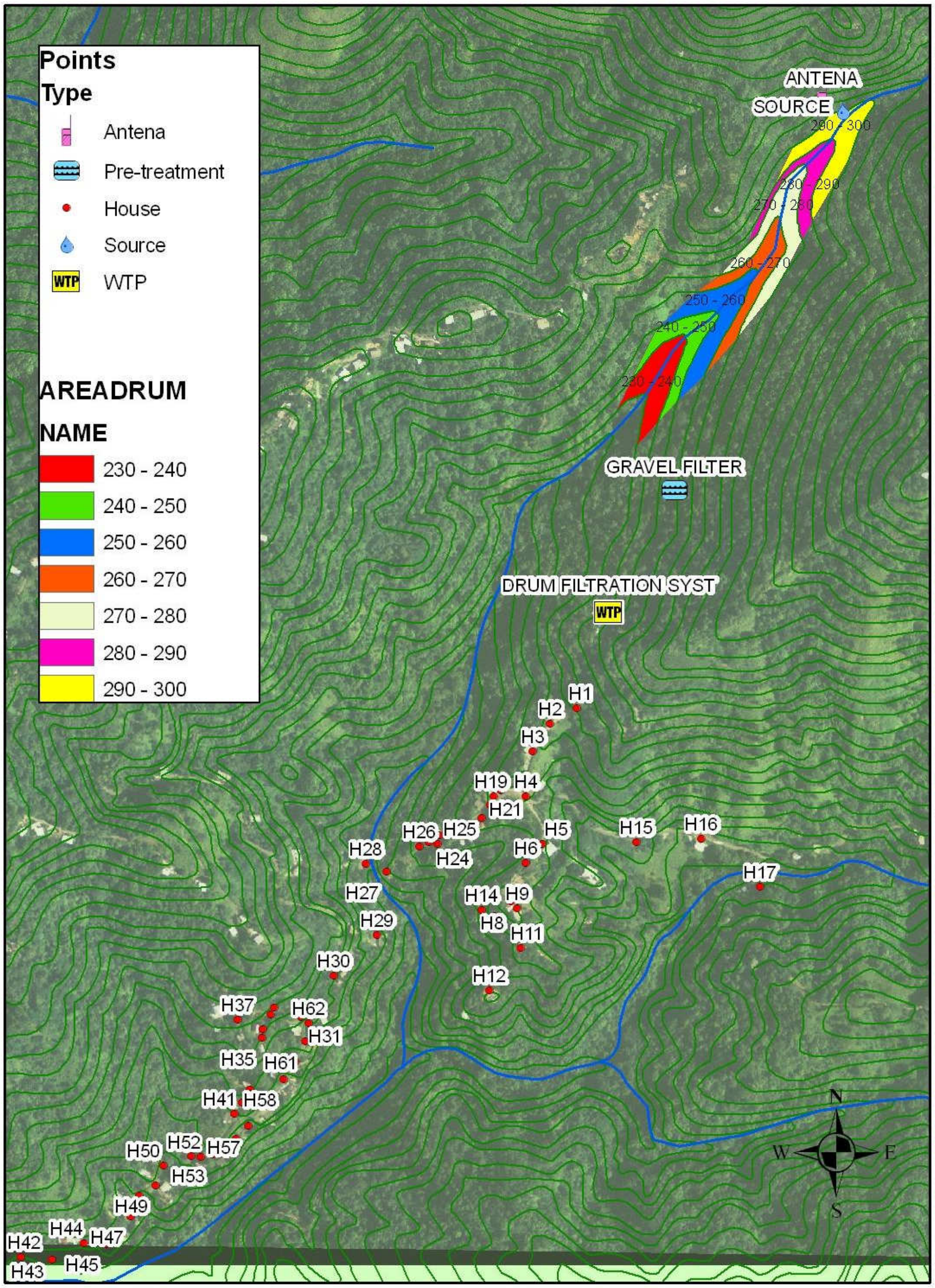

Figure 26. Selection Of Site In Las Piedras Community.

To determine the possible area in which the EDSF system can be located, the first house in the highest elevation was identified. With this elevation, the zones were identified in which the system could be operated by gravitational force and be located close to the Cain River. The areas were delineated using GIS and the zone selected was close to the community (Red area in Figure 26).

The study area in Las Piedras was located inside a zone with moderate susceptibility to land sliding, hence it had the same weight throughout the area. The flood area criteria was not weighted in the study area because it was outside the zone with flooding probability.

A similar procedure of site selection used for Las Piedras community was used in La Jurada community. In this case, areas were delineated larger than Las Piedras. Four possible areas were found, however the area with greater rank is delineated with green color (Figure 27).

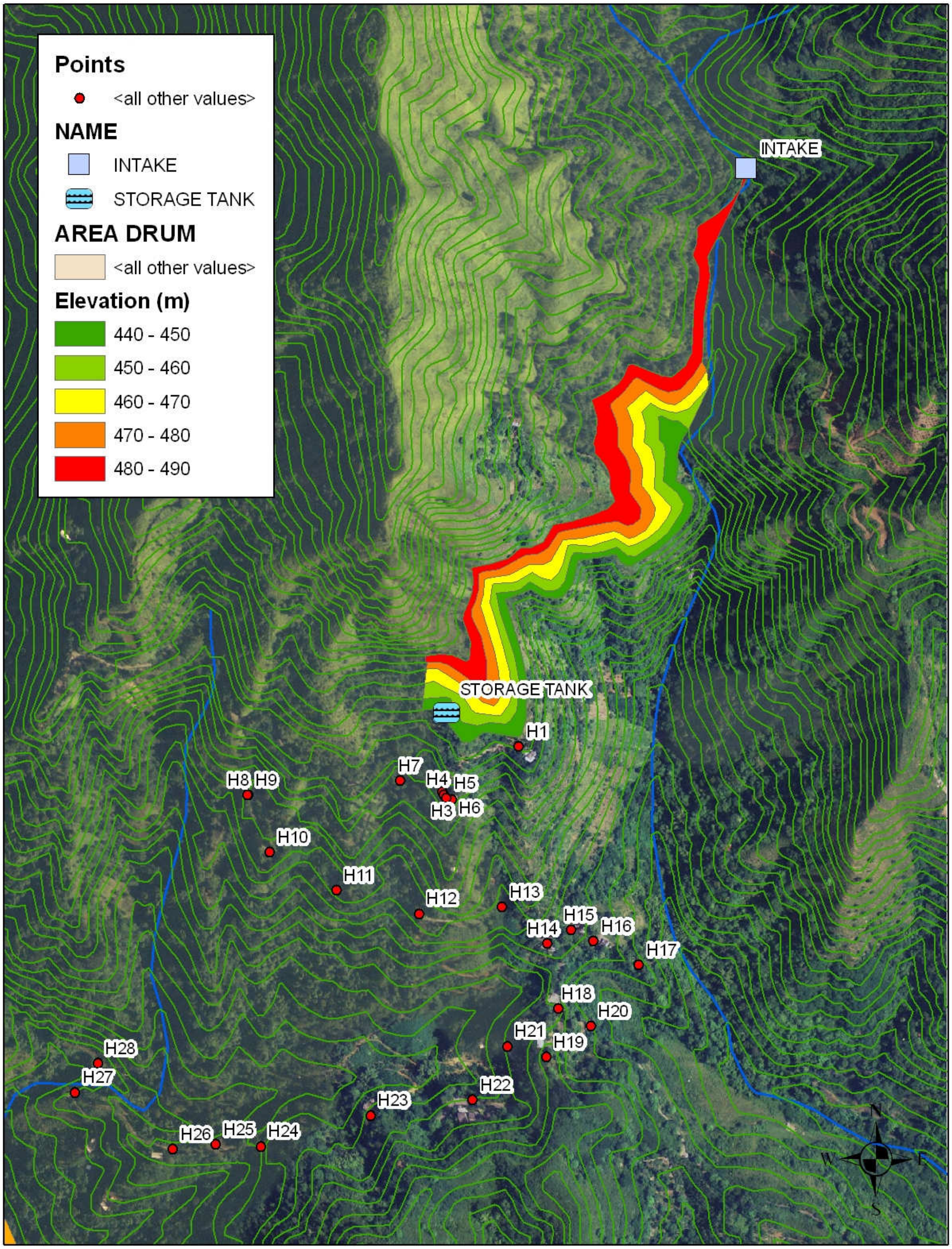

Figure 27. Selection Of Site In La Jurada Community.

Among the procedure and analysis of the variables for selecting the location, the most important criteria were topography and proximity community. The variables proximity to land sliding and flood areas were restrictive criteria.

The use of MCDA methodology complemented with the GIS tool was a good procedure to resolve problems of selecting the location of small drinking water systems such as, the EDSF system. However, the main weakness of the methodology was that the sites identified encompassed exceedingly broad areas. To make the selection more specific, it was necessary to complement the decision criteria with water quality data of the rivers and streams, headloss between water intake in the river and community, land availability and costs.

The process of selection of the location for a drinking water system is not regulated in Puerto Rico which makes identification criteria more difficult. Hence, the identification of criteria and the selection will be discretion of the engineers and other stake-holders.

5. CONCLUSIONS

- In Puerto Rico, 95% of the Non-PRASA rural communities do not meet the bacteriological standards, hence this communities is served of unsafe water supply. This generates a big risk to those communities because there is an increasing probability of contracting water-borne diseases related to the poor management of water and sanitation systems. The literature clearly shows the relationship between inadequate water, sanitation and hygiene and the incidence of diseases such as a diarrhea, malaria, cholera, dysentery, infectious hepatitis, trachoma, and dengue.

- In the study area, 21 Non-PRASA systems were identified and served approximately 10,500 populations. Almost 22% of the Non-PRASA communities do not have any type of treatment and 48% do not meet with bacteriological regulation. For this reason, it is necessary to carry out technical support in these sites to improve the drinking water, and to protect the public health and quality life.

- A useful tool was developed to identify the communities with drinking water problems that require urgent support. According to the tool developed, La Jurada community in Yauco municipality was scored the highest and therefore ranked the first. However, this strategy could be improved or complemented by incorporating variables that were not considered, such as diarrhea incidence or others diseases related to unsafe water, water quality of the rivers or streams, and among others.

- The EDSF system was evaluated with respect to the physicochemical and bacteriological water quality parameters. Physicochemical parameters such as dissolved oxygen and turbidity complied with the water quality standards. The THB analysis indicated that the EDSF system also met the national and state standards. Therefore, the EDSF system could be deployed to rural communities even without electricity supply as a small system producing safe drinking water. However, further care should be taken with respect to more biochemical water quality standards.

- The MCDA methodology proved to be an effective methodology for selecting the location of small drinking water systems such as the EDSF system. This methodology was used in Las Piedras-San Germán and the Jurada- Yauco communities. Optimized zones for potential implementation of the EDSF that met the selection criteria were delineated using the GIS.

6. RECOMMENDATIONS

- For the identification of communities with drinking water problems, it is recommended to consider more criteria related with diseases associated with drinking water, for example, diarrhea.

- A more objective ranking system would make a more consensus decision for selection of Non-PRASA communities which are in needs of technical inventions. This could be done by conducting surveys to choose more statistically optimized variables and relevant ranking methods.

- The assessment of the EDSF system as an engineering option to improve drinking water quality in the Puerto Rico Non-PRASA communities should be complemented with an analysis of several water quality parameters in detailed manners. Further monitoring of effluent water quality is recommended to corroborate its feasibility to be used as a small system solving water quality problems that rural, Non- PRASA communities have.

- The criteria, used to select the optimum site of the EDSF system in a community with drinking water problems, should also be complemented with accessibility data (roads), quality of source waters potentials of non point – and point – source contaminations, cost and land availability.

- The EDSF system needs to be tested with waters having different quality with respect to greater turbidity and the presence of indicator microorganisms to assess physical and germicidal effects, respectively.

7. REFERENCES

American Water Works Asociation (AWWA) Research Fundation. 1991. Manual of Design for Slow Sand Filtration, AWWA Research Foundation and American Water Works Association, Denver, CO, ISBN 0-89-867551-0.

American Water Works Association (AWWA) /American Society of Civil Engineers (ASCE). 2005. Water Treatment Plant Design, McGraw Hill Inc, New York, ISBN 0-07-141872-5.

Cardona, J. 2001. Field evaluation of a slow sand filtered coupled to a horizontal flow gravel pre-filter for the production of drinking water from a surface water source in Puerto Rico, Thesis, University of Puerto Rico, Mayagüez Campus.

Chaudhury, R.H., Gunasekera, P. and Gunasekera, D. 2006. *District-level Variations in Infant Mortality in Sri Lanka: A Challenge to Achieving the Millennium Development Goal on Child Survival,* Regional Health Forum, 10:96-103.

Cheremisinoff, N.P. 2002. Handbook of Water and Wastewater Treatment Technologies, Butterworth-Heinemann Publisher, Woburn, MA, ISBN 0-7506-7498-9.

Church, R.L. 2002. *Geographic information system and location science*, Computers and Operation Research, 29:541–562.

Conesa, A.E. 1991. Slow sand filtration: A pilot scale study using a sand of Puerto Rico, Thesis, University of Puerto Rico, Mayagüez Campus.

Ehrentein, S.O., Mazumder, D.N., Hira-Smith, M., Ghosh, Y., Yuan, Y., Windham, G., Ghosh, A, Haque, R., Lahiri, S., Kalman, D., Das, S. and Smith, A.H. 2005. *Pregnancy Outcomes, Infant Mortality, and Arsenic in Drinking Water in West Bengal, India,* American Journal of Epidemiology, 163(7):662-669.

Environmental Quality Board (EQB). 2003. Quality Water Standards to Puerto Rico, Puerto Rico Government.

Environmental Protection Agency (EPA). 2000. Environmental Planning for Communities "A guide to the environmental visioning process utilizing Geographic Information Systems (GIS), Office of Research and Development USEPA, Cincinnati, OH, EPA/625/R-98/003.

Environmental Protection Agency (EPA). 1994. Drinking Water Treatment for Small Communities, Office of Research and Development USEPA, Washington, DC, EPA/640/K-94/003.

Environmental Protection Agency (EPA). 2001. National Primary Drinking Water Standards, Office of Water, United States, EPA/816/F-01/007.

Environmental Protection Agency (EPA). 2003. Small Drinking Water Systems Handbook, A guide to "Packaged" filtration and disinfection technologies with remote monitoring and control tools, Office of Research and Development USEPA, Cincinnati, OH, EPA/600/R-03/041.

Environmental Protection Agency (EPA). 2006. Summary report and review of Non-PRASA community drinking water systems in Puerto Rico, Annual Report.

Environmental Protection Agency (EPA) and Smith, J. 1991. Technologies for upgrading existing or designing new drinking water treatment facilities, Noyes Publications, ISBN 0-8155-1262-7.

Felpeto, A., Martí, J. and Ortíz, R. 2007. *Automatic GIS-based system for volcanic hazard assessment*, Journal of volcanology and geothermal research, 166:106-116.

Fewtrell, L., Prüss-Üstün, A., Bos, R., Gore, F. and Bartram, J. 2007. Water, Sanitation and Hygiene: quantifying the health impact at national and local levels in countries with incomplete water supply and sanitation coverage, World Health Organization, Environmental Burden of Disease Series No. 15, Geneva, ISBN 978-92-4-159575-9.

Fox, K.R., Graham, N.J.D. and Collins, M.R. 1994. Slow Sand Filtration Today: An Introductory Review, An International Compilation of Recent Scientific and Operational Developments, American Water Works Association, USA.

Galvis, G. 1999. Development and evaluation of multistage filtration plants, Thesis, University of Surrey, United Kingdom.

Galvis C, G., Latorre M, J., and Visscher J, T. 1999. *Filtración en Múltiples etapas*, Universidad del Valle, Colombia.

Gleson, C. and Gray, N. 1997. The Coliform Index and Waterborne Disease, Published by E&FN Spon, London, ISBN 041921870.

Hafeman, D., Factor-Litvak, P., Cheng, Z., Van Geen, A. and Ahsan, H. 2007. *Association between Manganese Exposure through Drinking Water and Infant Mortality in Bangladesh,* Environmental Health Perspectives, 115(7): 1107–1112.

Huisman, L. and Wood, W.E. 1994. Slow Sand Filtration, World Health Organization. Geneva.

Hutchins Cairn, J. 2004. Water Treatment, Macmillan Reference, New York, USA.

Hwang, S. 2008. Remote Telemetry Monitoring of Surface Water Filtration Systems in the Rio Piedras Community in San Germán-Puerto Rico, Final Report, Department of Civil Engineering and Suveying, University of Puerto Rico, Mayaguez.

Keeney, R.L., Raiffa, H. 1976. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. John Wiley & Sons Inc, New York, ISBN 0-521-43883-7.

Kosek, M., Bern, C. and Guerrant, R.L. 2003. The global burden of diarrhoeal disease, as estimated from studies published between 1992 and 2000. Bull World Health Organization, 81:197-204.

Malczewski, J. 2004. *GIS-based land-use suitability analysis: a critical overview.* Progress in Planning, Canada, 62 (1), 3–65.

Malczewski, J. 1999. GIS and Multi-criteria Decision Analysis, John Wiley and Sons, Inc., USA, ISBN 0-471-32944-4.

McHarg, I.L. 1969. Design with nature, The Natural History Press, Garden City, New York.

Mulligan, J., Fox-Rushby, J., Adam, T., Johns, B. and Mills A. 2005 Unit costs of health care inputs in lowland middle- income regions. Disease Control Priorities Project Working Paper No. 9, World Health Organization, Geneva.

Natch, K.J., Bloomfield, S.F. and Jones, M. 2006. Household water storage, handling and point-of-use treatment, A review commissioned by IFH; published on http://www.ifh-homehygiene.org, accessed January 2008.

Pan American Health Organization (PAHO)/ World Health Organization (WHO). 2001. Informe regional sobre la evaluación 2000 en la región de las Américas. OPS Library, Washington D.C, ISBN 92-75-72379-6.

Puerto Rico Aqueduct and Sewer Authority (PRASA). 2007. Non- Prasa Systems Layer, Departamento de Infraestructura.

Prüss-Üstün, A. and Corvalán, C. 2006. Preventing disease through healthy environments: toward an estimate of the environmental burden of disease, WHO Library Cataloguing, Geneva, ISBN 92-4-159382-2.

Prüss-Üstün, A., Kay, D., Fewtrell, L. and Bartram, J. 2002. *Estimating the burden of disease from water, sanitation, and hygiene at a global level,* Environmental Health Perspectives, 100(5):537-542.

Simon, H. A. 1960. The new science of management decisions, Harper &Row Inc., New York.

Sodeberg, C. A. 2008. Status of Non-PRASA in Puerto Rico, In First Rural (Non-PRASA) Community Water Suppy and Sanitation Workshop, February 25, 2008, University of Puerto Rico at Mayaguez.

Spellman, FR. 2008. Handbook of Water and Wastewater Treatment Plant Operations. CRC Press Publisher. Boca Raton, Florida. ISBN 978-1-4200-7530-4

Tchobanoglous, G., Burton, F. and Stensel, D. 2002. Wastewater Engineering, Treatment and Reuse, Metcalf & Eddy Inc, New York, ISBN 0-07-01878-0.

The American Water Works Association (AWWA) and the Water Environment Federation (WEF). 1992. Standards Methods for the Examination of Water and Wastewater, American Public Health Association, USA.

Torres, J., (2008), Situación de los sistemas Non-PRASA en Puerto Rico, In First Rural (Non-PRASA) Community Water Supply and Sanitation Workshop, February 25, 2008, University of Puerto Rico at Mayagüez.

UN Millennium Project. 2005. Investing in Development: A Practical Plan to Achieve the Millennium Development Goals, Library Congress Cataloging, New York.

United Nations. 2006. UN Statistical Division. Progress towards the Millennium Development Goals, 1990-2005, New York.

U.S. CENSUS BUREAU. 2000. *www.census.gov*. Accessed June 20, 2007.

Wang, D. and Fiessel, W. 2008. *Evaluation of media for simultaneous enumeration of total coliforms and Escherichia Coli in drinking water supplies by membrane filtration techniques,* Journal of Environmental Sciences, 20 : 273 – 277.

World Health Organization (WHO). 2006. Guides for Drinking-water Quality: incorporating first addendum, Volume 1, Recommendations, Third Edition, Geneva, ISBN 92-4-154696-4.

World Health Organization (WHO). 2004. Water, Sanitation and Hygiene Links to Health Facts and Figures, General Comment No. 11, Geneva.

World Health Organization (WHO)/United Nations Children's Foundation (UNICEF). 2005. Meeting the MDG Drinking Water and Sanitation Target: A Midterm Assessmen tof Progress, Geneva, ISBN 92-4-156278-1.

World Health Organization (WHO)/United Nations Children's Foundation (UNICEF). 2006. Meeting the MGD drinking water and sanitation target: the urban and rural challenge of the decade. Geneva, ISBN-13 9789241563253

Zeleny, M. 1982. Multiple criteria decision making, McGraw Hill Higher Education, New York, ISBN 0-07072-795-3.