

## **Abstract**

San Cristóbal de las Casas, Chiapas, Mexico, is a thriving cultural and economic center with a strong tourism industry. Due to population growth from political unrest and economic promise in the past 14 years, the municipal water supply system has been unable to meet the water supply needs of new urban residents. The sewer system, limited to the city center, conveys untreated waste directly to the rivers. This project built upon the recommendations and background research of a 2005-2006 group project.

Eight practical solutions, or Best Management Practices (BMPs), were researched to address issues of water quality and water supply. Design manuals for these BMPs were created in both Spanish and English. Working with partners in Mexico, group members helped to implement two pilot projects – a household rainwater harvesting system and a community ecological clothes-washing station that provides clean washwater and treats effluent through a constructed wetland. Project members developed an educational campaign to complement the BMP designs and bridge the educational disconnect between environmental and human health. The project also monitored waterways to establish baseline water quality conditions in the watershed, and assessed the effects of BMP implementation in a watershed model. Finally, a reforestation prioritization map was created to guide local organizations actions.

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## **Executive Summary**

### **Background**

San Cristóbal de las Casas is a historic city located in Chiapas (the southernmost state of Mexico) which serves as the economic and cultural hub for the surrounding region (Bencala et al. 2006). Originally founded in 1528, the city rests within a high-elevation mountain basin. The state of Chiapas is both a hotspot for ecosystem biodiversity and home to a high concentration of indigenous populations (WWF 2007; INEGI 2005). It is also one of the poorest states in Mexico, and maintains the highest childhood mortality rates (INSP 2000).

An increasing number of indigenous people from the rural highlands of Chiapas have concentrated along the periphery of San Cristóbal, partially due to social unrest in the surrounding region. This trend has exerted a strain on the city's limited utility infrastructure, leaving many of the peripheral communities without access to sufficient electricity, water supply, and sanitation. For example, the community of Cinco de Marzo currently receives water through public spigots that turn on periodically, sometimes late at night. Residents can go days without a water supply from this source.

Rivers in the watershed serve as conduits for raw wastewater, leading to a high presence of illness-causing pathogens. The lack of water supply, sanitation, and environmental protection has not yet been fully addressed by the federal and local governments despite local concerns. Significant improvement in management of water resources within San Cristóbal's watershed is needed to improve public health, and address environmental concerns.

### **Objectives**

The initial objectives of this project were to:

- Implement pilot projects that address water resources issues while utilizing practical and appropriate management techniques
- Strengthen the long-term regional water quality and quantity monitoring program initiated in 2006, with a particular emphasis on increasing the accuracy of pathogen monitoring
- Create an educational program to inform community members on the effects of poor sanitation and contaminated drinking water, the benefits of watershed protection, and the functionality of recommended management practices
- Update and calibrate the WARMF watershed computer model to predict impacts on water quality that would occur if project recommendations were widely implemented

In addition to these project components, group members took on the following tasks:

- Write design manuals specific to Chiapas, but adaptable to other regions, for each recommended Best Management Practice (BMP)
- Produce case studies for those BMPs implemented or suggested for implementation in a particular location by this project, with a detailed outline of the objectives, functions, construction steps, and materials costs
- Perform a multi-criteria GIS analysis to prioritize sites within the watershed that should be targeted by a reforestation campaign

#### Best Management Practice (BMP) Implementation

BMPs represent a technology or practice appropriate to the environmental, cultural and economic situation for the area in which it will be applied. Management strategies for San Cristóbal were researched extensively, with some implemented as pilot projects. For those BMPs without sufficient community interest or financial support, a set of eight “design manuals” specific to Chiapas were created by merging literature research, evaluation of the San Cristóbal area, and partner collaboration. These manuals allow interested parties to learn about a particular BMP technology and how to design a project to meet their needs for potential future implementation.

Two pilot projects based on designs from this report were implemented as case studies, and three others have been proposed for construction in San Cristóbal. These working examples of BMP technology will help to inform interested parties as to their effectiveness, and will assist in their promulgation. Design manuals and case studies have additionally been posted on the publicly accessible project website in English and Spanish to promote the spread of these BMP technologies to other regions.

#### Education Campaign

One critical component in the implementation of this community-based resource management project was the creation of a supplementary educational program for the residents of Cinco de Marzo. Working with SYJAC, a San Cristóbal-based NGO, the project team developed education materials that aim to change local behavior through increased watershed health awareness and the development of responsible individual practices.

#### Water Quality and Quantity Monitoring

Monitoring is an important step toward understanding how water resources in San Cristóbal’s watershed are best managed. A monthly monitoring program of surface and spring water locations was undertaken by the university El Colegio de la Frontera Sur (ECOSUR) in May 2006. This project focused on refining the program and increasing the capacity of ECOSUR’s laboratory. Seven months of water quality data including nutrient values and bacteria levels data were analyzed for spatial and temporal trends. Nearly all monitoring sites exceeded US and Mexican maximum quality standards for coliform levels, indicating the presence of pathogens that can

cause gastrointestinal illness. Contamination levels tended to be higher within the urban area, most likely due to the direct discharge of raw wastewater into rivers.

#### Modeling of the San Cristóbal de las Casas Watershed

Computer simulation models can serve to help understand current watershed processes and predict the watershed's response to future changes. As a decision-making tool for environmental managers, this project estimated the benefits that widespread BMP implementation might have on water resource dynamics in San Cristóbal. The project began with a partially-built model from the first San Cristóbal group project, and then increased its utility by calibrating with water quality and quantity data collected during 2006. It was found that implementing composting latrines on a widespread scale would significantly improve the fecal coliform load in the watershed. The model will be transferred to partners in Chiapas for continual refinement and to analyze future proposed projects.

#### Reforestation

Increased demand for building materials and fuel wood, combined with the expansion of agriculture in the outlying areas of the city, has resulted in deforestation on the moderate slopes of the basin. To cope with these effects, local activist Alejandro Ruíz Guzmán heads a reforestation campaign, which is supported by a coalition including the municipal water supply agency, SAPAM. Sr. Guzmán requested that project members conduct an analysis to prioritize land within the watershed for reforestation efforts and present strategies for involving the local population.

The multi-criteria prioritization model focused on areas of high erosion potential, incorporating four equally weighted input layers: distance to streams, slope, soil erodibility, and precipitation. GIS results and program strategies based a literature review and interviews with organizations dedicated to reforestation in developing world were delivered to Sr. Guzmán.

#### Recommendations

Specific BMP technologies for addressing watershed-wide concerns including both human and environmental health have been researched, designed, and recommended for application in Chiapas, Mexico. Those BMPs that have been implemented during this project, along with the appropriate accompanying design manual, should serve as prototypes for other nearby communities who wish to construct similar projects.

Effectiveness of the constructed projects should be tested over time, using standards such as water quality or user satisfaction appropriate to the particular BMP. Extension of the technologies and reproduction of BMP materials to other areas and organizations through both formal and informal social networking is suggested. The lessons learned from this project and outlined in this report regarding communication, technical adjustments, scale, and partnerships should be applied toward future construction efforts.

The education campaign was designed to address public awareness of environmental and watershed health, as well as personal health and sanitation issues. This project encourages the reproduction of educational materials found in this report. The materials are also available to the public on the project website. This project recommends that a survey with questions regarding the link between water quality and human health be administered both prior to the use of educational materials, and within six months to one year after their implementation.

The Water Quality and Quantity Monitoring Program (WQQM) administered by ECOSUR should be expanded to include all recommended monitoring locations and laboratory tests, especially field measurement of volumetric flow rate. Capacity building should be made a priority to increase the resources available to the laboratory. This project recommends that ECOSUR solicit additional users of their laboratory who might require precise water quality assessments in order to augment monetary income and share resources across project partners, such that accurate and reliable water testing is available to any of the groups. Additionally, temporal flexibility should be incorporated into the monitoring dates, so that the data will capture a true reflection of actual conditions throughout the year.

The watershed model (WARMF) should be utilized to make management decisions. It can model the benefits of introducing BMP technology or other structures, such as water or wastewater treatment plants, within San Cristóbal. The quantitative results provided by the model, along with performance statistics, can be used in a cost-benefit analysis to determine the validity and cost-effectiveness of implementing various projects. As an example, in some cases targeted implementation of BMPs might eliminate the need for more costly water treatment or remediation techniques.

In terms of the reforestation campaign, tree planting should focus on the areas identified as “high priority” in this project’s multi-criteria model, if all other social and economic factors are held constant, including accessibility to land. The San Cristóbal campaign can also collaborate with the US-based NGO Trees for the Future to solicit further financial and technical expertise.

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## **1.0 Introduction**

### **1.1 Problem Statement**

San Cristóbal de las Casas is a historic city in Chiapas, the southernmost state of Mexico. Founded on March 31, 1528 (Bencala, Hains, Liu, Nogueira, Segan, and Stevens 2006), the city rests in the valley floor of a mountain basin, and serves as a cultural and economic center for the region. Despite the region's abundant annual rainfall, the access to clean water and sanitation services lags behind the national average (Bencala et al. 2006)). Contributing to the hardships of the populace, the state of Chiapas, along with the neighboring states of Oaxaca and Guerrero (World Bank), consistently ranks among the poorest states in Mexico.

In San Cristóbal, the human health and environmental problems associated with poverty and an inadequate services infrastructure have been exacerbated by a rapid increase in population. In the past 15 years, socio-political upheaval and religious conflict in the surrounding region resulted in an influx of immigrants to San Cristóbal, the region's urban center. The population growth drove the construction of new neighborhoods surrounding the historic city center, a building boom that continues today.

As the city expands, the water distribution and the limited sewer infrastructure have been unable to keep pace. As a result, most of the neighborhoods outside of the historic city center have limited access to water from the municipal system. The sewer conveyance system in San Cristóbal is also limited to the historic city center. However, the task of the existing sewer system is purely conveyance, not treatment. Untreated sewage is directed to the rivers of the watershed (Bencala et al. 2006). Though pit toilets and limited use of septic systems with leach fields do exist, much of the city's sewage is transported untreated to the river system. Beyond the city's outskirts, there is no conveyance system.

One issue associated with the lack of sanitation and the lack of a regular and consistent water source is the risk to health from such a common task as laundry. The women of some communities, including the group's partner community, Colonia Cinco de Marzo, wash their laundry using contaminated water as they stand in the stream. The risk associated with direct and persistent exposure to contaminated water is just one example of the challenges this project aims to address.

San Cristóbal's water resources are threatened by rapid unplanned growth, changing land use, and a lack of services. These factors contribute to the environmental degradation of the watershed, and threaten the health of the people who live within it. This project builds upon research completed by a Group Project thesis completed in 2006 (Bencala et al. 2006) at the Donald Bren School of Environmental Science and Management at University of California, Santa Barbara (Bren School). This previous

work sought to address key concerns such as a shortage of data in order to assemble a framework for a sustainable watershed management plan for the city and watershed of San Cristóbal. This project, described below, is a collaboration between research and community based organizations in both San Cristóbal and at the Bren School. It aims to address some of the concerns and recommendations of the previous Group Project thesis, as well as to develop further recommendations to aid the watershed in a sustainable manner.

## 1.2 Background of Study Area

The Mexican state of Chiapas is home to one of the highest concentrations of indigenous populations in the Americas. According to the 2000 census, 25% percent of the population in Chiapas speaks an indigenous dialect as their primary language, compared to the national average of 5% (Instituto Nacional de Estadística Geografía e Informática 2005). Chiapas is one of the poorest states in Mexico and mortality rates in children younger than 5 are the highest of any state in Mexico (Instituto Nacional de Salud Publico 2000). The national average per capita income in Chiapas, based on gross domestic product (GDP), was US\$1,466 in 2005 and has declined by an annual average of 6.5 per cent over the last decade, the sharpest decline in Mexico (Consejo Nacional de Poblacion 2000).

Over the last decade, a large number of indigenous people from the highlands of Chiapas have concentrated along the periphery of the urban center, San Cristóbal, and now exert a strain on the city's tenuous infrastructure. It is estimated that more than 40,000 of the current 132,000 inhabitants of the city were displaced from their rural communities and are currently residing along the periphery in neighborhoods that are collectively referred to as "the belt of misery" (Bencala et al. 2006). Although many of these people were displaced by civil unrest, they will most likely remain in the urban environment of San Cristóbal due to the higher probability of employment and likelihood of a more stable income. Watershed measure: The basin occupies 20,056 hectares and is topographically concave. The city of San Cristóbal is situated in the south central portion of the basin. The urbanized area occupies the lowest lying portions of the watershed, with elevations ranging from 2,180 to 2,200 meters. At the present time, the city occupies about 3,600 hectares or about 18% of the entire watershed.

The combination of diminished spring water supplies and population growth has caused extreme inadequacies in the potable water supply to the city of San Cristóbal. Currently, the city's water supply is so overtaxed that the operators are forced to alternate flow to different neighborhoods throughout the course of the day. In the poorest neighborhoods, the public spigot is left wide open at all times, with households' buckets stacked nearby. When the water begins to flow from the spigot, community members rush to the site to fill their buckets before the water is shut off again. It is not uncommon that the water is turned on during the late night and early



morning. This infrequency of delivery is true of many communities with household water connections, as well. When the water does arrive it is not generally potable, and the population relies heavily on bottled service for their drinking water supply.

Currently, wastewater in the city and outlying areas is not treated. The primary rivers, the Río Amarillo and Río Fogótico, are heavily contaminated with raw sewage and sediments (SAPAM 2003). Downstream of the watershed, these waters are used to irrigate agriculture – mainly vegetables, fruits, and berries that are sold in San Cristóbal and other parts of Mexico. In the low-lying areas of the basin, groundwater is found less than 50 cm below the soil. The proximity of this water to the surface has caused widespread contamination from pathogens, among other contaminants. Population growth also increases the concentration of pathogenic organisms. It is common knowledge in the city that drinking this untreated water will make you sick, and it is not considered potable by the residents.

The knowledge of these water quantity and quality issues is widespread throughout the region and has thus drawn the interest of several development projects to both the city of San Cristóbal and Chiapas in general. Several government-sponsored programs, non-governmental organizations (NGOs), and private donors have contributed resources towards the creation of both environmental and human health related improvement and education projects. Currently, there are an estimated 93 NGOs (Macias Guadeloupe 11 December 2006) working within the city of San Cristóbal alone, many of which focus on environment and water sanitation issues. This report does not purport to be the first attempt to research watershed issues in San Cristóbal, though it does offer new insight into watershed-based management techniques with specific recommendations for practical technologies and solutions.

### 1.3 Project Description and Approach

Previous analysis of the hydrology, water use, and options for improving water quality in the San Cristóbal de las Casas watershed led to a number of specific recommendations to improve access to, and security of, clean water. This project seeks to adopt some of these recommendations and to implement them in the field at the local level. The project's ultimate goal is to enhance sustainable utilization of water resources while improving access to safe water for local communities. It also aims to build local capacity in order to enable long term implementation of a sustainable plan for managing the watershed. The implemented practices will be evaluated under a water monitoring program developed for the San Cristóbal watershed, which will track both chemical and microbiological parameters. Furthermore, an educational campaign will increase awareness of the link between water and health, and the benefits of protecting water resources. This project is also meant to serve as a model to be adopted by other communities.

The principal objective of this project was to design and implement sustainable programs for the San Cristóbal de las Casas watershed. The main goals were to:

- Construct general design manuals for each of the recommended Best Management Practices (BMPs) for adaptation across a range of environmental conditions and regions
- Produce San Cristóbal-based case studies with detailed design manuals outlining the objectives, functions, construction steps, and materials costs necessary for building selected BMPs
- Implement a pilot project that utilizes BMPs for water capture and treatment
- Strengthen a long-term water quality and quantity monitoring program, with a particular emphasis on increasing the accuracy of pathogen monitoring
- Create a program to educate community members on the effects of poor sanitation and contaminated drinking water, and the benefits of watershed protection, with materials in both English and Spanish
- Update and calibrate the WARMF watershed computer model to better predict impacts on water quality of widespread BMP implementation, and to identify priority watersheds for BMP implementation
- Update the watershed map with layers indicating the location of implemented BMPs, potential locations for future BMP implementations, monitoring locations for water quality and water quantity data collection, and other community locations and demographics
- Perform a multi-criteria GIS analysis to prioritize reforestation sites within the watershed that will promote protection of the water supply, and develop strategies for a successful reforestation program
- Create and maintain a website that provides easy access to design manuals and education materials in English and Spanish for community leaders

This phase of the project expressly aims to move from the planning stage to on-the-ground implementation. The project seeks to determine what works, when it works, how well it works, costs, limitations or barriers for implementation, and solutions to those limitations. In addition, a more complete monitoring program ensures a more robust assessment of the beneficial effects of the implementation of these projects, while a comprehensive educational campaign ensures understanding about the human-environmental health link. The project website provides accessibility to all of the education materials and BMP design manuals, which are freely available for use by community leaders to assist in decision-making, guide the design and construction process of BMPs, and educate community members. Maintaining relationships with old partners and forging new ones with local communities helps to create a sense of ownership of the projects and builds local capacity that will increase the probability of success and sustainability of the projects in the long run.

Unfortunately, San Cristóbal's plight is not unique. Sustainable watershed management is a major issue for many communities, particularly in areas

experiencing rapid population growth. Because of inadequate infrastructure, management, and sanitation, over one billion people – nearly 20% of the world’s population – lack access to clean drinking water (UNESCO 2006). The United Nations set a millennium development goal to cut that number in half by 2015. Hopefully, the research and lessons resulting from this project will contribute to progress in this realm, and may serve as an example to other similar communities.

### *1.3.1 Sustainable Development and Appropriate Technology*

This project’s title is “Design and Implementation of *Sustainable* Water Resources Programs in San Cristóbal de las Casas, Mexico.” Group members would like to define the term sustainable in terms of this project, especially since the word can be used in many different applications.

Group members agreed that the Brundtland Report provides the best definition of sustainable development as it relates to this project by defining it as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs"(Brundtland 1987). In this 2005 World Summit Outcome Document, the United Nations General Assembly identified three components of sustainable development – economic development, social development and environmental protection – which it recognized as “interdependent and mutually reinforcing pillars” (United Nations General Assembly 2005). This document further states that “[eradicating poverty], changing unsustainable patterns of production and consumption, and protecting and managing the natural resource base of economic and social development are overarching objectives of, and essential requirements for, sustainable development.”

When making decisions about which BMPs to select and promote in San Cristóbal, project members always evaluated the technology in terms of both satisfying present needs and future sustainability. However, rather than focusing only on sustainable development, this project also attempted to identify and promote “appropriate” technology, defined as a technology or practice that is appropriate to the environmental, cultural and economic situation for the area in which it will be applied. Among other aspects, an appropriate technology in a small community such as San Cristóbal de las Casas should require fewer resources, address a felt need, and have a positive impact on the environment. Section 2.2 further describes the criteria used to evaluate researched BMP technologies for appropriateness.

### 1.4 Summary of the first San Cristóbal de las Casas Group Project Objectives

The group of students who worked on the 2006 project, “A Framework for Developing a Sustainable Watershed Management Plan for San Cristóbal de Las Casas, Chiapas, Mexico,” set out to achieve three main objectives:

- Analyze the water balance of the city (including climate, precipitation and groundwater flow)
- Consider water treatment and recycling options
- Formulate a water management plan to provide San Cristóbal with a framework for evaluating their water use, as well as serving as a framework for analyzing water resources for similar communities

When the project was completed in the spring of 2006, the previous group presented six deliverables from their research:

- Watershed map and model analysis detailing water inputs, groundwater recharge estimates, run-off patterns, water balance estimates, and at risk areas
- Options for improving water quality and implementation requirements
- Options for water management and implementation requirements
- Recommended Best Management Practices (BMPs)
- Municipal wastewater treatment plan

### 1.5 Partnerships and Collaboration

The first group project collaborated with several groups in San Cristóbal which have overlapping interests in the fields of sustainable urban growth, and human and watershed health. Building on past relationships with partner organizations, this project continued work with two of the previous group's partner organizations: El Colegio de la Frontera Sur (ECOSUR) and Skolta'el Yu'un Jlumaltic, A.C. (SYJAC). An additional partnership was established with the local indigenous community of Cinco de Marzo, where two of the recommended BMPs are being implemented.

#### *1.5.1 ECOSUR, Chiapas*

ECOSUR (El Colegio de la Frontera Sur) is a publicly chartered research institution providing research and post-graduate education focused primarily on the sustainable development of Mexico's southern-most states. The University specializes in three areas of study: Biodiversity Conservation, Society, Culture and Health, and Systems of Alternative Production. ECOSUR maintains five campuses, including one campus in San Cristóbal. Jesús Carmona served as a vital partner due to his Senior Researcher position at ECOSUR and his role as Vice President of SHRP. He provided the group with local water resource information and with data on SAPAM's operations. Additionally, he aided the project by connecting the group to additional researchers at ECOSUR. For example, Antonino García García's doctorate thesis provided the first San Cristóbal group project members with information on the history of water resource management in San Cristóbal. Essential maps of the watershed detailing elevation, land use, and land cover along with many other useful layers of GIS data were provided by another ECOSUR department, the Laboratorio de Análisis de Información Geográfica y Estadística (LAIGE). Juan Morales, a graduate researcher

at ECOSUR, assisted in setting up a monitoring program around the San Cristóbal watershed that has helped to quantify levels of nutrient and bacteria loads in the local rivers. More information on ECOSUR can be found at <http://www.ecosur.mx> and information on LAIGE can be found at <http://200.23.34.25/>.

As a continuing partner, work with ECOSUR has greatly expanded. Juan Morales implemented the water quality monitoring program designed by the first San Cristóbal group project members, which enabled this project group to gain a more accurate understanding of the watershed's health. The ECOSUR campus serves as the site of one of this project's rainwater harvesting system designs, which is expected to provide roughly one third of the needed water to the campus. Continuing actively in the project, Jesús Carmona shared environmental education materials with the group and provided input about the specifications and preferences of the rainwater harvesting design. Emmanuel Valencia of the Laboratorio de Análisis de Información Geográfica y Estadística (LAIGE) generously provided us with additional information sets necessary to analyze potential areas in the watershed for reforestation, to inform the watershed model and to design the rainwater harvest system.

#### *1.5.2 SAPAM Advisory Board*

SAPAM (Servicio de Agua Potable y Alcantarillado Municipal) or Municipal Potable and Waste Water Utility, is responsible for “implementing potable and waste water services, and conducting studies and improvements for the operation, administration and conservation of the water supply in the municipality of San Cristóbal.” The Advisory Board is a citizen-staffed, citizen-elected board in charge of administering the actions of SAPAM and ensuring public participation and consensus with the activities of the organism. SAPAM collaborated with the first San Cristóbal group by supplying them with data about pumping sites which assisted the group to estimate water use in San Cristóbal. With this and other data, the first San Cristóbal group project recommended designs for a municipal wastewater treatment plant to SAPAM. As this portion of the project was completed by the first San Cristóbal group project, this group did not work with SAPAM.

#### *1.5.3 SYJAC*

Skolta'el Yu'un Jlumaltic, A.C. is a nonprofit organization based in Mexico, whose objective is to support community empowerment and improve quality of life in the indigenous communities around San Cristóbal. SYJAC regularly participates in the execution of sustainable works projects in indigenous communities, including potable water supply and sanitation improvements. The director of SYJAC, Sabás Cruz García, and the education coordinator, Hilda Guadalupe Macías Samano, were integral in providing information on the socio-economic context of San Cristóbal. SYJAC helped set up informal interviews in some communities surrounding the city, enabled meetings with doctors serving the local community, and provided

information about the current social and political climate in San Cristóbal. Another member of SYJAC, Jesús Miguel Peñate Martínez Peñate Martínez Peate Martinez, assisted the project by collecting water quality samples.

Work between this project and SYJAC occurred in many capacities. Director Sabás Cruz Garcia continued to aid in connecting us with helpful contacts and strategizing ways to most efficiently affect the health of the watershed and its residents. A retired teacher, Hilda Guadalupe Macias Samano provided project members with her valuable input on the educational materials that are to accompany recommended BMPs. She also served as a primary contact with the community of Cinco de Marzo. Likewise, Jesús Miguel Peñate Martínez Peñate Martínez Peate Martinez worked with the community to guide construction of the community EcoLavadero. SYJAC also connected us with the community of Cinco de Marzo, where project members and partners implemented pilot projects within the community.

#### *1.5.4 Colonia Cinco de Marzo*

A community of 450 primarily indigenous families located on the outskirts of San Cristóbal, Colonia Cinco de Marzo was initially settled twelve years ago. Though long-standing, residents of the community live illegally on private or publicly owned land, and therefore have no formal property rights. As an irregular community, residents face a severe water shortage since only intermittent water is supplied by SAPAM, and water from the local creek is grossly contaminated. Residents expressed interest when SYJAC proposed that the community work together to construct an EcoLavadero, or clothes-washing station, which provided the women a clean place and clean water to wash their clothes. A group of 80 families expressed interest in constructing the EcoLavadero and a group of 25 families assisted in the physical construction. The group is comprised primarily of women, and meets when necessary to take action on community issues.

#### *1.5.5 Alianza Civica Chiapas*

Alianza Civica is a local nonprofit organization that seeks advancement in all sectors of the population, increased civic participation to contribute to the just democratization of society and conditions of peace. Alianza Civica Chiapas has branches in several municipalities of the state of Chiapas and is part of the Alianza Civica Nacional. In February, Alianza Civica held a forum of Energy and Water that enabled idea-sharing between communities and demonstrations of alternative solutions. Through the forum, Director Theresa Zepeda Torres enabled the distribution of educational materials to over 500 attendees.

Project partners have made it possible to carry out this implementation project while the UCSB researchers studied at the University. On-the-ground contacts are vital to maintaining an impetus for work on the pilot projects and enable continual

communication. Project members are grateful for the many hours of volunteer work each partner has provided.

### 1.6 Data Contribution of the First Group Project

The report of the previous group project supplied us with a wealth of information upon which this report builds. The section below briefly describes the data presented. More detailed information can be found in the original report, which can be found at <http://fiesta.bren.ucsb.edu/~chiapas/documents.htm>.

The first report presents a physical characterization of the watershed, outlines major physical features, defines the sub-watersheds, and provides information about habitat, flora and fauna, climate, and land use. It also describes the sudden and dramatic land use change caused by major population growth experienced around San Cristóbal since 1994. The report points out that this transition from forested land to agricultural and urban land have led to new ecological problems in the region, such as increased erosion and stormwater runoff. In addition to this information, the group members utilized basin hydrology data sets and meteorological data obtained from their partners to analyze the watershed.

With collaboration from the partner organizations, the previous San Cristóbal group also put together a socio-political characterization and an assessment of water resource use in San Cristóbal. The characterization includes a description of local political movements in the region, estimates of past, current, and future population growth, and discussion of some of the reasons for such sudden population growth. The assessment of the basin's water resources and SAPAM's supply capabilities includes estimates of the number of residents served and not served in the region. It is followed by a discussion of socio-economic and health effects of this heavily-burdened system, and the results of a cost-benefit analysis of much-needed infrastructural improvements.

In addition to presenting the background information, the previous report also provided various recommendations. It was from many of these recommendations that the idea for a second project was formed. The previous group designed a water quality monitoring program which has been carried out by one of this project's partner organizations, ECOSUR. This information was utilized during this year's project to calibrate the hydrological model of the watershed. The previous group also defined and recommended various BMPs that could be built throughout the watershed to lower the level of water pollution. This project group evaluated and elected the most appropriate BMPs for the region. One additional piece of information that was not utilized by this year's project members is a recommendation for a wastewater treatment plant to treat the surface and sewage waters of San Cristóbal.

### *1.6.1 SAPAM Wastewater Treatment Recommendations*

Wastewater from the municipality of San Cristóbal is currently discharged directly to surface water without treatment. During the previous group project, the utility provider for the city, SAPAM, requested an analysis to identify the best treatment method and location for a wastewater treatment plant, as they intended to invest in installing a comprehensive system (Bencala et al. 2006). This would include an expanded sewer system to convey combined wastewater and storm water flows into surface streams, but then treat this water at some point downstream. UCSB students analyzed the available data, and recommended three technologies: advanced integrated treatment lagoons, a multi-pass intermittent filtration system, or a modular wastewater treatment plant. The group strongly suggested that wastewater be directed to the treatment facility rather than the surface water in order to improve environmental quality. Separating wastewater streams from storm water flow, and moving the facility 6 kilometers closer to the city from the intended location, were also recommended to reduce costs of treatment.

Though results of this analysis were supplied to and considered by SAPAM, there is no indication that the recommendations supplied by UCSB were used for the final construction plan. Rather, from the most recent communications, the decision is expected to be influenced strongly by local political factors. Thus, this project has shifted focus away from municipal wastewater concerns, and has not embarked on any further analysis. Instead, it has operated under the assumption that wastewater discharge to ambient waters will continue for some time into the future, and that treatment will most likely occur only after the water leaves the city. Thus, the recommended best management practices for dealing with wastewater revolve around onsite treatment systems that proactively prevent discharge of polluted waters.

### 1.7 Preliminary BMP Recommendations

The first San Cristóbal Group Project's Framework for a Sustainable Watershed Management Plan included an analysis of potential Best Management Practices (BMPs) and recommendations for the most applicable BMPs for the San Cristóbal de las Casas area. The criteria for analysis of these BMPs were: the effectiveness in improving the water quality, implementation costs, physical requirements, and the potential local barriers to implementation. The first San Cristóbal group first looked at whether the particular BMP and its associated technology would address the water quality or quantity concerns of the stakeholders. If it did address one or more stakeholder concerns, then the feasibility of the BMP was assessed by looking at the remaining analysis criteria. After an analysis of some 13 BMPs, six were judged to meet the necessary criteria and were considered feasible enough to be recommended for implementation:

- Rainwater Capture and Collection System



- Composting Latrines
- Retention Basins
- Contour Water Retention Trenches
- Buffer Zones and Bioswales
- Education Campaign

#### *1.7.1 Rainwater Capture and Collection System*

Rainwater harvesting can be used to address the problem of a lack of clean water for domestic use. Rainwater harvesting systems capture rain during a storm event and channel it to a storage tank where it then can be accessed as needed. Generally, the volume of water these systems are able to collect is not enough for uses beyond drinking, cooking, and washing dishes and clothes. Systems placed on larger buildings or a system that combines the catchment areas of multiple buildings can capture water in volumes large enough for irrigation purposes or even manufacturing processes. For the purpose of this project in San Cristóbal and the Chiapas area, however, the main focus of rainwater harvesting systems is to supplement a scarce domestic supply of water.

#### *1.7.2 Composting Latrines*

Composting Latrines do not directly address the problem of water quality, though when used appropriately they can greatly reduce the transmission of pathogens from human waste into waterways. Composting latrines isolate human fecal waste, store it, and allow it to decompose so that when the compost is returned to the environment, it is an organic fertilizer that can benefit local agricultural by increasing productivity. In Chiapas, composting latrines help to offset the utter lack of centralized sanitation and active treatment of human waste.

#### *1.7.3 Retention Basins*

Retention basins are designed to mitigate the effects of stormwater runoff. As runoff waters flow overland they pick up soil, soluble solids, and pathogens, and eventually discharge them into a river, lake, or similar water body. Retention basins capture some of the stormwater runoff and store it for a brief period. During the water's period of storage physical and biological processes improve the quality of the water so that when it exits the retention basin it does not contribute as much pollution to the down-field environment. This BMP is particularly applicable to Chiapas where the terrain is quite mountainous, deforestation has exposed much open soil, and sanitation services are frequently non-existent.

#### *1.7.4 Contour Water Retention Trenches*

Contour trenches are a very simple yet effective way of slowing down stormwater runoff and allowing sediment loads to settle out. As stormwater flows down a hillside

it collects soil, sediments and debris. Contour trenches reduce the erosion caused by runoff by blocking and diverting the path of the water. Slowing the runoff waters allows much of the sediment load to deposit on the land. With the expansion of agriculture onto the hillsides of the San Cristóbal area, this BMP is an effective and relatively simple way to reduce erosion and sediment loading of streams.

#### *1.7.5 Buffer Zones and Bioswales*

Buffer zones and bioswales function very similarly to retention basins, but with a bit more emphasis on biological filtration. While retention basins hold water for a period of time in order to allow sediments to settle out, bioswales are more active in the biological breakdown of pollutants in stormwater. Stormwater runoff flows into and out of a bioswale in a relatively short amount of time. The technology relies on the length of the channel and the type of plants and bacteria present to absorb or kill many of the pollutants. It is a BMP that is effective in areas with regular and steady flows of stormwater such as Chiapas, with its six 6 months of almost daily rain.

#### *1.7.6 Education Campaign*

None of these BMPs can be successful without an educational component or a general water quality education program. While the concepts behind of many of these BMPs are not new to the people of Chiapas, for the BMPs to be effective they must hold to certain design criteria and receive proper maintenance. Furthermore, people are much more likely to use and maintain systems over which they take ownership and for which they understand both their utility as well as their ability to address the specific concerns and problems within their particular communities.

### 1.8 Current BMP Implementation

#### *1.8.1 Selection and Stakeholder Input*

The first step in the BMP implementation process was selecting which BMPs to focus on. This project expanded on the evaluation criteria used by the first San Cristóbal project and examined additional qualities of each BMP before making the selections. The following criteria were used for BMP evaluation: ecological effectiveness, ease of construction, ease of replication, ease of maintenance, cost-effectiveness, ability to meet a felt need, ability to provide a health improvement, and cultural acceptability. BMPs in addition to those described above were also discussed by the group and considered for implementation in San Cristóbal.

After evaluation according to the above criteria, the researchers agreed to focus on the BMPs recommended in the previous San Cristóbal project, listed above. It was determined that the first San Cristóbal project had conducted a comprehensive assessment of the San Cristóbal area and produced reliable suggestions regarding which projects and technologies were feasible to implement. However, it became

obvious that the last criterion, cultural acceptability, was impossible to assess without traveling to San Cristóbal and talking to the inhabitants about their preferences. To this end, researchers completed short design manuals and two-page documents describing each of the originally researched BMPs (except the Education Campaign) to present to the partner organizations and community members in San Cristóbal. Group members traveled to San Cristóbal to present materials and information about selected BMPs to partners at SYJAC and ECOSUR. Materials were left in San Cristóbal so that SYJAC could propose construction of these BMPs to the community group in Cinco de Marzo. A copy of each of the design manuals can be found in Appendix A.

Once each of the stakeholders, including the Cinco de Marzo community group, had provided input on each BMP, the list of BMPs being considered for implementation was updated. The group decided to further research two of the practices recommended by the first San Cristóbal project, along with three other BMPs that were deemed appropriate for San Cristóbal according to the criteria. The final list of BMPs that this project chose to conduct extensive research on includes:

- Residential Rainwater Capture and Collection System in the community of Cinco de Marzo
- Rainwater Harvesting system for ECOSUR campus
- Education Campaign
- EcoLavadero, an ecological clothes-washing station incorporating rainwater harvesting and a greywater treatment system
- Greywater Treatment Constructed Wetlands
- Blackwater Treatment Constructed Wetlands

For each of these new BMPs, except the Education Campaign, researchers formulated site-specific designs and produced extensive design manuals which can be found in Appendix A. The group treated the Education Campaign as its own program, and developed the program to complement the implementation of BMPs and teach multi-aged groups about ecological health and sanitation. More information on the campaign can be found in the following section.

### *1.8.2 Implementation*

During the winter of 2006-2007, with the collaboration of the partners in Mexico, the group initiated two pilot implementation projects based on the initially recommended BMPs. Both projects fulfill the needs of the community and provide a clean source of water. In a collaborative decision-making process, SYJAC and the community of Cinco de Marzo elected to construct an EcoLavadero, which would benefit the entire community. Designed by project members and supporters to serve the needs of the community, this integrated system is the first of its kind. The EcoLavadero consists of a community clothes-washing station that incorporates rainwater harvesting and storage, as well as biological filtration of the soapy water by way of a greywater

treatment constructed wetland. The EcoLavadero eliminates the need to wash clothes in the contaminated stream and avoids further contamination of the environment by soapy water, in addition to providing a comfortable place to wash and dry clothes. The second project is a domestic rainwater harvesting system designed to provide a reliable water supply to the household during the rainy season. Both of these projects were carried out in the community of Cinco de Marzo, with an emphasis on reducing the exposure of the local residents to water contaminants.

### *1.8.3 Future Projects*

As mentioned above, this project developed design manuals and site-specific case studies, in some cases, for the remaining BMP technologies that were originally recommended, but not implemented. Though these design manuals will be provided to the stakeholders and community, the timeline of the projects' lifespan – from approval through implementation to completion – falls beyond the completion date of this group project. One project has already been approved and will be implemented after the publishing of this report: a rainwater harvesting and water potabilization system in collaboration with ECOSUR. Designed with the goal of improving water quality for the university and reducing its dependence on municipal water provided by SAPAM, the project is expected to be constructed in the spring and summer of 2007.

## 1.9 Education

Based on recommendations from the previous group, educational materials linking water quality and human health were developed to be used in the primary school classrooms of Cinco de Marzo as well as in community centers in the greater San Cristóbal area. Working primarily with SYJAC, the main goal of the materials is to address the gap in knowledge between local water source quality and common illnesses and skin problems. Issues that promote realistic and feasible practices such as simple hygiene and sanitation measures that can be taken to reduce the risk of waterborne diseases are emphasized. Education materials regarding the implemented BMPs are also included in order to ensure community awareness and involvement.

The education campaign is targeted to several audiences, each with different concerns and levels of education, from elementary school-aged children to community leaders. Though the message is the same – explaining the need to protect water resources – the content and level of detail of the materials has been tailored for each audience. Given the fact that community members speak several languages and dialects, as well as the high level of illiteracy found in some of the communities, the information is primarily visual, with the use of simple language, diagrams and illustrations in order to ensure widespread understanding across communities. During this project, several lesson plans, classroom activities, posters, visual aids, and brochures were prepared in Spanish which were then reviewed with local educators during the site visits in

September and December 2006. Interviews to assess the effectiveness of the educational campaign will be conducted in collaboration with SYJAC within six months of the initial campaign implementation date.

#### 1.10 Recommended Monitoring Plan

The previous group project strongly recommended that a water quality and quantity monitoring program be implemented to provide reliable data for management and planning in the watershed (Bencala et al. 2006). Additional baseline data was gathered by UCSB students, including flow, nitrogen as ammonia or nitrate, phosphate, and pathogens at sites ranging from “pristine” conditions to a high anthropogenic impact. These helped to establish parameters for watershed modeling. Data from this preliminary monitoring, the initial WARMF model parameters, and contacts with researchers at ECOSUR were passed on to the second Chiapas group project.

The proposed monitoring plan for ECOSUR included 16 priority-ranked surface water monitoring points, based on expected classes and loads of pollutants, as well as all of the municipal drinking water supply wells. They recommended that physical, chemical and biological parameters be tested and suggested that these points be monitored by ECOSUR at least once a month. A sampling protocol, some water testing equipment and training were provided to the partners at ECOSUR from December 2005 to March 2006. Newly purchased materials included a Hach DR850 Portable Colorimeter capable of detecting up to 50 different water constituents and several Hach reagent kits. In return, any gathered data was requested to be shared amongst fellow researchers. ECOSUR began monitoring in May 2006, and has provided the results to UCSB students electronically.

#### 1.11 Watershed Modeling

In order to develop a framework for a sustainable watershed management plan it is necessary to understand how the watershed functions from the perspective of water transport and contamination. To this end, the first group used a watershed model to develop a basic understanding of the study area’s watershed processes. The model chosen, Watershed Analysis Risk Management Framework (WARMF), uses inputs of land use, meteorological data, soil depth, and subsurface water conductivity to model flow and pollutant loading (Systech 2007). Using this tool, and despite the paucity of available primary data, the researchers developed a replicable, though uncalibrated, baseline scenario of the watershed function.

After establishing this baseline scenario, the group used the model to estimate the effects on water flow and water quality that will result from the area’s rapid population growth. Two different population estimates were used, as well as the

estimated effect of upstream sewage treatment. The first San Cristóbal group project members also performed a sensitivity analysis to determine which model inputs have the most influence on the model output.

The first San Cristóbal project provided this project with an invaluable head start on modeling the San Cristóbal watershed. To improve upon the model, this project calibrated the baseline scenario using the water quality and stream flow data that the second group project members and ECOSUR partners collected starting in May 2006. Once calibrated, the model was used to identify the source loads from various locations as they affected the watershed's rivers. The areas were then prioritized as potential BMP implementation sites, and then analyzed under various scenarios to simulate potential pollutant load. The first group analysis indicates that the benefits of wastewater treatment on the outskirts of the study area is negated by the pollutant concentration of the city center waste stream, and that these concentrated sewages should be treated with a traditional wastewater treatment facility. Due to this project's focus on alternative treatment technologies and the scarcity of space to implement these technologies in the city center, this analysis concentrated on locations outside of the city center. The subsequent recommendations reflect the best scenario for BMP placement locations, and include per unit reaction from BMP implementation and aggregate estimated implementation costs.

#### 1.12 Continued Water Quality and Quantity Monitoring Plan

During this project span, the water quality and quantity monitoring carried out by ECOSUR has been supported in various ways by students at UCSB. Some additional monitoring was performed by students themselves, with ECOSUR's assistance, during trips to Chiapas. Flow monitoring is useful for establishing the water volume per time in different areas, while concentrations of various water quality parameters then determine the mass flux per time. The monthly monitoring data provided by ECOSUR was compiled and analyzed to determine trends and problem areas, which are detailed in a later section of this report. GPS locations of current monitoring sites were recorded, and the water parameter data obtained from these points was used to calibrate the WARMF model. Funding was obtained through UCSB to provide partners at ECOSUR with a new flow monitoring device, testing reagents for use with the Hach colorimeter, and a new state-of-the-art bacterial enumeration system. It has been communicated that disposable supplies for these devices will need to be purchased by ECOSUR after the end of this project.

The results of the water quality monitoring data are particularly helpful in determining the prime locations for BMPs, and what expected impact these will have on water quality. The WARMF model can then be used to project future water quality scenarios ranging from no change in BMP implementation to a higher rate of BMP use. By encouraging widespread BMP projects, a beneficial watershed scale impact on water quality is anticipated. Additional monitoring data was used to support the

development of BMPs. For example, water samples from the roof runoff at ECOSUR were examined to support the development of a filter for a rainwater harvesting system, while samples of wash water from Cinco de Marzo allowed the design of an appropriately sized wetland for grey water filtration from the EcoLavadero.

### 1.13 Outcomes of the First San Cristóbal Group Project

The outcome of the research conducted by the previous group was a management plan that included the identification of the key problems regarding water quality in the watershed, as well as a series of tools and recommendations that could be used to improve the water quality of San Cristóbal.

The primary areas of concern identified by the previous group were:

- Limited access to water
- Diminishing water supply
- Limited sanitation and wastewater services
- Poor surface water quality
- Municipality fines
- Human health and environmental impacts
- Population growth

In order to address these problems in a manner that would have a beneficial impact at the greater watershed-scale, the group devised a management plan that included four parts:

- Water Quality Monitoring Program: to provide reliable physical, chemical and biological data for improved management and planning in the watershed
- Best Management Practices: recommendations of the six most applicable solutions for the San Cristóbal de las Casas area – Rainwater Capture System, Composting Latrines, Retention Basins, Water Retention Trenches, Buffers, and Bioswales
- Education: to create materials that address the gap in knowledge between local water source quality and human health
- Watershed Modeling: to estimate the effects on water flow and water quality that will result from the area's rapid population growth.

### 1.14 Summary

The research and recommendation outcomes of the first group project were extensive and comprehensive. They provided a great deal of information and practicable solutions for their partner organizations in Mexico as well as a series of innovative

tools and management plan approaches that could be applied to other regions exhibiting similar conditions.

The deliverables from the first report provide an invaluable base from which this project was able to adapt ideas and direct further research into the area of implementation. With a solid understanding of the watershed dynamics and management needs of San Cristóbal, this project was able to assess the recommendations presented by the first group in terms of how they affected the objectives of this project. Since the implementation focus of this project was a move away from the goals of the first project, some of the recommendations were adopted in collaboration with both old and new partners, while other recommendations remained solely in the hands of the previous group's partners as they were deemed to fall outside the scope of this project.

The following chapters address the components of this project in greater detail. First, the report addresses in detail the best management practices investigated and implemented by this project. The chapter will examine the justification for the selection of each BMP and the methods used to collect data on these potential projects. The chapter then outlines the structure and function of each BMP and explains it with a narrative, a diagram, and a design manual, before addressing the detailed project implementation process.

Educational support is integral to ensure that the efforts of this project are successful. The education materials, themselves a BMP, aim to make the link between human health and water quality, as well as clarifying the purpose and benefits of the various BMPs investigated by the project. The education chapter discusses the development process of the education materials, identifies of the specific needs the program addresses, and lays out the strategy for overcoming these challenges.

Chapters 4, 5, and 6 focus on the tools and methods of scientific analysis that the project employed to gain an understanding of the current and potential future watershed conditions. Chapter 4 discusses the Water Quality and Quantity Monitoring Program that is currently being carried out in partnership with ECOSUR. The data from this program helps to clarify the understanding of how the practices in the watershed specifically impact its waters, and is used to inform and calibrate the watershed model. Chapter 5 explains the methods used in modeling the watershed, the scenarios modeled, and the results of the model. Finally, Chapter 6 addresses the analysis efforts to analyze future priorities for reforestation opportunities.

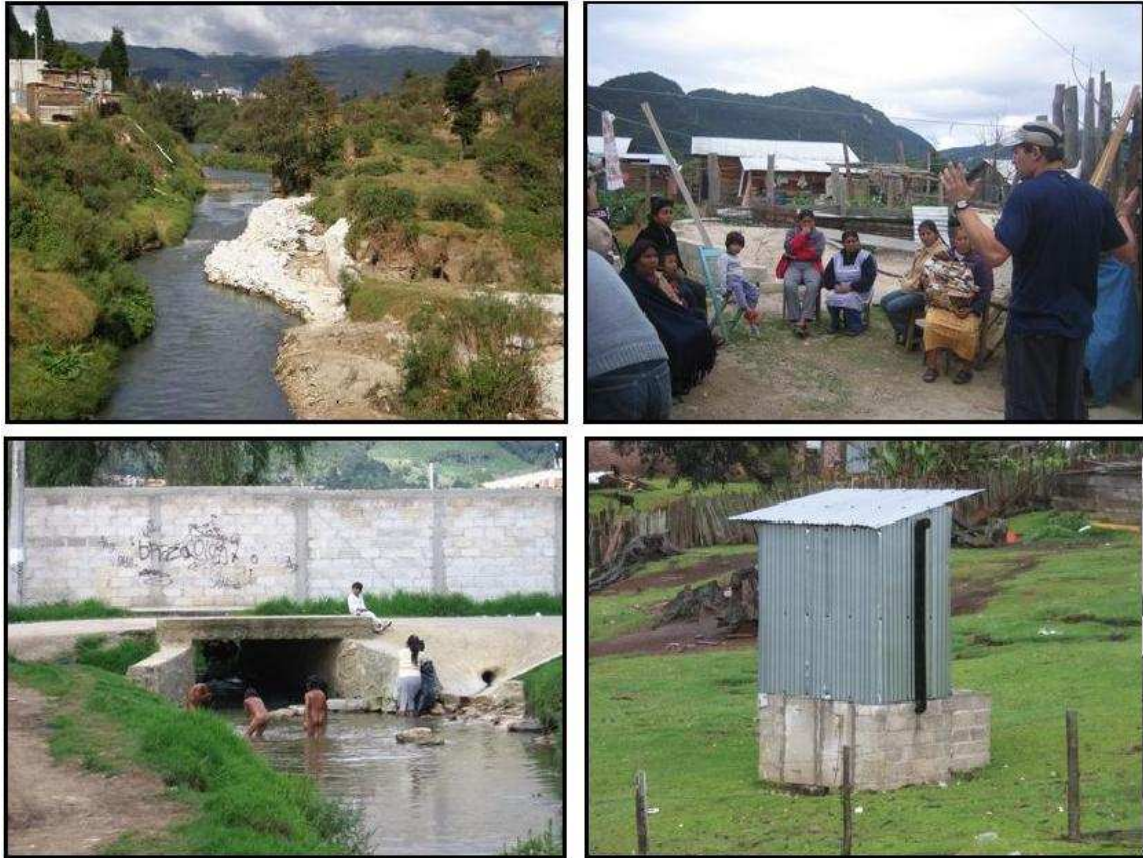
The final four chapters of this report look to the future of the San Cristóbal watershed. These chapters first address the lessons learned by the group during this project since the researchers confronted a number of challenges that were initially unforeseen or underestimated. Based on these lessons as well as the results and deliverables of the report, the project members developed a number of recommendations. Looking



forward, the report discusses future actions that will begin to address these recommendations.

## 2.0 Best Management Practice (BMP) Implementation

A significant portion of this project focused on the development of Best Management Practices (BMPs) aimed at addressing the pressures that have been placed on San Cristóbal's water resources (Figure 1). Given that detailed BMP designs alone are not enough to tackle water resource issues, the design and construction of these projects was supplemented by an education campaign, as well as quantitative watershed analyses intended to better develop water resource management strategies. Without a scientifically sound water quality and quantity monitoring program to assess the condition of water resources, a modeling program to estimate the effects of large scale BMP implementation, an educational program to promote understanding of watershed issues and local buy-in of implementation projects, the BMP designs alone would be ineffective.



**Figure 1.** Clockwise from top left: Amarillo River leaving the watershed through El Tunel (tunnel); Matthew Elke discussing the domestic rainwater harvesting system with residents of Cinco de Marzo during a rainwater harvesting system demonstration day; free-standing latrine in San Cristóbal; children bathing and women washing dirty clothes in river.

## 2.1 Approach and Justification

BMPs apply recognized management concepts in the most appropriate way for a particular set of local problems and concerns. BMPs encompass physical structures such as composting toilets or retention basins, land management conversions such as reforestation, and behavior modification resources such as education materials for classroom use. A BMP implementation regime aimed at long-term sustained water resource improvement must take a technologically comprehensive approach by combining various adaptable BMPs, as opposed to relying on one BMP in the belief that it is adaptable to all conditions regardless of site specificity. With the lack of water supply infrastructure in San Cristóbal, BMP projects must be both creative and flexible if they are to succeed.

Members of this project quickly realized that constructing a rainwater harvesting system, composting latrine, or any other management technology would be more successful with a complementary educational component that enhances local understanding of the function and benefits of the BMP, and therefore increase the probability of acceptance and maintenance of the project. In order for this water resources management project to work, local stakeholders must be educated not just about the BMP technology, but also about basic sanitation and resource efficiency issues.

Beyond the promotion of BMP education, subsequent monitoring helps to determine whether or not the BMPs are performing as expected, and computational modeling of the sites serves to anticipate what effect they will have if implemented on a large-scale basis in the watershed. This robust evaluation protocol, coupled with a comprehensive educational program is designed to achieve an effective and sustainable BMP implementation process.

This project researched many different varieties of BMPs to help address the issues associated with water pollution and water resource availability specific to San Cristóbal. The initial focus of the BMP research was based on the management options recommended by the first San Cristóbal project for cost-effective watershed improvement. The six initial BMPs studied were:

- Rainwater Harvesting Systems
- Composting Latrines
- Retention Basins
- Buffer Zones and Bioswales
- Contour Water Retention Trenches
- Education Campaign

It became clear as the project progressed, and as stakeholders expressed specific interests, that the initial six BMPs would not fully address the concerns of all the

actors involved. Therefore, in addition to the initial set of BMPs, two additional BMP technologies were researched and evaluated.

- Greywater Treatment Constructed Wetland
- Blackwater Treatment Constructed Wetland

In one case, multiple BMP technologies were combined to provide a unique solution to the specific needs of stakeholders. Furthermore, several BMPs were tailored to address the meteorological, environmental, and social constraints of Chiapas. The following BMPs were proposed as pilot project designs to address the water resource problems facing San Cristóbal:

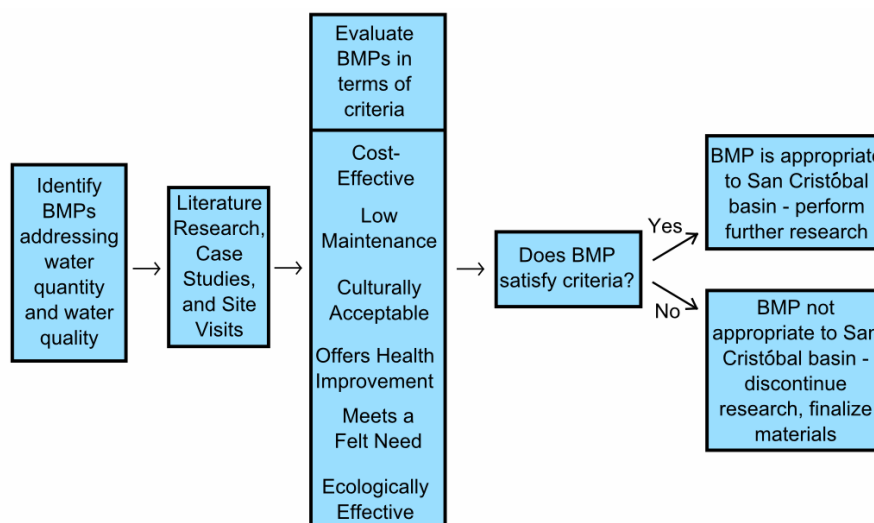
- Residential rainwater harvesting and storage system in the community of Cinco de Marzo
- EcoLavadero: an ecological clothes-washing station incorporating both rainwater harvesting (RWH) and a greywater treatment constructed wetland system
- Rainwater harvesting and storage system for Cinco de Marzo school buildings
- Community blackwater treatment constructed wetland in Cinco de Marzo
- Rainwater capture and storage system for the ECOSUR campus

None of these BMP designs has the ability to independently solve water resource issues. Rather, a strategic combination of a range of BMP technologies can help reduce the pressures on water resources at the watershed scale. The constraints of this project – temporally, spatially, and financially – limited the scope of BMP implementation. The project aimed to implement pilot projects, evaluate their effectiveness, and model their effects if applied over a larger area.

## 2.2 Approach to Research and Implementation Decisions

A main project goal was to implement *sustainable* pilot projects. Researchers determined that a sustainable project is effective, durable, and appropriate. Recognizing that an implemented project will not serve to improve watershed and human health if it is not properly used, malfunctions, or is abandoned, researchers considered these elements in all stages of the BMP selection process.

BMPs selected for research, except in the case of the EcoLavadero (because it is an original design), are recommended by water managers in the United States and around the world. A large body of literature provides data on design considerations and results of implemented BMP projects. Project members recommended only BMPs that are likely to succeed in San Cristóbal. A number of criteria were chosen to evaluate each BMP in terms of appropriateness, which are listed in Figure 2 and described below.



**Figure 2.** Schematic of initial steps in the BMP selection process

This project approached the research and decision-making process about pilot project implementation in both a methodical and scientific manner (Figure 2). The initial step sought to determine which BMPs were applicable as water management technologies within the framework of problems and interests unique to San Cristóbal. BMP recommendations from the previous project were evaluated, determined appropriate, and further researched. An extensive literature review of each of the BMPs followed.

The project team performed a comprehensive examination of the scientific function of each BMP technology to guarantee proper understanding. Research was not, therefore, limited to case studies and methods of application, but also included an understanding of the general chemistry, biology, and physics related to the BMP and its implementation. Furthermore, in an effort to include future possibilities of BMP application beyond the geography of this project, research was not limited to applications within Mexico or the developing world. Information was gathered from studies in various locations in order to assess BMP qualities such as the breakdown rates of human waste, the efficiency of water transport by different materials, and the appropriate water retention time needed for contaminant removal through constructed wetlands.

Once a firm understanding of the theory and data behind these BMP technologies was established, project members observed real world applications of these BMPs. Santa Barbara, the city and county in which UCSB is located, is the site of several projects that have been implemented using the BMPs that were researched in this project. The project team visited several bioswales designed to catch and treat stormwater runoff from residential neighborhoods. In addition, the group visited a local residence that incorporates a domestic rainwater harvesting system, as well as a local working farm that utilizes a fully functional composting latrine. The purpose of these field observations was to augment the literature-based theoretical and scientific knowledge

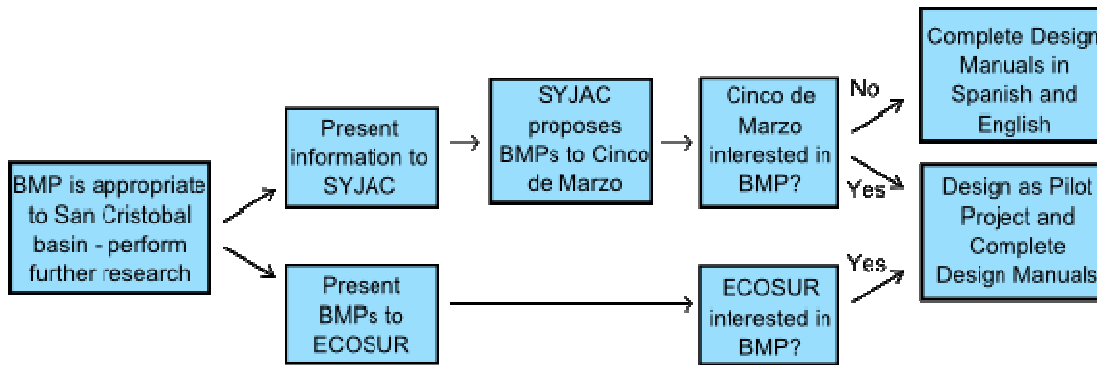
with the practical knowledge (including the inherent requirements and restrictions) observed in the application of the technologies.

Project members then turned to literature on sustainable development strategies to assess the BMPs “appropriateness” to the San Cristóbal area and plan the implementation process. According to Ronald Bunch, there are a number of criteria that must be considered when planning and implementing a project in a developing country. Experience shows that practices that “stick” within a poor community in a developing area have a number of characteristics in common. For instance, the practice or project must meet a felt need in the community, fit local cultural patterns, address those factors that most limit community health, be simple to understand, be safe for the area’s ecology, and require minimal financial resources that can be easily obtained (Bunch 1982).

Professional experiences of group members working with communities in Africa and Latin America also contributed to establishing criteria for the evaluation process; as a result of seeing one too many projects abandoned due to community members inability to perform maintenance, it was determined that low maintenance should be a requirement for all recommended BMPs. Project members also strengthened Bunch’s criterion of being safe for the area’s ecology, and asserted that the recommended BMPs must contribute positively to the environment, as this project focuses on solutions for environmental problems. These criteria were used to determine which BMPs would be initially recommended to partners at SYJAC and ECOSUR.

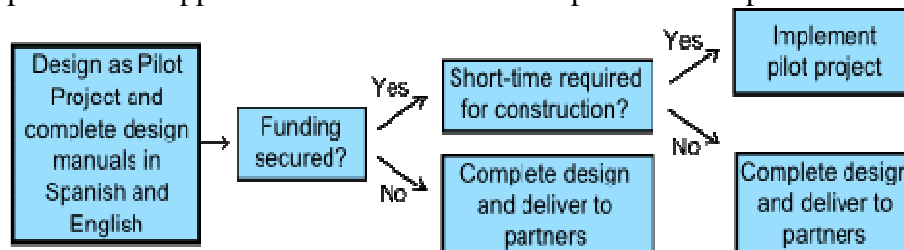
In order to ensure that the technologies were appropriate to the residents of the city of San Cristóbal, local conditions, personal attitudes, material availability. This project used survey data obtained from ECOSUR to assess general demographics, extent of water infrastructure, water use intensity, and water quality concerns (Alianza Cívica, COCIDEP, and ECOSUR 2006b). This information was supplemented by an initial visit to the San Cristóbal area by one of the project team members, wherein the concerns and requests of clients and stakeholders were clarified.

The initial research process culminated in the production of short two-page informational sheets, along with longer design manuals (Appendix A). The purpose of these manuals was to explain to project partners and stakeholders the advantages and limitations of each BMP option. Each design manual included information about the BMP’s purpose, function, siting and size requirements, maintenance procedures, and cost estimates. It was communicated to the stakeholders that the researched and recommended BMPs were only options, and that project implementation was ultimately not the decision of the UCSB group, but rather that of the stakeholders. Furthermore, these manuals were designed to allow other partner organizations to disseminate BMP information to any interested parties in a simple yet comprehensive package.



**Figure 3.** Schematic of decision-making process with partners

As the project progressed, some of the BMPs were selected on the part of stakeholders for implementation in San Cristóbal (Figure 3). Additional research on these BMPs led to the creation of specific pilot project designs for the greywater and blackwater wetlands, the EcoLavadero, and the rainwater harvesting system at ECOSUR. Ultimately, the group created design manuals for eight BMPs and proposed five specific designs to stakeholders for pilot project implementation, one of which is completed, one of which should be completed in April 2007, and a third that is planned for construction during the summer of 2007 (Figure 4). All of the design manuals and pilot project proposals were translated into Spanish and distributed to project partners to support immediate and future implementation plans.



**Figure 4.** Schematic of BMP implementation decision-making process

## 2.3 BMP Descriptions

### *2.3.1 Rainwater Capture and Collection Systems*

#### Background

Rainwater capture and storage is a historically documented method for providing a regular supply of freshwater for domestic use (Figure 5). Rainwater harvesting systems have been found in India dating back to 3000 BCE, while cisterns have been discovered in the Negev Desert of Israel dating from 2000 BCE. In Venice, Italy, rooftop catchment systems were the main source of domestic water from the 3<sup>rd</sup> century up until the 16<sup>th</sup> century, a span of 1,300 years (Gould and Nissen-Peterson 1999). Rainwater has been traditionally valued for its purity and softness, characteristics credited to a neutral pH due to the absence of salts and minerals commonly found in ground and surface water sources.





**Figure 5.** A domestic rainwater harvesting system constructed in the community of Cinco de Marzo.

### Purpose

With increasing global population, the pressure being placed on water resources is growing. The problems associated with these pressures are often amplified in the developing world due to a lack of both water supply infrastructure and a comprehensive plan to manage regional water resources. At the end of the millennium only 60% of the rural residents in developing countries had access to any type of improved water resources (Gould and Nissen-Peterson 1999). Throughout many parts of Latin America, where rainfall is prevalent and water abundant, access to water resources can be severely limited due to contamination, a lack of storage facilities, and inadequate delivery systems (UNEP 1997). In San Cristóbal, this shortage of water storage facilities, inadequate supply systems, and severe contamination all serve to inhibit reliable access to clean fresh water.

From a survey of city residents performed in 2006, 62% of respondents were not satisfied with their water service, over 60% experienced regular service interruption, and 6% received water only once per week (Alianza Cívica, COCIDEP, and ECOSUR 2006a). While the respondents to this survey all had connections to the city municipal water provider, SAPAM, the survey did not account for the thousands of people in the city and its periphery who are not serviced by SAPAM's water infrastructure. In the face of the water supply limitations in San Cristóbal, the use of

harvested rainwater can provide numerous advantages (Texas Water Development Board 2005):

- The water is free; the only cost is for collection, storage, and use
- The point of use of the water is close to the source, eliminating the need for costly infrastructure
- Rainwater provides a source of useable water when surface or groundwater sources are of unacceptable quality
- Rainwater harvesting reduces the quantity of stormwater runoff that would lead to erosion

While rainwater capture and collection do have many applications, there are several limitations as well. Much of the success of a rainwater harvesting systems is determined by the duration and frequency of the rain in a given region. Rainwater harvesting may not be an effective option in dry areas or those prone to drought. Even in wet climates, prolonged dry periods will have a negative effect on the ability of the system to supply sufficient water. If not properly maintained, systems can quickly become contaminated and create a health hazard. Furthermore, the storage tank or cistern portion of the system can pose a safety hazard to small children (UNEP 1997).

Even with these limitations, however, rainwater collection and capture has substantial benefits. It is flexible enough to be applied in a wide range of conditions – rainwater harvesting can be adapted to most climatic and ecological conditions, as well as nearly all socioeconomic situations. The inherent flexibility of rainwater capture and storage systems is one of its greatest attributes.

#### General Description

Independent of the design or specific application, any rainwater harvesting system has three basic components:

- A water catchment surface
- A water conveyance system
- A water storage unit

The water catchment surface is usually the roof of a house, school, or other building. However, the catchment surface can alternatively be a simple lean-to or elevated metal sheet. The only requirements are that the catchment surface be impermeable and clean so that water will not become contaminated once it hits the surface. Many types of materials can be used for the catchment surface including galvanized metal, corrugated plastic, pesticide-free wood, ceramic or clay tile, and concrete. Even painted surfaces are acceptable so long as the paint is neither lead-based nor toxic so that it will not leach into the water (Gould and Nissen-Peterson 1999).

The conveyance system usually consists of collection gutters to catch the water running off the roof, and piping to transport that water to the storage tank. Similar to



the catchment surface, several materials can be used for the conveyance system. Galvanized metal is often used for gutters, while plastics such as PVC and HDPE are common materials for piping (Gould and Nissen-Peterson 1999). Wood can also be used for gutters and is often the material of choice for gutter supports.

Normally, the biggest expense and most critical part of any RWH system is the storage vessel. For small domestic projects, a prefabricated plastic (usually HDPE) tank or a constructed Ferro-cement tank are the most common options. For larger buildings, or systems that incorporate water gathered from a number of catchment surfaces, an underground Ferrocement or concrete cistern is a more logical option. By no means are storage containers limited to what is described here and in fact any durable material that does not leach contaminants can be used to store harvested rainwater. It is important, however, to take into account both the setting and the proposed use of the captured water when determining the type of storage container to be incorporated.

#### Costs

Rainwater capture and collection systems, especially small-scale domestic ones, can be relatively inexpensive compared to other water supply sources, often the individuals and communities who would receive the most benefit from this technology lack the resources necessary to implement such systems. Although much interest was expressed for rainwater harvesting systems, initial reservations concerning the cost of materials prevented immediate acceptance and subsequent implementation. Research of costs conducted by this project revealed that in San Cristóbal the materials for a single family domestic system cost between \$200 and \$300 (In section 2.0 of this report all costs are in US Dollars unless otherwise stated). A larger, more complex system designed to capture water from the roofs of several buildings for storage in an underground cistern costs up to \$10,000. A complete breakdown of the costs for a single family domestic system can be found at the end of the Rainwater Harvesting and Storage design manual located in Appendix A.1. A complete breakdown of costs for two multiple building community systems, one for ECOSUR and the other for Cinco de Marzo, can be found in Appendix B.

#### Applicability to Target Area

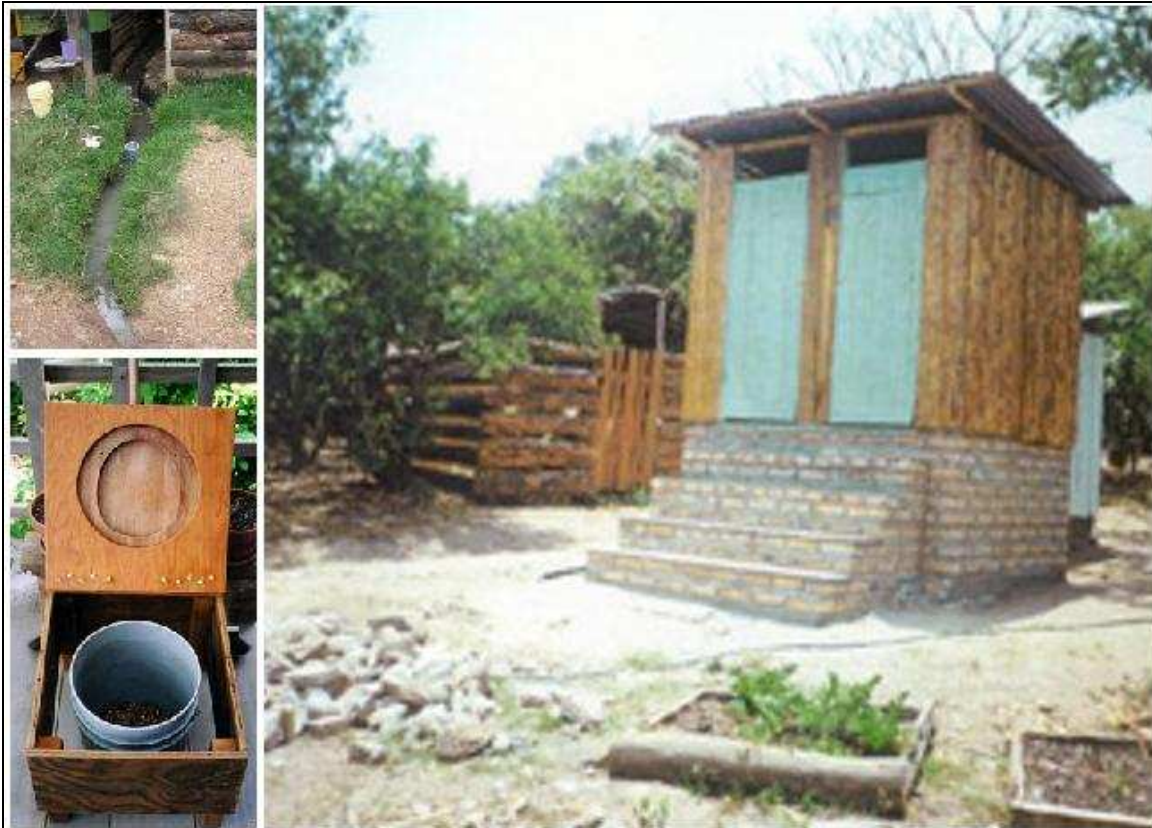
Rainwater harvesting is not a new practice for the people of San Cristóbal. In fact, systems of various designs can be seen throughout the city and the outlying areas. Nevertheless, it is clear from the types of systems in use that there is a lack of understanding and/or available resources to construct systems that efficiently capture rainwater and store it in a way that does not promote contamination. A properly designed and well-maintained system is able to capture up to 90% of rainwater that falls on the catchment surface and store it in a manner that almost completely limits the probability of water contamination (Gould and Nissen-Peterson 1999). Design oversights and lack of proper maintenance, however, can quickly result in a system that is inefficient, increases erosion pressures, and promotes contamination of stored water. The lack of access to water resources by a large portion of the

population in the San Cristóbal region increases the appeal of rainwater harvesting as a useful and effective means of improving local accessibility of high-quality water. Properly designed systems coupled with local understanding of system functions and benefits will help to guarantee a relatively clean water supply for local communities.

### 2.3.2 Composting Latrines

#### Background

Human waste collection and composting is a practice that has been used by numerous cultures for thousands of years. Chinese farmers collected and stored human waste for use as a fertilizer on their fields. This “night soil”, or humanure, when handled properly and given enough time to degrade reduces the danger of diarrheal diseases which are common in the handling of human feces ("Using Human Manure ("Nightsoil") in the Tai Lake Region of China" 2003). In Yemen, dehydration and urine separation is still commonly used to treat human waste. The hot and dry climate ensures that urine and feces quickly dry out for harmless collection and disposal. Today in Vietnam and many regions in Mexico and Central America, composting toilets can be an effective means of human waste management when used properly (Winblad and Simpson-Hébert 2004).



**Figure 6.** Clockwise from upper left: An untreated flow of blackwater from in the colonia of Cinco de Marzo; a standard double-chambered composting latrine (Herbert); an in house sawdust toilet

### Purpose

Inadequate sanitation and polluted water are two of the chief environmental problems facing developing nations. It is estimated that 40% of the world's population is without adequate sanitation (UNDESA 2004), and the World Health Organization (WHO) estimates that more than 80% of all diseases are related to inadequate sanitation and polluted water (Jenkins 2005). Nearly two million people die each year from diarrhea and dehydration-related illness, with 90% of those victims being children under the age of five. Studies conducted by the WHO have shown that improved water supply reduces diarrheal disease by 6-25 %, while improved sanitation can reduce incidents of these diseases by up to 32% (NWP 2006). Isolating human waste so that it decomposes or dehydrates is an effective method of improving sanitation (Figure 6). It can also produce a useable fertilizer that has economic benefits. Many areas that would benefit from composting latrine projects also have high numbers of small scale or subsistence farmers. The fertilizer that can be obtained from composting latrines could increase crop yields, reduce chemical fertilizer inputs, or be sold to other farmers.

Many of the residents of San Cristóbal completely lack any sanitation services. Human waste is either left to collect in pit toilets or is simply allowed to run off the land into neighboring streams or wetlands without any form of treatment. Consequently, the surface waters and, in some cases, the groundwater in the city is highly polluted. Composting latrines provide an effective means for isolating human waste so that it does not come in contact with surface and groundwater resources. If used and maintained properly, composting toilets are a very effective human waste management option.

### General Description

Solid human waste is loaded with pathogens when leaving the body. Over 60% of the dry mass of feces can be attributed to bacteria (McDougall 2005). Not all of these bacteria are directly harmful to humans, but there is a sufficient amount to cause raw human feces to be a major source of pathogen-related diseases. Composting latrines work by isolating and containing human feces, which creates an environment where harmless bacteria and fungi accelerate the die-off of harmful pathogenic bacteria found in the human digestive track. This pathogenic breakdown can also be caused by the dehydration of feces, as it is in Yemen. The wet humid climate in San Cristóbal and much of the rest of Chiapas, however, rules out dehydrating toilets as a viable management option.

The two main factors leading to pathogen destruction in composting latrines are temperature and time. This composting process can be accelerated by increasing the temperature of the active pile to promote the growth of beneficial thermophilic bacteria. It takes one month in the proper conditions at a consistent temperature of 43°C (109.4°F) to fully destroy the pathogens in human feces. This process is accelerated to one week at 46°C (114.8°F) and to only one hour with a consistent temperature of 62°C (143.6°F) (Jenkins 2005). It is unlikely that a humanure pile will

ever reach these high temperatures and, in fact, it may never reach consistent temperatures above that of the human body, 37°C (98.6°F). Due to the difficulty associated with reaching such elevated temperatures, as well as the difficulty related with maintaining the elevated temperature, it is generally recognized that a humanure pile should be allowed to cure for approximately one year in order to ensure complete pathogen destruction (Jenkins 2005).

While composting latrines are not a complicated technology in terms of construction, they do require operation and maintenance beyond filling up a chamber with feces and then letting it cure and compost for a year's time. A number of important steps must be followed to ensure that the latrine functions properly and does not turn into a pit toilet (Jenkins 2005):

- An aerobic environment must be maintained in the compost pile at all times to facilitate beneficial bacterial growth.
- The compost pile needs to be kept sufficiently moist so that the beneficial aerobic bacteria do not dehydrate and die.
- A carbon rich topping material such as hay, straw, sawdust, ash, leaves, or even weeds is needed to balance the low C:N (carbon to nitrogen) ratio in feces.
- The added topping material should occasionally, if not exclusively, be a coarse material (hay, straw, weeds) to keep air passages open within the pile.
- Once the composting chamber is filled, the pile should be allowed to cure for approximately one year.
- At a minimum two collection chambers are needed – one where feces are actively being deposited and the other where compost is curing.

An aerobic environment is necessary because anaerobic conditions stifle the recruitment of aerophilic bacteria, resulting in a foul smelling compost pile due to the production of hydrogen sulfide ( $\text{H}_2\text{S}$ ), acetic acid ( $\text{C}_4\text{H}_2\text{O}_2$ ), and butyric acid ( $\text{CH}_3\text{CH}_2\text{CH}_2\text{COOH}$ ). Sufficient moisture can usually be provided by urine and/or rain (if the compost pile is outside and exposed), and would rarely require water additions. The C:N ratio in feces is generally around 8:1. To promote the composting process, help eliminate odors, and get the ratio closer to the ideal level of 30:1, a carbon-rich covering material needs to be added after each use of the toilet (Jenkins 2005).

Though they represent an adaptable, simple, and effective way to improve sanitation, composting latrines do have limitations. They require more space than a simple pit toilet due to the addition of topping materials. This can be a problem in urban areas where space is limited. They also require regular maintenance and attention to ensure that they don't begin to foul and stink. This can happen rapidly if the latrine is neglected, and once fouling has begun it can be difficult to fix. Some communities also have difficulty understanding the process of composting or simply have social taboos about handling and recycling human waste. Any project that attempts to implement composting latrines must address the need for complementary education.

This information not only needs to cover the functional steps of the latrine, but also sanitation basics and common misunderstandings.

### Costs

Composting latrines are very economical and can produce valuable results without much resource input. The inherent flexibility of composting latrine design leads to a wide variability in costs. A simple indoor sawdust toilet costs between \$20 and \$25 in materials and can be made by anyone with access to a hammer, saw, and nails. The price is even less if the toilet is made from used materials. The composting bins or chambers can be built for around \$100, but would again cost even less if old pallets or wooden boards are salvaged. Covering material can be purchased for a marginal cost or they can be scavenged for as well. A past project in a different area of Chiapas constructed nine freestanding composting latrines with an average material cost of around \$210 per toilet (Beaudoin and Cuéllar 2005). Around \$200 is also the cost estimate this project determined for a freestanding outhouse style composting latrine. When one considers the lost wages due to care of sick children, the money spent on medicines needed to combat diseases caused by fecal pathogens, or even the money that can be generated from decomposed fertilizer, composting latrines are a very cost effective BMP option.

### Applicability to Target Area

Composting latrines are a very appropriate BMP in San Cristóbal and especially the more rural villages of the watershed. They address the lack of sanitation infrastructure and the resultant pathogenic exposure. They are also simple enough in design that no special training or skills are required to construct them, and they are flexible in both material design and application. Composting latrines can be built as an indoor toilet coupled with external composting bins, or as a self-contained freestanding outhouse. There is abundant access to various covering materials due to the climate and lush vegetation. When operated correctly, composting latrines are one of the most cost-effective BMP options for treatment of human waste. They even produce a commodity with value – fertilizer – a product that could potentially recoup the initial capital costs of implementation. The main reasons the composting latrine BMP did not experience widespread acceptance in San Cristóbal was due more to existent cultural mores and inadequate knowledge of the technology than to the effectiveness of the BMP.

### *2.3.3 Retention Basins*

#### Background

In the second half of the 20<sup>th</sup> century and into the first decade of the 21<sup>st</sup>, changes in land use have continued to progress at a fast rate. More urban land is becoming covered with impervious surfaces and the increased reach of development is leading to more widespread erosion and runoff pressures. Agriculture and livestock grazing on sloped hillsides is increasing the loading of nitrogen, phosphorus, pesticides, herbicides, and sediments. This loading is exacerbated by the fact that these areas

were historically covered by forests which retained top soil and nutrients. Such land use changes can lead to thinner and more fragile soils with less water infiltration capacity. This creates a positive feedback situation which exacerbates the erosion and the pollution loading problem (Bencala et al. 2006). These factors have increased the levels of stormwater runoff and the sediment and pollution loads carried by the stormwater. Retention basins are a BMP designed to mitigate the negative effects of these large quantities of water and associated pollution loads (Figure 7).

#### Purpose

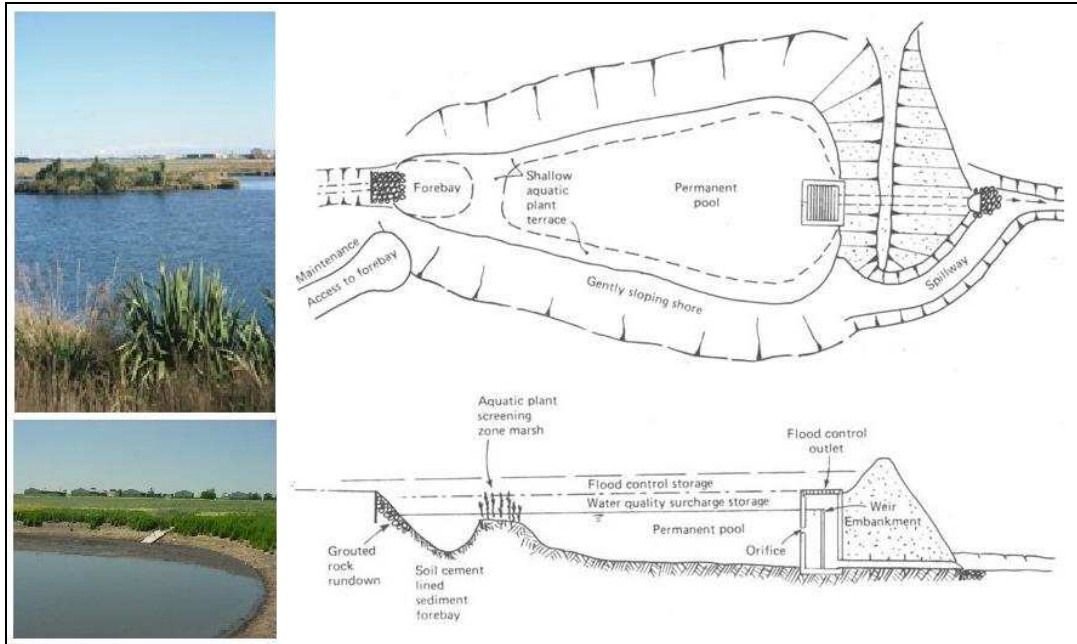
San Cristóbal currently has no municipal infrastructure in place to treat the large volumes of stormwater runoff that flows from the mountain or urban landscape and is discharged directly into the urban river system. Stormwater often causes both flooding in the streets and deposition of sediments. This is not only a concern because of high pollutant levels in the water, but also because the force of these large volumes of water can be a hazard to urban residents. Retention basins help to mitigate and reduce these effects by capturing stormwater runoff, retaining it for a period of time, and then slowly treating it through natural biological means (Clar, Michael L, Barfield, and O'Connor 2004a). The basins slow runoff and allow the water to infiltrate into the ground or drain gradually into the surface water. Retention basins have the potential to remove 65-70% of the suspended solids delivered to them, 45-50% of the total phosphorus, 30-35% of total nitrogen, 25-70% of metals, and up to 65% of bacterial loads (US Environmental Protection Agency, U. E. 2002).

#### General Description

There are two types of retention basins:

- Wet retention basins, or retention ponds, maintain a standing supply of water year round.
- Dry retention basins only contain water during periods of rain.

While there are some differences that should be considered when choosing the type of basin (discussed below), both types of retention basins function largely in the same way. The basin can be dug out of the ground or an embankment can be built in a low lying area that naturally channels the flow of runoff. The length:width ratio of the basin should be no less than 2:1, with a level bottom to ensure correct directional flow, maximum treatment time, and subsurface water infiltration (Clar, Michael L., Barfield, and O'Connor 2004b). Oblong structures with inlets at opposite ends are best, as this configuration promotes directional flow (Stahre and Urbonas 1990). Figure 7 is an example of a properly designed wet retention basin, with two photos depicting wet ponds in the environment.



**Figure 7.** At Right: Diagram of a sample “wet retention basin” pond (StahreandUrbonas 1990); at left two real world examples of retention basins similar to the diagram on the right

The optimal removal of nutrients occurs with a retention time of 2-3 weeks for pools with 1-2 meters of depth before the water is discharged or infiltrates into soil. Too short a retention time will lead to insufficient biochemical processing, while too long a retention time will cause stratification within the pool, therefore leading to incomplete treatment (Clar, Michael L. et al. 2004b). The retention time of water in the basin can be calculated by [Equation 1].

[Equation 1]

$$T = VB / (n \cdot VR)$$

T = retention time

VB = the volume of the basin

n = the number of runoff events in a given period

VR = volume of runoff in an average rain event for that period

The type of retention basin most applicable to a given set of conditions may be different due to a variety of reasons ranging from climactic, to demographic, to economic. Wet basins have been shown to provide greater treatment than dry basins, but they must have a reliable source of runoff for much of the year to maintain their permanent pool (StahreandUrbonas 1990). There may not be enough precipitation spread out over the course of the year to maintain a wet basin. The variation in mean monthly precipitation in San Cristóbal could make a permanent wet pool an impossibility in some locations (Comisión Nacional del Agua 2005). While a wet basin can be adapted to account for this variation, it may not make economic sense, in which case a dry basin may be the more appropriate application.

### Costs

Construction costs are site-specific and depend a great deal on labor inputs and available land. Some maintenance procedures are labor intensive, with operational expenses closely tied to labor rates for the region. Typical US costs are: \$45,700 for a 1 acre-foot pond, \$232,000 for a 10 acre-foot pond, \$1,170,000 for a 100 acre-foot pond (US Environmental Protection Agency, U. E. 2002). One acre foot is the equivalent of a volume of water one foot deep over an area of one acre, or one meter of water depth over 0.123 hectares. Determining exact costs for San Cristóbal and Chiapas was difficult without good data on land values or the average hourly wage for laborers and construction workers. In addition, retention basins were not a BMP in which project partners took a close interest, so specific production and operational costs for San Cristóbal were not obtained.

### Applicability to Target Area

The lack of any real municipal stormwater management system reinforces the applicability of retention basins. They do not require complicated manufactured materials that are difficult or costly to deliver to the San Cristóbal area. Though an appropriate engineering evaluation should be done prior to construction, this technology is not overly complicated and finding competent engineers in the area is likely. Further, the two principal resources needed for retention basin construction are sufficient labor and sufficient land. While labor is relatively cheap in the area, finding available land is more difficult, however the inherent flexibility in sizing and configuration of retention basins makes this less of an issue.

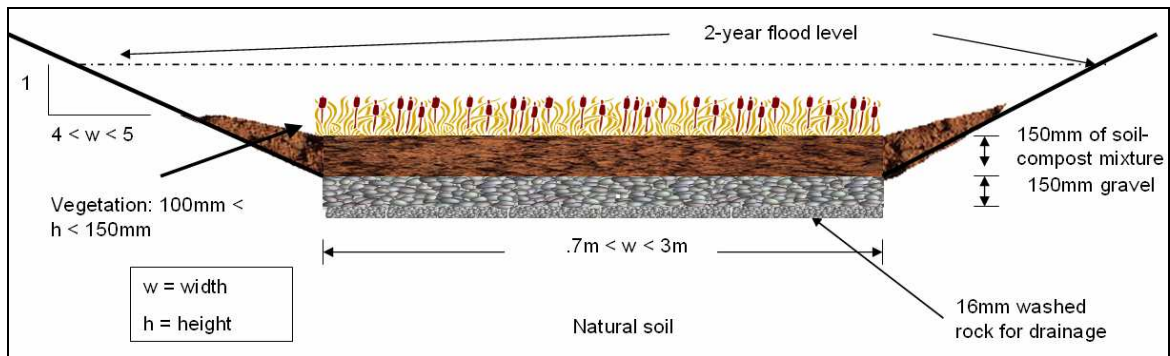
While retention basins have many advantages, there are a few issues that could limit their appeal. This is a relatively foreign technology to the people of San Cristóbal, where it is often difficult to generate acceptance of new technologies and ideas. Retention basins are inherently large-scale projects, generally requiring government approval, not to mention accord from the local community and other stakeholders. It might become difficult to implement a project that requires the approval of many different stakeholder groups at both the local authority and the property owner levels.

#### *2.3.4 Buffer Zones and Bioswales*

### Background

Bioswales serve a similar function to retention basins in that they treat stormwater runoff by retaining it for a short period and by allowing natural biological processes to break down pollutants and nutrients (Figure 8). Expansion of impervious surface cover and altered land use has increased the need for BMPs geared specifically toward stormwater runoff. Bioswales have been widely implemented in the past to reduce pollution loads in runoff from parking lots, roadways, basketball and tennis courts, and small agricultural areas (Figure 9). During the preliminary research phase, the project team visited two bioswales in the Santa Barbara area intended to reduce stormwater runoff from a residential development.





**Figure 8.** Diagram of typical bioswale (King County 2005)



**Figure 9.** Application of a bioswale in Chiapas (left); plant removal as part of bioswale maintenance (right) (Clark County Corrections)

### Purpose

Bioswales are designed to reduce the pollutant loads in stormwater runoff before the water joins surface waters. They also reduce the flow rate of fast-moving stormwater, therefore abetting erosion and other physical damage caused by stormwater. Bioswales can serve the dual purposes of allowing biological treatment of water during storm events and providing recreational open space during dry periods. However, it must be noted that bioswales can be flooded easily and the technology is not designed to treat large flows of water. For this reason, a peak flow bypass structure should be incorporated into the design to prevent overtopping of the bioswale banks in the event of excessive flows (Jurries 2003).

### General Description

A bioswale is a very generic term used to describe many subtly different types of stormwater treatment channels that use biological filtration. The common components are the presence of vegetation as the primary treatment media, and the fact that bioswales only contain water during storm events. A bioswale is created by excavating a shallow depression in the earth to receive and then slowly convey stormwater runoff. Bioswales use natural filtration elements, including herbaceous vegetation and soil, to treat stormwater by filtering out contaminants in water through both adsorption onto soil particles as well as uptake by vegetation. The bioswale should have shallow slopes and should be built over soil that drains well.

This technology functions best under light to moderate runoff conditions. Large stormwater flows can quickly flood the bioswale and reduce the effectiveness of the vegetation and soil to remove pollution loads. Check dams, which create temporary pools and increase residence time and infiltration, can also be planned into the design in order to abate flows entering the bioswale (Jurries 2003; Yu, S. L., Juo, ASCE Members, Fassman, and Pan 2001). The five main steps in this BMP's implementation process are:

- Site identification
- Flow calculation, including the two year maximum flow event
- Canal design and check dam location
- Inlet location and siting of peak flow bypass
- Determination of construction start date

When determining site location, the total land area that drains into the bioswale must not be larger than the swale's capacity to ensure that the bioswale will function properly and that the swale will dry in between storm events. In California, the transportation administration, CalTrans, recommends a tributary area of less than four hectares (CalTrans). The structural specifics of the bioswale, including the location(s) of check dams, the structures of the inlet and outlet, and the mechanism for peak flow bypass, need to be determined. Finally, construction should be timed so that the completion date is at least three months prior to the onset of the rainy season in order to allow the vegetation sufficient time to establish itself (Mazer 1998). Bioswales with compost added to bed material have been shown to experience faster growth, thicker coverage, and higher removal efficiency than those with only soil (The Clean Washington Center and E & A Environmental Consultants 1997).

#### Costs

Bioswales can vary greatly in cost, depending on design and availability of materials. For instance, in Mexico, soil and compost can be obtained free of cost, or often very inexpensively. Other materials include rock, gravel and seeds for vegetation. It is estimated that a bioswale measuring seven by 30 meters (210 m<sup>2</sup>) would cost approximately US \$200–800 in Mexico. However, construction costs soar when labor and engineering advice are included. As an example, 227 m<sup>2</sup> bioswale in North Carolina treating a drainage area of 2.8 hectares cost US \$4,000 to construct, while a much larger 400 m<sup>2</sup> bioswale treating water from 2.0 hectares cost the same amount (North Carolina Green Building Technology Database (NCGBTD) 2003).

#### Applicability to Target Area

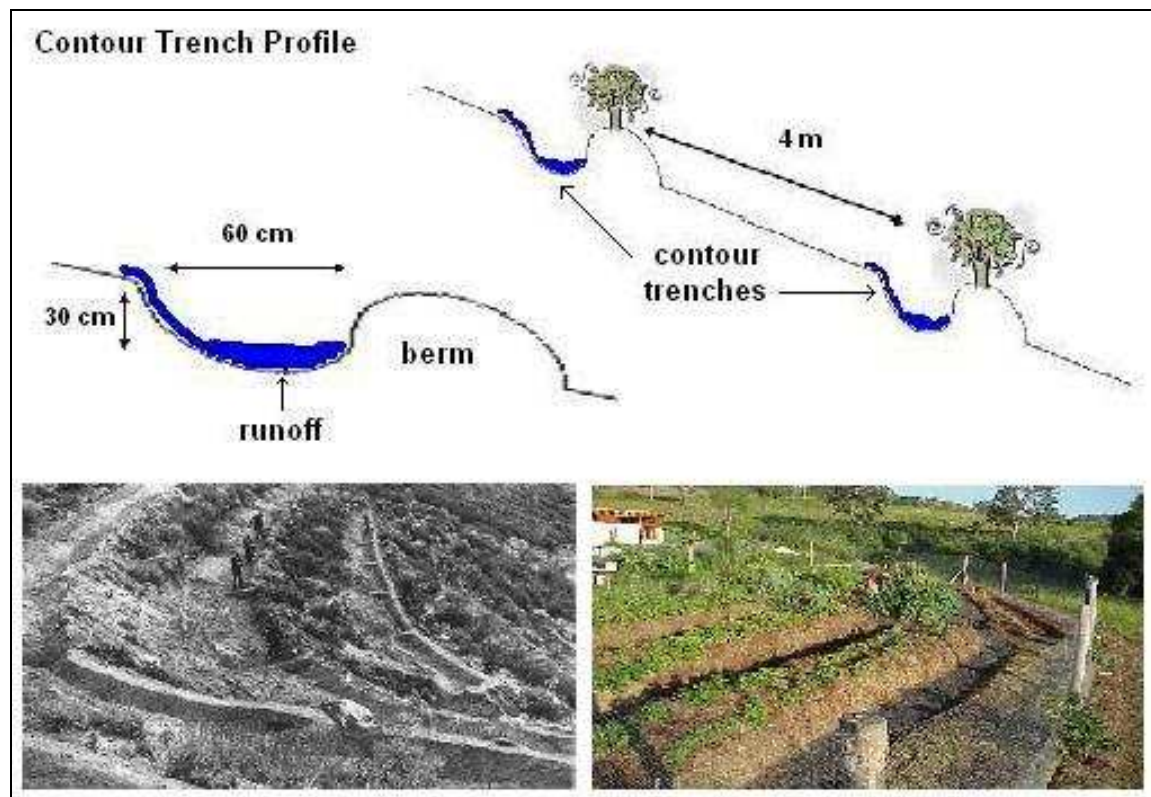
Like retention basins, the ability to effectively implement bioswales in the San Cristóbal area is limited by the difficulties of coordinating all stakeholder groups. Functionally, bioswales are very effective at treating stormwater pollution loads. Political and social barriers, however, present a difficulty for implementation in San Cristóbal's watershed. As an adaptation, relatively small bioswales can be designed to

treat small runoff areas. This may reduce the number of stakeholder groups involved and thereby ease the implementation process.

### 2.3.5 Contour Water Retention Trenches

#### Background

As more and more land is claimed for agricultural and habitation purposes; development has encroached upon slopes and hillsides of San Cristóbal's watershed. Land that was once deemed marginal is now being cultivated to grow corn and other staple crops. Development on sloping hillsides increases erosion levels and sediment loads as changes in use reduce the ability of the land to retain soil. Soil erosion is not the only problem associated with hillside development, though. Applications of fertilizers, both natural and synthetic, have led to significant loads of nitrogen, phosphorus, potassium, and other compounds in runoff waters throughout the watershed. The high pollutant loads have severe impacts downstream at lower elevations where runoff waters converge. Contour trenches can help to reduce this pressure by decreasing and diverting runoff flow, thereby reducing the energy and capacity for carrying sediments and pollutants off the hillsides (Figure 10).



**Figure 10.** Clockwise from top: Diagram of the typical shape of a contour trench; contour trenches used in a permaculture application; contour trenches in the western US (Harper)

### Purpose

Because of the geographical position of San Cristóbal, numerous rivers and streams drain the hillsides and run through the city before flowing out of the mountainside via the Sumidero tunnel. Contour trenches can reduce downslope migration of topsoil and associated nutrients. Load reduction values have been reported of 75% and 70% for phosphorus and nitrogen, respectively (U.S. EPA 2006). In addition, experiments indicate that contour trenches can reduce sediment in runoff by as much as 50% (IIRR 1998). Properly maintained contour trenches perform the dual roles of reducing pollutant loading of the waterways and increasing the productive life of hillside agriculture.

### General description

A contour trench combines a ditch or trench with an elevated berm just down slope that allows the runoff to be diverted so the course is elongated through the perpendicular run of the trench. Contour trenches are most effective where the soil has good infiltration rates. The added distance the water must travel, combined with friction from the land, reduces flow energy and allows sediments and pollution to filter out. Figure 10 near the beginning of this subsection shows an example of spacing and orientation of a contour trench and berm.

Contour trenches accumulate nutrient-enriched soil sediments while channeling and diverting runoff. Occasionally, the deposited soil must be physically removed and placed onto the source field or similarly managed area. This maintenance is required to prevent the contour trench from filling up and losing its ability to function. It is also a beneficial way to conserve topsoil on the managed area.

### Costs

Contour trenches have very few material costs. Locally harvested plants can be transplanted onto the berms to act as a vegetative buffer to further minimize erosion and help trap sediment in any water that would overflow the trench (IIRR 1998; NRCS 1999). Trench excavation tools (shovels and picks) might be rented or borrowed at little to no cost. Contour trench construction is highly labor intensive and requires long-term maintenance. However, if the labor can be donated or incorporated into the existing culture of farming operations, then contour trenches may be the most cost-effective BMP studied by this project.

### Applicability to Target Area

Contour trenches are a great option for runoff management throughout the San Cristóbal watershed. They are a cheap and effective means of reducing the pollutant loads in runoff water and, furthermore, many of the hillside farms scattered throughout the watershed are of a small enough size that a single family could construct and maintain contour trenches on their land. Unlike other BMPs, the appeal of contour trenches to those designated to implement them is not necessarily the reduction in pollution, but the benefit to soil conservation and increased agricultural productivity (an economic incentive). A farmer living in the upper elevations of the

watershed is not likely to be directly affected by the pollution loads in runoff that is channeled downstream, but he or she will be affected by the increased crop yields that may come from greater top soil retention. These benefits should be clearly explained to stakeholders in order to achieve more widespread implementation of contour trenches.

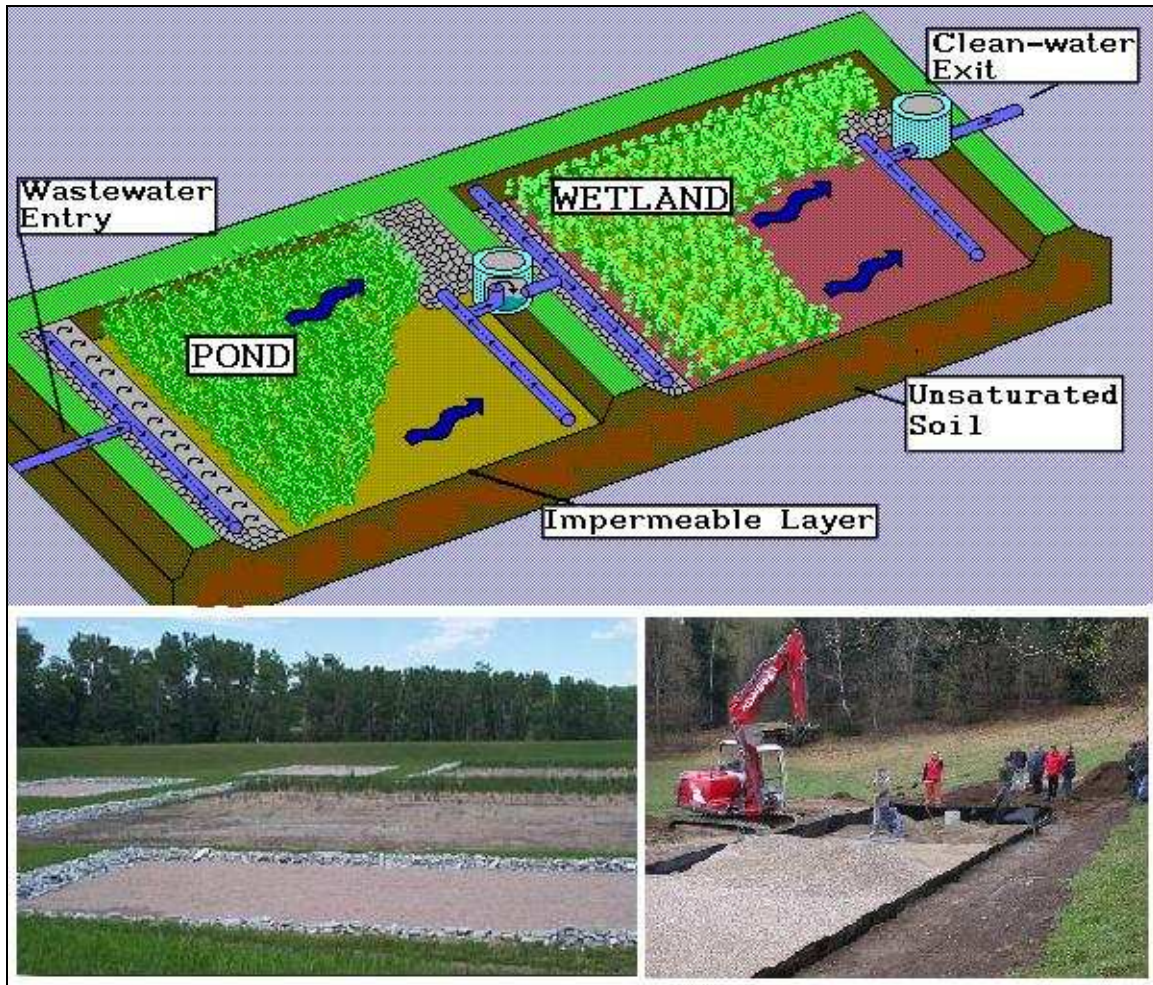
Despite the benefits contour trenches offer, there was little interest in this BMP from clients or main stakeholders. Contacts and relationships were developed almost exclusively with the urban residents and communities in the city of San Cristóbal itself. The project had very little contact with the rural communities located outside of the city due to the fact that making contacts and establishing a productive relationship with new stakeholders who worked in the rural areas around San Cristóbal was a prohibitively time intensive process. Moreover, issues of social trust required contact with an additional Mexican project partner who could have served as a liaison to the community.

### *2.3.6 Blackwater Constructed Wetlands*

#### Background

Natural wetlands are one of the environment's primary means of waste treatment. Rivers, streams, and even unincorporated waters flow through wetlands. These low-lying inundated areas provide a means of decreasing high pollution loads in waters through biological filtration and detoxification. Constructed wetlands mimic natural wetlands and are a method of treating the wastewater stemming from human activities (Figure 11). In the US, constructed wetlands have been used in municipalities for secondary treatment of wastewater flows. For nearly 30 years the city of Arcata, California has supplemented its wastewater treatment plant operations with a constructed wetland system so that the effluent discharged into Humboldt Bay meets the EPA's National Pollution Discharge Elimination System (NPDES) permitting requirements. Emmetsburg, Maryland also uses a constructed wetland to treat municipal wastewater effluent. By 1984, the demand for sewer hookups in Emmetsburg was increasing due to population growth, and the city needed to increase its wastewater treatment capacity. The city determined that a single-basin constructed wetland would be the best way to accomplish their goals (US Environmental Protection Agency, U. E. 1998).





**Figure 11.** Clockwise from top: Schematic showing a stabilization pond coupled with a constructed wetland (Marshlands.com); construction of a wetland cell (Purdue Residential Onsite Wastewater Disposal 2007); a blackwater wetland ready for plant establishment (Agrium US)

### Purpose

Discharge of untreated human waste effluent is one of the most significant pressures on water resources in the San Cristóbal region. San Cristóbal has no central waste management system. Rather, municipal sewage pipes simply convey and discharge untreated human waste directly into the rivers. Further, in rural communities throughout the watershed, as well as some peripheral urban neighborhoods within the city, there is a lack of sewer conveyance mechanisms to transport wastewater in a sanitary manner. Fecal coliform and total coliform concentrations of both surface water and groundwater sources are one of the primary causes of diarrheal diseases throughout the region. Constructed wetlands can reduce illnesses caused by poor sanitation by destroying the pathogens that cause disease. Blackwater wetlands also help to reduce odors and prevent human vulnerability to wastewater (Hammer 1989).

### General Description

A constructed blackwater wetland uses mechanical settling and biological filtration to treat sewage. Blackwater wetlands can stand alone or they can be coupled with either traditional water treatment plants or, in less sophisticated systems, oxidation ponds and septic tanks. Usually sewage treatment by a blackwater wetland is preceded by primary treatment by a septic tank or stabilization pond to remove solids. Then, as water flows through the wetland cell, bacteria in the wetland media break down the harmful pathogens in the wastewater for secondary treatment. Metals and nutrients are absorbed via the roots of the wetland plants, so that once the water flows out of the wetland cell, its pollutant concentration is substantially reduced.

One of the real advantages of a constructed wetland is the simplicity of its progression through the system. If water has not gone through a wastewater treatment plant (a process description that is beyond the scope of this paper), it first encounters a stabilization pond or septic tank where solids are separated from the water through mechanical settling. Once separated, the wastewater flows into the wetland cell where the remaining dissolved and suspended organic matter is processed by microbes. As water flows through the gravel substrate in the wetland, pollutants are removed through a combination of physical processes (sedimentation and filtration), chemical processes (precipitation and adsorption), and biological processes (bacterial metabolism) (US Environmental Protection Agency, U. E. 1999).

Some of the most important considerations when planning a blackwater constructed wetland system are:

- Siting and location of the wetland
- The volume of effluent to be treated
- The availability of proper materials and vegetation
- Availability of paid or volunteered labor for construction and maintenance

Blackwater wetlands should be located near the effluent source that is to be treated and should rely on the natural slope of the land to transport the waste stream through treatment cell. Areas with high water tables should be avoided as this can lead to wastewater percolation and ground water contamination (US Environmental Protection Agency, U. E. 1999). This contamination potential can be exacerbated if more effluent is being delivered to the wetland than was estimated in the design capacity. Poor sizing may result in inadequate treatment or wetland fouling. Conversely, inadequate wastewater effluent delivery to the wetland can result in plant death, thereby destroying filtration capabilities. Maintenance of constructed blackwater wetlands is not overly complicated, though it is imperative that the operation and maintenance protocol be clearly defined.

### Costs

Costs will vary significantly depending on the site and the type of materials used. In the US, total cost of subsurface flow constructed wetlands was on average \$601,716 per hectare (1998 US dollars) (Crites, R. W., Middlebrooks, and Reed 2006).

### Applicability to Target Area

From a strict design and performance standpoint, constructed blackwater wetlands are one of the very best BMP options available for the treatment of human wastewater effluent. There is no wastewater treatment plant in San Cristóbal, nor is there any other effective method to treat human waste flows. Constructed blackwater wetlands, perhaps more effectively than any other BMP referenced here, have the ability to greatly reduce the harmful effects of large amounts of untreated human waste being released into the environment indiscriminately.

Though constructed wetlands are highly applicable to San Cristóbal's wastewater issues, there are two main barriers to implementation. The first is the prohibitive costs to local stakeholders. Small blackwater systems that serve one or two homes cost relatively little, but a large constructed wetland designed to treat the wastewater of an entire community can become very expensive. This expense is compounded by the fact that time and maintenance-related resources are very limited in San Cristóbal, especially in the beneficiary communities. The second main barrier concerns oversight of the wetland's construction and operation. For example, issues that arise may include the type of municipal approval and permitting required, management and operations funding for a large community-based system, and addressing free-rider issues. These issues indicate that projects of substantial size and scope, which involve many different stakeholders, have logistical and sociological hurdles to overcome that small family-based systems do not have.

### *2.3.7 Greywater Constructed Wetlands*

#### Background

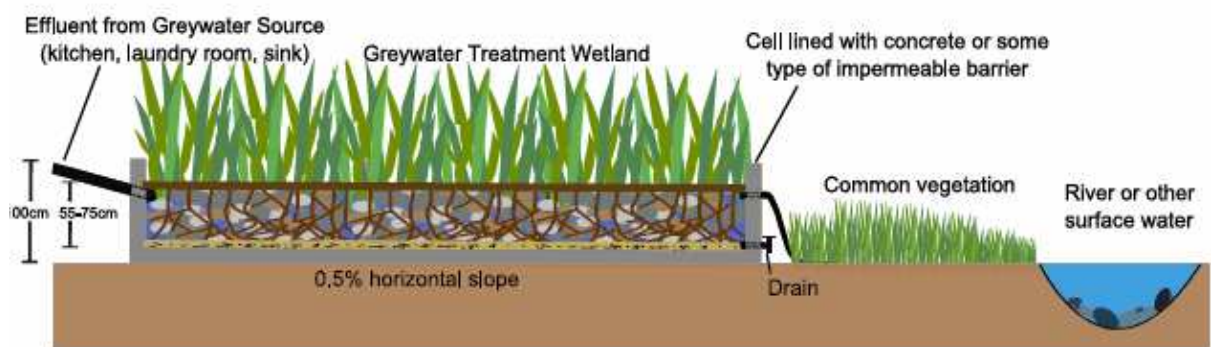
The pollutant loads in domestic wastewater streams do not contain the high level of fecal pathogens that exist in blackwater. For a single household, 50-80% of all wastewater is greywater; this includes the washwater from dishwashing, bathing, and laundry activities (Ludwig 2005). While greywater, unlike blackwater, does not pose an immediate health hazard, inadequate treatment of greywater can lead to many problems. As the population of San Cristóbal increases and residents gain access to more modern amenities, the use of soaps, detergents, and other household chemicals, as well as the discharge of metals, salts, oils, and organic nutrients rises markedly. Consumption of greywater-contaminated drinking water can expose individuals to harmful chemicals and heavy metals. In addition, greywater can create pH imbalances, increase oxygen demand, and contribute to eutrophication in surface waterways. It can also become stagnant and produce foul odors, while serving as a breeding ground for mosquitoes and other insects that are sources of harmful diseases



(Winblad and Simpson-Hébert 2004). Despite these potential impairments, it is not uncommon for management plans to overlook greywater treatment and pollution.

### Purpose

A greywater constructed wetland (Figure 12) addresses the problem of pollution from components commonly found in greywater such as nitrate, phosphate, soaps, salt, bacteria, bleach, foam, food particles, organic matter, suspended solids, perfumes and dyes. By flowing through a subsurface constructed wetland, many pollutants in the greywater are retained in the soil or gravel media and processed by microbes. The effluent thus contains decreased loads of Biochemical Oxygen Demand (BOD), nitrogen, and other pollutants, and surface waters are spared these contaminant loads.



**Figure 12.** A typical subsurface flow greywater wetland system

### General Description

While constructed wetlands are designed differently depending on the targeted pollution source, greywater constructed wetlands function very similarly to blackwater wetland systems. Due to the decreased bacterial loading and fewer solids found in greywater as compared to blackwater, there is no initial septic treatment or settling pond needed. Water simply flows into the wetland cell where particles and adsorbed contaminants settle within the gravel substrate medium of the cell. Among the roots of the wetland plants, bacteria and other aerobic microbes break down the organic pollutants and absorb nutrients and trace metals. The wetland is designed to promote a residence time of two to ten days in order to allow plants and microbes to remove as many pollutants as possible. Similar to constructing blackwater wetlands, a number of considerations must be taken into account when designing greywater systems:

- Location of the wetland cell
- Volume of greywater to be treated
- Pollutant composition (usually simplified as BOD levels in mg/L)
- Vegetation

Greywater systems tend to be smaller than blackwater systems. Due to the elimination of pretreatment requirements, they are easier to site and are more flexible in design. However, just like blackwater wetlands, proper sizing is important. A series of calculations can help determine approximate cell sizes (these can be found in the greywater manual in Appendix A.5). An undersized greywater wetland can become clogged or overflow. Conversely, a system that is oversized may not have enough consistent throughputs to sustain the vegetation and the microorganisms living within the wetland cell.

All wetland plants can use the nutrients and other materials in the wastewater to some extent, though relatively few plants thrive in the high-nutrient, high-BOD waters of treatment wetlands (Mitsch and Gosselink 2000). There are a few plants that are most frequently used for greywater biofiltration wetlands such as cattails, bulrushes and reed grasses, all of which are found in natural wetlands. Wetland plants found close to the constructed wetland area are the most beneficial because they are already accustomed to the local climate and the roots are already colonized by helpful water treatment microorganisms. If natural wetland plants cannot be found locally, any wetland plants that can adapt to the site may be used.

#### Costs

Based on this research, there are few examples of constructed wetlands devoted to treating greywater. Basic materials needed include an impermeable liner (concrete or impermeable plastic), medium-sized gravel, sand, or mulch for the medium, wetland plants, an inlet pipe, outlet pipe, drain, and fine plastic mesh grate to prevent clogging. Costs will be determined by the size of the system and price of materials.

#### Applicability to Target Area

Greywater wetlands, like blackwater wetlands, are one of the most effective BMPs for treating wastewater flows. In the developed world, there are often city-wide wastewater collection, conveyance, and treatment systems that account for the greywater-producing activities of daily life. In San Cristóbal there are no municipal systems to serve this function. A solution to this problem is to couple greywater treatment wetlands with each greywater-producing flow such as sinks, showers, or laundry stations. Alternatively, combining and channeling effluent produced by a single family home to a small greywater wetland or garden is a feasible domestic application of this BMP.

A community clothes-washing station combined with greywater treatment is an effective way to reduce exposure to polluted surface waters. Furthermore, washwater is treated and returned to the environment in a cleaner state. An application of this idea is currently being implemented by one of the group's partners in San Cristóbal. A detailed description of this "EcoLavadero" project can be found in section 2.4.1 of this report.

Treated greywater can also be used in irrigation, since many beneficial nutrients are still present in the effluent. Stakeholders can treat their washwater and irrigate their crops at the same time. The ability to obtain a direct benefit from something traditionally viewed as waste will always increase its viability in San Cristóbal.

#### 2.4 Application of BMP Pilot Projects

A main focus of this project was the physical implementation of BMP pilot projects within the San Cristóbal watershed. The project team realized early on that there were a number of factors that had to be taken into account to ensure proper, successful, and legitimate BMP implementation, including:

- BMP project designs would have to be complete and specific to the San Cristóbal region and its unique set of conditions. If possible, design manuals were made flexible to allow for future application under a different suite of conditions in other regions.
- Clients and stakeholders had to play an active role in the BMP project design and implementation process.
- Clients and stakeholders held the ultimate decision-making power in the selection of BMP designs for implementation.
- The project team acted as a facilitator, providing advice, recommendations, and implementation assistance.

With these factors in mind, eight design manuals were developed to address various issues confronting partners, target audiences, and levels of specificity. The variation in the design manuals is a function of the inherent differences among BMP technologies and the varying levels of acceptance on the part of local stakeholders. Three pilot projects were approved for implementation and two of those projects were initiated prior to March 2007. A fourth project was proposed and received preliminary interest from stakeholders, but it has not yet received the necessary support to determine whether it will be implemented in the foreseeable future. Table 1 below lists the three approved projects and their current stage in the implementation process.

**Table 1.** Current projects in various stages of implementation

<b>Project</b>	<b>Stage of Implementation</b>
<b>Clothes Washing Station (EcoLavadero):</b> Project incorporates rainwater harvesting and greywater treatment in a community clothes-washing station.	Project is midway through the construction phase as of March 2007.
<b>Domestic Rainwater Harvesting Demonstration:</b> An individual home in a stakeholder community was chosen to demonstrate the construction process and the advantages of domestic rainwater harvesting.	Project was begun in December 2006 and was completed by mid-January 2007.
<b>Multi-Building Rainwater Harvesting and Filtration:</b> A rainwater harvesting and filtration system designed to provide a seasonal source of supplementary potable water to a stakeholder university.	Project funding has been approved; no start date has been set.

#### *2.4.1 Clothes-Washing Station (EcoLavadero)*

##### Purpose

In many parts of San Cristóbal, not only is there very limited access to adequate water sources, but indoor plumbing with running water is also rare. Several communities have difficulty obtaining enough water for the fundamental tasks of drinking, cooking, bathing, and washing clothes. For many local communities, the solution to the latter problem is simply to wash clothes and household linens directly in nearby streams or rivers. Surface waters flowing through the city are extremely polluted, though, with high concentrations of fecal bacteria and organic nutrients. This leads to higher incidences of skin rashes and diarrheal diseases for those who come in direct contact with river water. Furthermore, the process of washing clothes directly in streams adds more pollution to surface waters in the form of detergents, soaps, metals, and oils. During the project team's second visit to San Cristóbal in July of 2006, it became clear that this was a practice that should be addressed through the BMP and educational campaigns.

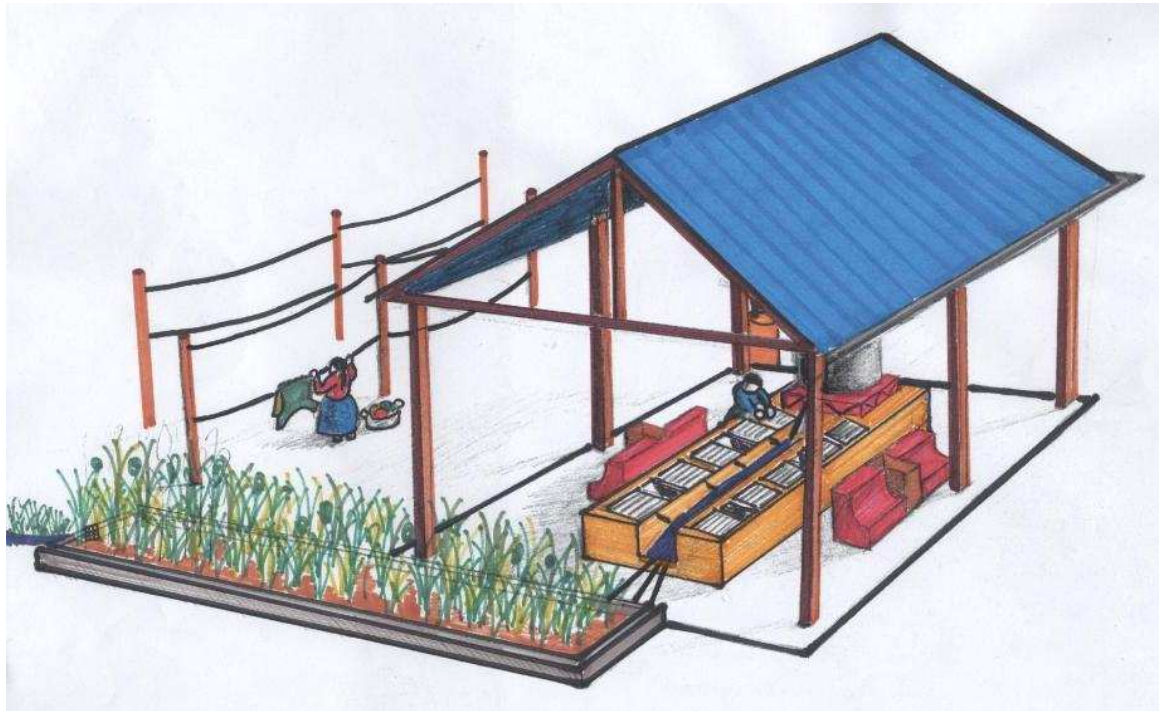
With the help of Grace Keller, an architect from Mexico City, a preliminary design for a clothes-washing station or "EcoLavadero" was developed. The purpose of this EcoLavadero was to provide a safe and clean environment where people could wash their clothes without being exposed to the pathogens and other pollutants present in contaminated surface waters. Two BMPs were employed to increase the pilot project's resource efficiency and reduce its environmental impact:

- Rainwater harvesting is used both to provide a steady, reliable water supply during the rainy season and to eliminate the need for year-round groundwater extraction.
- Greywater filtration ensures that the pollution loads to the environment are less than what they would be with traditional washing practices.

### General Description

The EcoLavadero design has evolved over the course of the project, although the basic structure and function has remained the same (Figure 13). There are three main subsystems within the EcoLavadero:

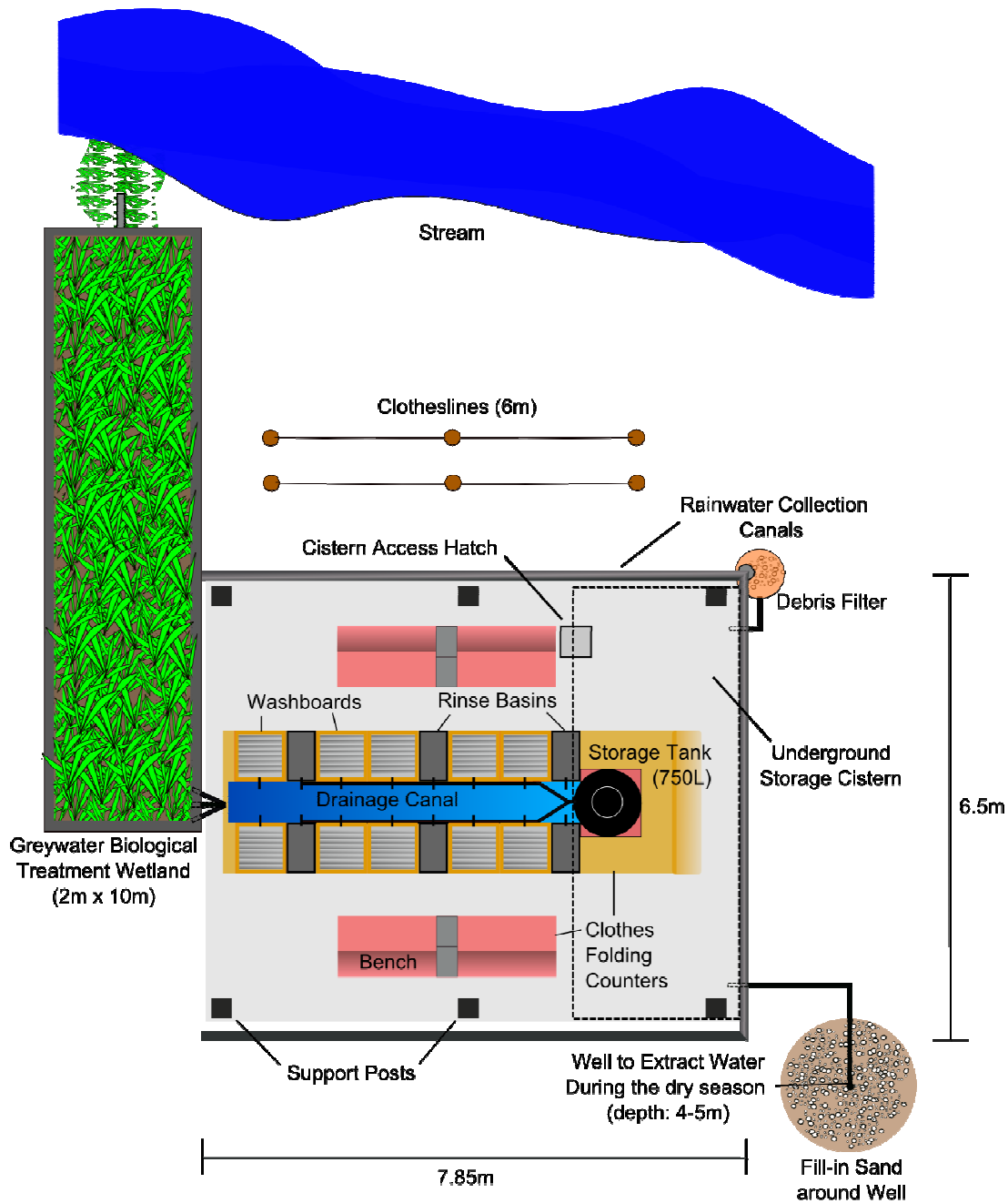
- Water collection and storage infrastructure;
- Wash basins and rinse basins where clothes are laundered; and
- A greywater treatment wetland that removes pollutants from the residual washwater.



**Figure 13.** Stylized drawing of the completed EcoLavadero

The EcoLavadero has two water supply sources, as seen in the upper right corner of Figure 14. The primary source is a rainwater harvesting system that utilizes a roof above the wash basins for water collection. The rainwater that falls on this catchment surface is transported by gutters and piping through a rough sand filter to remove debris, then stored in an underground cistern. During the dry season, water can be pumped from a small well nearby. As the level of water in the storage cistern begins to decline, the pump can be used to refill it. Under either scenario, before clothes can

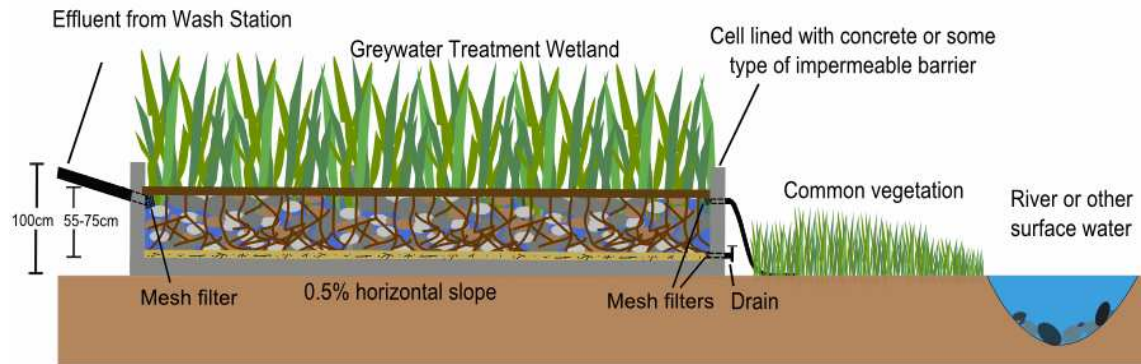
be washed, water must be pumped into an elevated storage tank. Water then flows from this tank via gravity to each wash basin on demand.



**Figure 14.** Overhead schematic view of the EcoLavadero

The actual washing bank is divided into two halves with five wash boards and three rinse basins on either side, a total of ten and six respectively. Each side of the wash bank has its own clothes folding ledges, sitting benches, and trash bins for both

organic and inorganic waste. Once clothes have been cleaned, they can be hung on the adjacent clothes drying lines. The dirty washwater then runs down the central drainage canal and into the constructed greywater wetland (Figure 15).



**Figure 15.** The structure of the greywater biofiltration treatment wetland

Once the greywater drainage water enters the constructed wetland, it begins the treatment process with mechanical treatment through the soil and gravel substrate. As the washwater makes its way slowly through the wetland, biological breakdown is carried out by the bacteria living on the roots of the wetland plants. Further water treatment occurs through the absorption of nutrients by the plants and other microbes. Finally, clean washwater is discharged from the wetland and flows harmlessly into river.

The description above gives only a brief overview of how the EcoLavadero functions. A much more comprehensive description of the EcoLavadero can be found in the accompanying design manual entitled, *Ecological Clothes-Washing Station Incorporating Rainwater Harvesting and Greywater Biofiltration Constructed Wetlands* (Appendix A.6). Additionally, more complete descriptions of rainwater harvesting and constructed greywater wetlands can be found in Appendices A.1 and A.5.

### Costs

As of March 2007, the EcoLavadero had yet to be completed and so the total cost of the project is unknown. A good estimate for the material costs is in the US \$2,200-\$2,400 range. Due to certain construction aspects requiring the special skills of a professional mason, an additional \$500 has been spent for these services to date.

### Lessons Learned

The EcoLavadero is a community-based project both in its implementation and its use. Having many community members involved in the construction and development process increased the sense of project ownership throughout the community. The size of this project also required the labor input of many community members. Without this labor contribution, the increased costs for this system would have severely limited its appeal. It is therefore very important to cultivate and



maintain good working relationships with all stakeholders. Without community buy-in and a sense of ownership, the long-term sustainability of this project would be compromised. If the construction was not initially driven by community interest, any motivation to maintain the project would dissolve, therefore resulting in a failure to address the problem the system was originally designed to combat, and a waste of time and resources.

For the EcoLavadero, it has become apparent that buy-in is not necessarily complete without clear leadership. One important step in the preparation procedures is identifying a stakeholder who provides local direction and maintains enthusiasm to complete the project. It has been observed that one of the women working on the project (Sonja) has taken it upon herself to organize and motivate the community. However, when she is absent from the project or the community the work slows. An important point of further research remains regarding differing motivation levels among community members as well as tools for inspiring self-motivation and drive in the non-participatory members of the community.

#### *2.4.2 Domestic Rainwater Harvesting Demonstration*

##### Purpose

Hundreds of families in San Cristóbal lack improved water resources service in their homes. Instead, some communities have shared spigots that deliver water intermittently from the municipal water district. Other communities use long hoses to divert water from nearby hillside streams. Due to the high water table, personal household wells are occasionally dug to access groundwater. In many of these situations the quality of water is quite low and/or the dependability of the supply is not high. An individual household rainwater harvesting system can provide a family with a consistent supply of clean water during the rainy season. If the dry season is short in duration, the RWH system's storage tank can extend the period of water availability. A large capacity storage tank need only be filled a few times during the dry season if water is used judiciously.

A central reason for implementing a domestic rainwater harvesting pilot project was to provide an example of a family with a consistently dependable water supply system. Further, the project aimed to observe whether the pilot project would perform as well as expected. However the overriding impetus for the RWH demonstration project was to demonstrate to families in the community what benefits this type of system can offer. The true success of this pilot project lies in the momentum it can produce for more families and communities to understand water supply and water quality issues, and to create the desire to adopt this type of system where applicable.



## General Description



**Figure 16.** The domestic rainwater harvesting system constructed in *colonia* Cinco de Marzo.

Figure 16 above shows the functioning domestic system. A complete explanation of the entire project can be found within the Rainwater Harvesting and Storage design manual located in Appendix A.1. The construction of a functioning domestic RWH system was combined with an educational curriculum to be used during the demonstration of the construction process. The implementation of this BMP took place in two phases:

- Education and information dissemination during the demonstration
- Longer-term monitoring of the functioning domestic RWH system and assessment of its effectiveness in meeting water supply goals

The development of the demonstration required careful planning so as not to alienate any stakeholders. The project had the resources to construct a single system, so the process of choosing a family had to be done with careful consideration. Group members discussed the sensitivity of the situation – funding was limited to one system – with partners at SYJAC and with leaders of the community group. A meeting was held with the members of the community that were present to work on the EcoLavadero. At this meeting, the financial limitation was explained to the group and the community leaders decided to conduct a raffle to determine whose house would be used for the demonstration.

After the raffle, project members accompanied the winner, Señora Maria Gomez Lopez, to her house, where they measured the dimensions of the house's roof and courtyard. In order to minimize costs, building materials and tools that were available in the Gomez Lopez household and in neighbor's houses in Cinco de Marzo were used or borrowed whenever possible. Later, the group members and Señor Gabino Gomez Lopez (the husband of Señora Maria Gomez Lopez) bought supplies for the house in preparation for the demonstration. Most materials were brought back to the community immediately, but some were delivered in the days leading up to the demonstration.

The demonstration and accompanying educational component lasted for one day, while the whole system was constructed over the course of four days. Over this time period, four construction stages were required to complete the project in its entirety. A system like this can be built easily in two days when all of the needed materials are on site; however, due to scheduling and logistical constraints, more time was needed for this pilot project.

Two buildings make up Señor Gomez's house, and this domestic system utilizes both roofs. On one of the buildings the entire roof ( $27\text{m}^2$ ) was used, whereas only 25% of the other building's roof ( $\sim 10\text{m}^2$ ) was used. Additional roof surface area was not used since the increased engineering difficulties did not outweigh the benefits, and the family's stated water demand also did not require use of a wider catchment area. The existence of this surplus adjacent roof area, though, would allow for a future expansion of the harvesting capacity from approximately 30,000 liters currently to about 40,000 liters.

The educational component of this demonstration was designed to inform community members about why the project was being promoted and implemented. It was explained that this type of project could improve both water availability and the overall quality of the water supplied. The education aspect of the demonstration helps to create sufficient interest in construction of other rainwater harvesting systems. In fact, reproduction of the design in other homes and communities symbolizes the ultimate goal of the demonstration day.

### Costs

Compared to the other pilot projects this was by far the least expensive. It does not have the potential to benefit dozens of people like the EcoLavadero project described previously, or the ECOSUR design that follows this pilot project description. However the material cost for this project was only \$280 (see the domestic system section in the Rainwater Harvesting and Storage manual in Appendix A for a complete itemized cost breakdown). Future projects based on this design are likely to be modestly cheaper as this project was a prototype with many of the inefficiencies and waste that comes with doing the first of anything. Furthermore these costs could

drop by about 15% if many rainwater harvesting systems were constructed at the same time and materials were bought in bulk.

### Lessons Learned

This project was a very positive experience all around. The community's members got to participate and learn about the project. From concept to completion they got to see a project be implemented that will better manage water resources. From the group's standpoint this project showed how cooperation and collaboration can really make the implementation of an idea successful. Group members focused on their strengths and readily deferred to other group members in areas that were not their specialty. It truly was a group effort and that is one of the reasons why it turned out to be so successful

### *2.4.3 Rainwater Harvesting and Potabilization System for ECOSUR*

#### Purpose

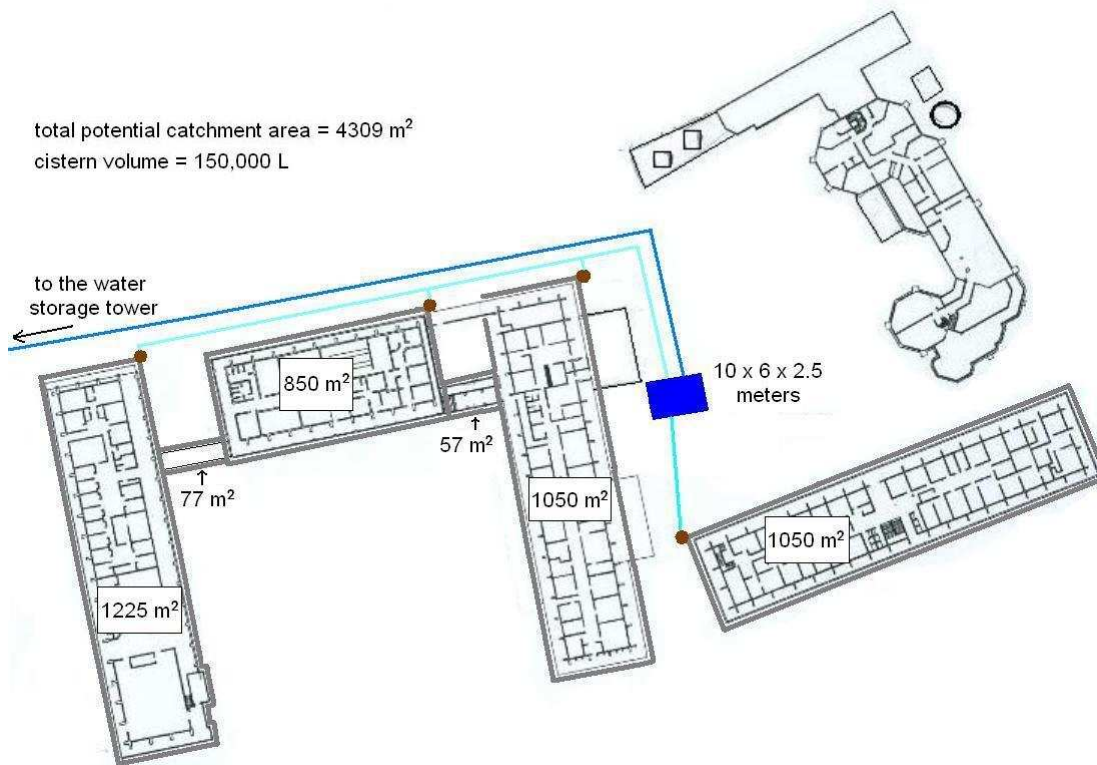
ECOSUR is a publicly chartered research institution located on the periphery of San Cristóbal. Currently the university is dependent upon the municipal water utility, SAPAM, to provide the campus with its water. The university would like to reduce its dependence on SAPAM for its water needs by constructing a rainwater harvesting system that incorporates a filtering and treatment system to make the water potable. ECOSUR further sees this project as a way of promoting the campus as a leader in environmental research and stewardship.

The reasons for constructing this system are not solely ideological. From a practical standpoint it makes sense for the university to have a supplementary water supply. SAPAM is not always reliable with its water delivery and the quality of the water is almost always poor (Carmona 2006). Furthermore this variability in supply could very well increase as urban expansion and the increased demand it is bringing puts even more strain on municipal water sources. Having their own source of water that they are responsible for, and that they treat themselves, gives ECOSUR more independence and enables them to provide for much of their own water needs.

#### General Description

This system can be broken into two connected yet distinctive parts (Figure 17 and Figure 19).

- The rainwater harvesting system utilizing the roofs of the campus buildings
- The potabilization filter which treats the water to safe drinking quality



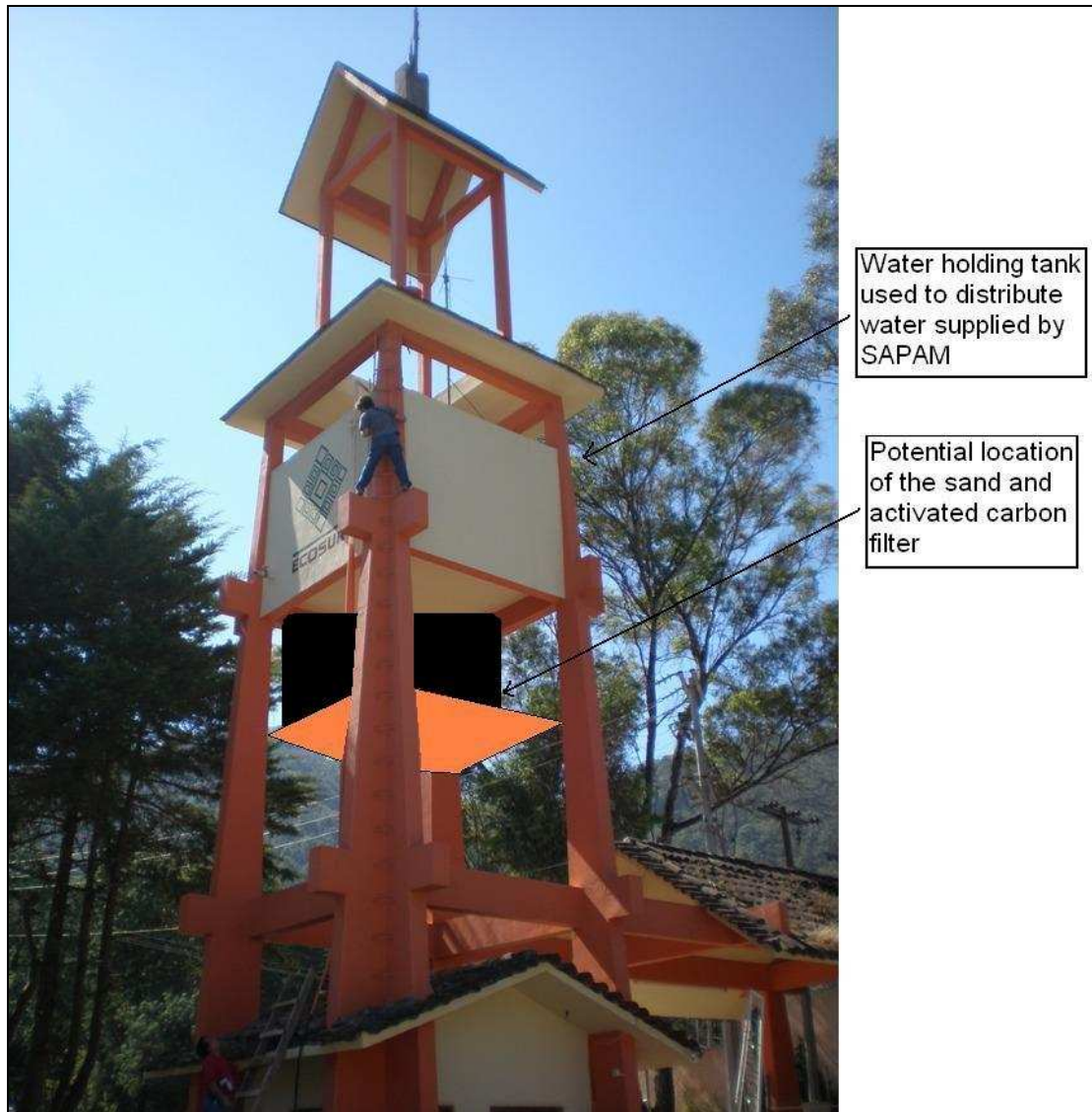
**Figure 17.** Diagram of the ECOSUR rainwater harvesting system

One of the group's partner's primary requirements was that this system be easy to maintain. They wanted a system that could be totally maintained in house, without having to rely on outside vendors for service or repairs. This requirement had a lot to do with costs, as the budget for the system does not have sufficient funds to pay for outside service and maintenance. However ECOSUR also stressed that it valued the idea of being independent and handling all aspects of this system itself. ECOSUR wants to take complete ownership of this system in every facet

As can be seen in Figure 17 the roof areas of the four primary campus buildings make the catchment surface. Rainwater runoff is collected off these four buildings and transported via gutters and underground pipes to an underground cistern located behind the main laboratory building. The cistern will have a capacity of 150,000 liters. The roof catchment and transport system will be able to provide over 2,000,000 liters of water for campus to use. Demand estimates provided by partners at ECOSUR indicate that this could meet most of the universities water demands for roughly 130 days. The rest of the year ECOSUR would be dependent upon SAPAM for its water needs.

Water stored in the cistern will be pumped up to the holding tank located at the top of the guard tower near the entrance to the campus. From the tower water will flow via gravity through a sand and activated carbon filter. Due to the still preliminary nature of this design a number of different filter configurations are being proposed for

consideration. Figure 18 below shows the water storage tower and one of the recommended locations for the sand and carbon filter.



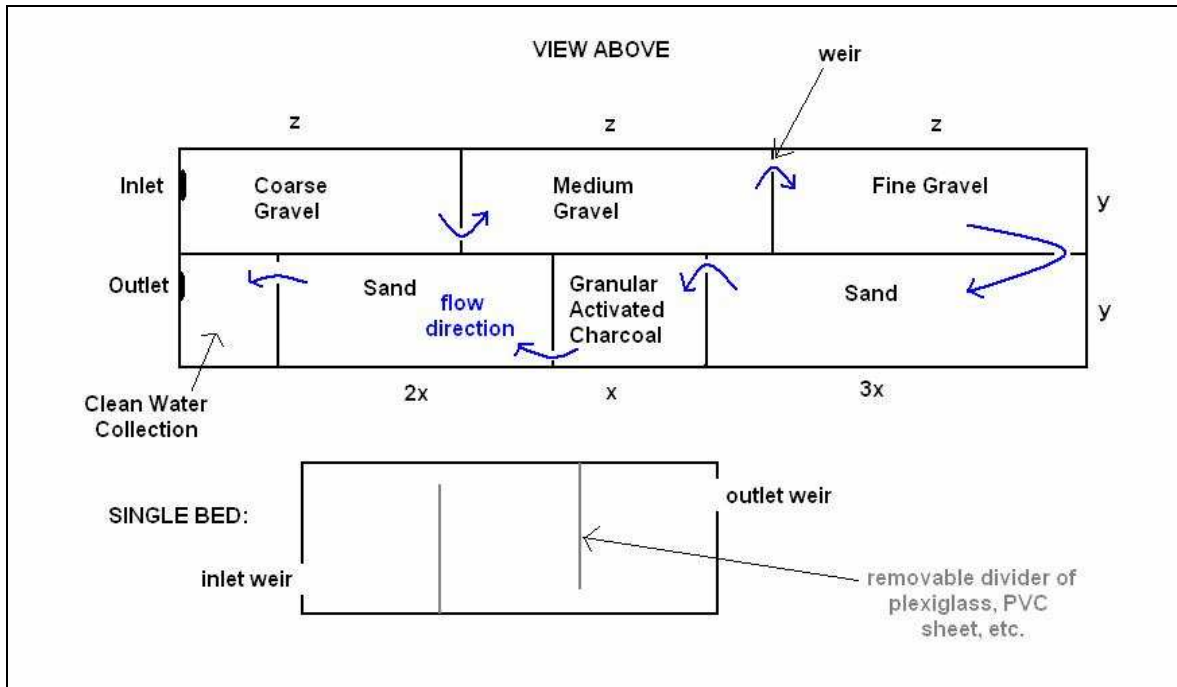
**Figure 18.** Water holding tank in the tower and proposed location for the sand and carbon filter.

#### Potabilization Filter

While a rainwater harvesting system would increase water supply available to ECOSUR's campus, further effort is needed to improve the quality of this water, so that it might be suitable for washing, food preparation, drinking and laboratory applications. There are several steps to water filtration, including mechanical filtering of solids and chemical treatment of contaminants. Water used for drinking or food preparation should also be disinfected to eliminate pathogens. Requirements for a filtration system to complement ECOSUR's rainwater harvesting system included simplicity of materials and design, achievement of potable standards, and finally an aesthetically pleasing design that would not detract from the campus ambiance.

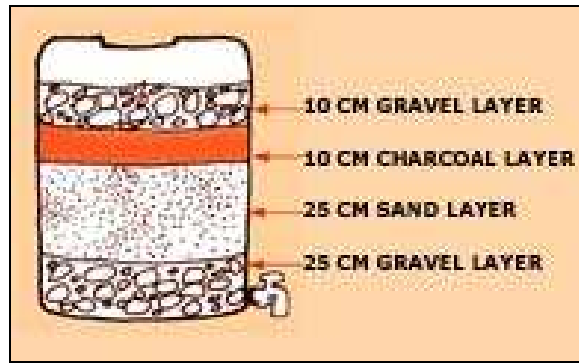


With these needs in mind, several options were reviewed for types of filters. Two designs stood out as appropriate for this application. Both incorporate similar materials and technologies, although they are laid out in different ways. First, a horizontal roughing filter followed by a slow sand filter containing granular activated charcoal was considered as a simple-to-maintain yet easy to hide from plain view option (Figure 19). Water enters the system by gravity, and passes through materials of decreasing size to accomplish mechanical filtration of suspended solids and debris. Some bacterial degradation also takes place during this phase (Committee on Small Water Supply Systems 1997). Next, the water passes slowly through a sand filter containing a sandwiched layer of granular activated charcoal. The sand provides a growth medium for helpful microorganisms that can digest pathogens in the water as it flows through the sand. Charcoal adsorbs other contaminants in the water, leaving it much purer.

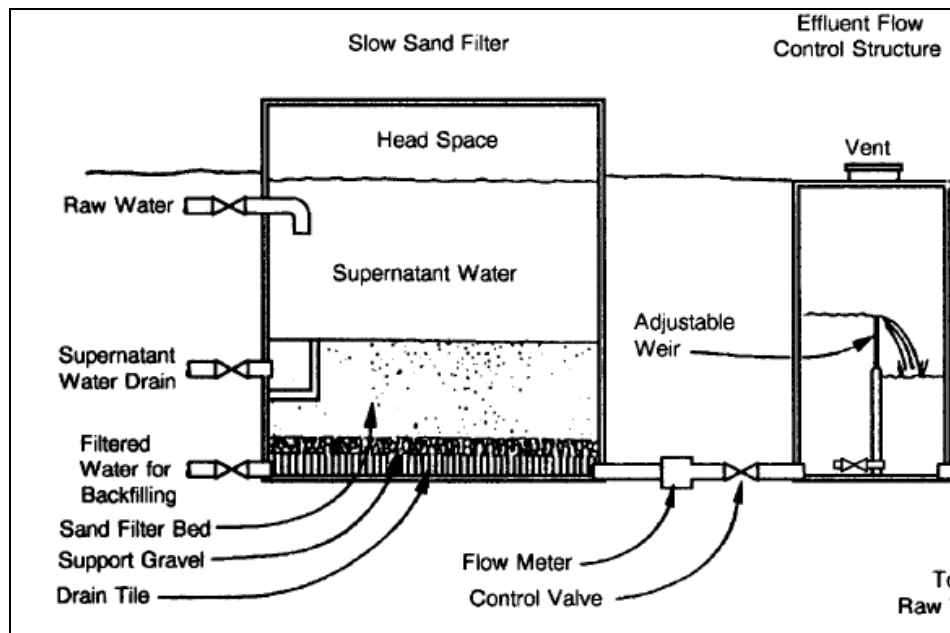


**Figure 19.** View of the horizontal roughing filter and sand filter from above, including the routing design within a single bed.

A second option utilizes much of the same technology cited above, but is positioned for vertical flow rather than horizontal. This filter can be made using a concrete reservoir, similar to the current water tower holding chamber, or can utilize a pre-fabricated HDPE tank. Here, again, water is introduced evenly over the top surface of the filter and then collected by perforated tubing placed along the bottom of the tank. A simple example of a vertical flow slow sand filter is shown in Figure 20, and an example of a more complex filter in Figure 21.



**Figure 20.** A basic application of vertical slow sand filtration (Centre for Science and Environment 2006)



**Figure 21.** Diagram of a vertical flow slow sand filter (US Environmental Protection Agency, U. E. 1990)

Replacement of filter media would be more difficult with this design, although the maintenance needed is minimal and it is possible to install a backfilling device that allows washing of the material by high speed reverse-direction flushing with clean water. Backfilling periodically will prolong the effective life of the materials before it needs replaced.

#### Costs

ECOSUR has already received approximately \$24,000 (264,000 pesos) in funding for this project. Based on information gathered from ECOSUR and other contacts in San Cristóbal roughly half of that money will go to materials and the other half to the labor involved with construction of the system. Given that this design is only a preliminary one that partners at ECOSUR will have to refine, the costs estimates are very rough. After discussions with partners during trips to Mexico, and subsequent

revisions made by the group in Santa Barbara the estimated material costs for the system are \$10,000 – \$13,000 (110,000 – 143,000 pesos). A much more specific cost estimate table can be seen in Appendix B of the ECOSUR pilot project manual.

### Lessons Learned

This pilot project provided a number of challenges. Previous to this group project, none of the members had experience designing a multi-component treatment system. Consequently, integrating the different components of the system – an underground cistern with a submersible pump, which feeds an intermediary holding tank, attached to a sand and activated carbon filter, which should supply 15,000 liters of clean drinkable water to the university workers – into a workable design proved a challenge.

This task was daunting and frustrating along the way, but ultimately a good workable design was produced for project partners. While this design may not be ultimately what is built, the main benefits of it are that it does provide ECOSUR with a clearer understanding of what they need to do to meet their goals, and what it will cost.

## 2.5 BMP Design Manual and Pilot Project Construction Descriptions

This section succinctly describes each BMP design manual and proposed pilot projects featured in Appendices A and B of this report. Each design manual is intended be used as a “pull-out” for those interested in assessing the applicability of the BMP for their community or watershed. They are written in the form of an instruction manual that guides the reader through the design and construction process for each system. Each design manual provides information on the BMP’s purpose, sizing, location, expected performance, maintenance, and estimated costs. Descriptions of the implementation of BMPs found in Section 2.4 are termed “Pilot Project Proposals” in the Appendix (Appendix B), and are intended to provide an applied case study for the chosen BMPs. These should be read alongside the corresponding BMP and the information referred to both prior to and during BMP implementation. They describe design considerations specific to the chosen site and discuss the lessons learned, barriers to implementation, and successfully implemented strategies.

### *2.5.1 Rainwater Harvesting and Storage Design Manual*

The rainwater harvesting design manual provides guidance for choosing the type of domestic system appropriate for a given set of parameters. It also provides information that shows whether a particular area is even a good place for RWH to be implemented. The manual contains information that helps determine the amount of water a given system can collect and store. There are recommendations for designing a system according to the desired level of system performance. In addition, it presents step-by-step instructions for the construction of a generic domestic system and the



proper maintenance regime. Here, variations in the construction process are noted to account for slightly different implementation issues that go along with systems of a fundamentally different scale. The manual also has a list of essential materials as well as the approximate costs for a small domestic system constructed in the local community of Cinco de Marzo.

The accompanying Pilot Project sections detail the specific parameters used to construct the harvesting and potabilization system at ECOSUR and the proposed school building, sink and pour flush toilet, system in Cinco de Marzo. While both of these systems share the similarity of rainwater harvesting their juxtaposition, as well as the comparison with the small domestic system, clearly illustrate the variation in design and application of this BMP technology.

#### *2.5.2 Composting Latrines Design Manual*

The composting latrine design manual focuses on two different types of composting latrines. Complete descriptions and construction steps are provided for both the free standing outhouse style composting latrine as well as the combination system of an indoor toilet coupled with outdoor composting bins. The comparative advantages and disadvantages between the two types of systems are discussed along with the recommended applications for each type. The manual also contains materials lists with cost estimates and maintenance requirements provided for both options. Finally the manual discusses the uses and value of the fertilizer (the humus) produced by the composting process.

#### *2.5.3 Retention Basins Design Manual*

The retention basins design manual discusses both wet and dry retention basins insofar as their purpose, structure, siting, materials, and costs of construction are concerned. This is followed by step-by-step illustrated instructions for the construction of a basin. Equations used to calculate the needed size of a basin depending on the volume of runoff and the desired treatment time are also presented, along with suggested values for maximizing effectiveness. Finally, the maintenance regime and problem-solving strategies are outlined.

#### *2.5.4 Bioswale Design Manual*

Project members put together the Bioswale design manual in the beginning stages of the project. Intended to give the interested user an idea of what considerations must be made before and during construction, the manual lists the basic steps one must take to construct a bioswale. Because bioswale dimensions are based on the 2-year storm flow, it is recommended to seek the help of a hydrologist in order to complete the calculations accurately.

#### *2.5.5 Contour Trenches Design Manual*

The contour trench manual was assembled at the outset of the project. It is intended for use with sloped agricultural plots. Many of the hill slopes of the San Cristóbal watershed are cultivated for the production of corn, among other crops. The corn is planted in rows down the slope of the hill. The contour trenches design manual shows how to cultivate the rows of crop along the contour of the hill using trenches as physical barriers to slow the speed of runoff water and stop the down slope migration of eroded soils. The document provides step by step instructions on how to find and mark the contours of the field. It also provides recommended distances between trenches, based on hill slope, and maintenance tasks to perpetuate the efficacy of this BMP.

#### *2.5.6 Blackwater Design Manual*

The blackwater constructed wetland design manual details the benefits of this BMP, and how it functions to reduce water pollution. A thorough consideration of design parameters, including siting, choice of materials, and plant establishment are discussed. This is followed by the generalized construction steps for both the primary treatment system and wetland cell, along with diagrams and photos that illustrate how the various components are assembled. Finally, common values for design parameters are listed, followed by the expected water quality treatment, an example of typical maintenance procedures and troubleshooting techniques. In the accompanying case study manual, “BMP Technology: Constructed Wetlands for Treatment of Blackwater – Pilot Project Proposal in Chiapas, Mexico,” the calculations needed for wetland sizing are detailed. In addition, the suggestions from the design manual are applied to the specific conditions in Cinco de Marzo in San Cristóbal.

#### *2.5.7 Greywater Design Manual*

The greywater design manual serves as a complete guide to designing and constructing a greywater bio-filtration constructed wetland. A greywater constructed wetland can be used at a household or community level, although design considerations vary widely between the two. Apart from discussing function, purpose, expected performance, applications, and maintenance, the manual also describes the calculations necessary to determine the size of the wetland cell. (the EcoLavadero Design Manual then provides an example of how these calculations are applied.) The manual also outlines major considerations that are necessary before and during construction of a greywater wetland.

#### *2.5.8 EcoLavadero Design Manual*

The Design Manual for the EcoLavadero, or Ecological Clothes Washing Station, is one of three BMPs that commenced implementation during this project. Of all the manuals prepared for this project, the EcoLavadero manual contains the most detailed instructions for construction. A community group in Cinco de Marzo, located on the

outskirts of the San Cristóbal de las Casas urban center, chose to construct this system with the assistance of SYJAC, one of the project partners in Mexico. This system provides both a source of clean water on demand and a comfortable place to wash clothes. Additionally, the EcoLavadero was identified as a practical solution to skin irritations caused by washing clothes in the contaminated Navajuelos Creek that passes by the community.

As the EcoLavadero is a combination of two other recommended BMPs (rainwater harvesting and greywater constructed wetland), this design manual describes an application of both these practical solutions. This particular system employs a rainwater harvesting technique that catches a significant portion of the estimated annual water demand. The second feature is a constructed wetland that biologically treats the greywater exiting the system before releasing it to the surface water. As a pilot project, the EcoLavadero in Cinco de Marzo is the first implementation of the design that was created collaboratively by Grace Keller and UCSB project members. It is hoped that the design manual will help other communities construct their own community wash center.

### **3.0 Education Campaign**

In order to inform the community of Cinco de Marzo about the importance of watershed management and to complement the construction of BMPs, an environmental education campaign was created that aimed to modify local behaviors through the development of individual responsibility and increased awareness toward watershed health. Educational materials linking water quality and human health were developed to be used in the primary school classrooms of Cinco de Marzo, as well as in community groups in the greater San Cristóbal area, while educational materials related to watershed function and specific to BMPs were also developed.

#### **3.1 Approach and Justification**

Partners at SYJAC and ECOSUR expressed interest in the development of targeted educational campaigns during the first San Cristóbal Group Project, which ultimately led to the recommendation for implementation of an educational campaign to address water contamination in the region. It became clear during the early stages of this project that there was a unique opportunity to realize immediate environmental and human health benefits from implementation of this BMP through collaboration primarily with the local partner SYJAC. An education campaign represented a cost-effective means to spend time and money to prevent environmental mismanagement and disease rather than to remedy it retroactively (HeuckandDeom 1991).

Initial communications with SYJAC revealed that the community of San Cristóbal as a whole does not understand how individual actions are linked to water quality in the

region and how degradation of water quality leads to increased instances of human illness (Bencala et al. 2006). There is a general awareness of environmental problems, and an interest in safeguarding resources, but the community still lacks the tools needed to identify the link and address it. This deficiency in knowledge regarding the water quality-human health link was therefore identified by this project as a significant issue that could feasibly be addressed through an education campaign. Members of SYJAC had extensive experience working in community centers around San Cristóbal and were interested in furthering their involvement in these centers as well as communities with fewer resources, such as Cinco de Marzo.

Residents of the *colonia* of Cinco de Marzo and the greater San Cristóbal area are known to suffer from elevated rates of illness as a result of a lack of education regarding basic sanitation practices and potential problem areas (Bencala et al. 2006). Thus, in an effort to significantly reduce rates of illness and improve quality of life, this project chose to work together with SYJAC to develop a series of lesson plans, instructive materials, and activities that could be used in both formal and informal settings. Other issues, such as watershed ecological processes, waste management, and wastewater treatment were also integrated into educational materials to increase comprehension of the role of the individual in the ecosystem. Furthermore, materials were created to complement the design, construction, and use of the technical BMPs this project recommended. By including the more technical BMPs in the education materials, their importance and practicability were enforced in a familiar and empowering context.

### *3.1.1 Justification of Approach*

As discussed in a previous chapter, the “primary objectives of sustainable development are... to overcome poverty and to protect ecosystems as well as human options” regarding environmental access and use, as well as basic health (SinghandTiti 1995). One of the most effective ways to pursue sustainable development is through environmental education. Oftentimes, communities will express a sense of helplessness when facing recognizable environmental problems but lacking the causal information or the corrective tools to solve them. They are frequently concerned because the problem appears impossible to solve on a solely individual basis. Through educational lessons and activities, individuals within the community can learn how to approach the problems both independently through their daily actions and as a group (Holdgate 1996). Thus, the environmental education approach involves a multidisciplinary process focused on critical analysis of environmental issues. This takes place by gathering, organizing, and interpreting locally relevant information with the aim of promoting responsible behavior that enhances environmental quality within a community. Preliminary analyses are used to generate a comprehensive campaign that tackles concerns regarding ecosystem health and human behavior, while functioning within the framework of poverty alleviation, capacity building, and improved resource management.

At the United Nations Conference on Environment and Development (UNCED) in 1992, Mexico, along with 177 other nations, adopted the Agenda 21 Plan of Action which stated that:

Education, including formal education, public awareness and training should be recognized as a process by which human beings and societies can reach their fullest potential. Education is critical for promoting sustainable development and improving the capacity of the people to address environment and development issues.... Both formal and non-formal education are indispensable to changing people's attitudes so that they have the capacity to assess and address their sustainable development concerns. It is also critical for achieving environmental and ethical awareness, values and attitudes, skills and behavior consistent with sustainable development and for effective public participation in decision-making (36.1 - 36.27) (UNDESA 1993).

The education campaign developed by this group strives to fulfill the objectives of Agenda 21 and to help the residents of Cinco de Marzo and San Cristóbal reach their fullest potential as environmental and human resource managers by promoting lessons and activities that increase environmental awareness and participation. In order to mobilize a community to become participatory and aware managers, however, the campaign must simultaneously work to build capacity among community residents. Too often, affected groups are marginalized groups that do not have the experience or the means to speak up and voice their concerns. Moreover, they usually have not been taught the essential skills to assess and then address their environment and development needs. If an effective educational campaign is to be implemented, it must be based on the concerns and abilities of those groups that are most immediately affected. In Mexico, despite a 63% increase in foreign aid between 2001 and 2005, several sectors of society "continue to be excluded from the benefits of development: the poorest segments of society, people in rural areas... and women" (UNDP 1993; USAID 2005).

According to 2006 human development indicators, the GDP per capita for the municipality of San Cristóbal was 5,073 in adjusted US dollars, while the Chiapas average was 3,302 dollars and the national GDP per capita was 7,495 dollars for the same period (Table 2). San Cristóbal achieves only 67% of the national per capita income while the state of Chiapas, which includes both more rural and urban (in the case of the city of Tuxtla Gutierrez) areas and communities such as Cinco de Marzo, reaches just 44.5%. School attendance follows a similar trend, with non-urban areas, especially in the state of Chiapas, showing a lower percentage of attendance for students ages 6-24 than the national average (Consejo Nacional de Poblacion 2000). Poverty is a visible barrier to engaging in social benefits such as basic education, and it is most detrimental to children because it is a denial to future opportunities based on a bias beyond their control. When children are unable to attend either primary or

secondary school due to family expenses and work commitments, or do not have properly funded or staffed schools, they are impeded in their ability to participate in their country's future development. Currently, approximately 24 million Mexicans live in extreme poverty, and 43.5% of the population is under the age of 18 (UNICEF 2007). For any educational effort to work, it must function within both the formal and informal education system. With both of these pathways, the interests of the majority of children can be addressed.

**Table 2.** Socio-economic indicators in San Cristóbal Compared to State and National Averages  
(Consejo Nacional de Poblacion 2000)

Indicator	San Cristóbal	Chiapas	Mexico
Percentage of Literate People Over 15 Years of Age	82.2	77.1	90.5
Percentage of People Aged 6-24 Who Attend School	61.1	57.0	62.8
GDP Per Capita In Adjusted US Dollars	5,073	3,302	7,495
Index Of Infant Survival	0.848	0.790	0.839
Index Of Human Development	0.752	0.693	0.791

Though accounting for over 50% of the global population, women are the world's largest marginalized group to commonly be denied social benefits. In rural communities around San Cristóbal and Chiapas as a whole, women often contribute a majority of household and community-based labor, but are still restricted from fully participating in household or community decision-making opportunities (*Women and Children: The Double Dividend of Gender Equality* 2006). And while children's interests are critical in the formation of materials that will ensure capacity building for current household information dissemination and future planning and implementation, women's needs are the most immediate in regards to their daily tasks. Because women are largely uneducated in Cinco de Marzo and in other areas outside of city centers, the group and SYJAC focused on producing a series of educational brochures, posters, and activities that could easily be extended to an uneducated community.

36.5% of the population of Chiapas is unable to speak Spanish, a majority of whom are women, and a quarter of the state's population is fluent in only an indigenous language, such as Tzotzil or Tzeltal (UNHCR 2002). Hence, the group based the development of the education materials primarily on colorful and familiar pictures which, in the experience of the SYJAC facilitator during her work around San Cristóbal, capture the attention and interest of children and minimally-educated adults alike. The resultant informal education materials serve to "build the motivation, skills and understanding on which environmental citizenship may be based.... [After all,] environmental communication is aimed at changing practices and behavior, and inviting participation or action" (IUCN 1994).

### 3.1.2 Technical Approach/Methods

In order to create and identify appropriate content for the environmental program, the UCSB students decided to use a dynamic and adaptive process characterized by full

participation on the part of the researchers, partner organizations, and community members. It was necessary that the process reflected the specific circumstances of the Cinco de Marzo community and the primary school target groups, encompassing social, cultural, environmental and economic realities. A thorough understanding of the community on the part of the UCSB and SYJAC educators, and a careful planning process that defined the community's needs and goals, as well as the project objectives tasks was identified as the most promising method to yield effective and relevant program content. Only through this approach could the project possibly ensure that education directed at sustainable “development [would be] be woven around people, not people around development – and [that it would] empower individuals and groups rather than disempower them” (UNDP 1993).

To facilitate the production of an effective and relevant education campaign, the group had to assess the current level of knowledge regarding environmental and human health in order to determine the level of environmental awareness. Perhaps one of the most reliable and straightforward means for gauging individual understanding of specific environmental management issues is through a simple oral survey that is both easy to understand by both educated and uneducated individuals. It should also be affordable to reproduce so that it can be used repeatedly across various communities.

The group therefore developed a survey consisting of 43 questions divided into six topical sections: deforestation, composting latrines, health and sanitation, retention basins and bioswales, contour trenches, and rainwater catchment systems (Appendix C.1). The choice of sections reflected the BMPs that were initially recommended to the group to implement in spring 2006. The intention of the questions in regards to the education campaign was to evaluate local knowledge of natural watershed processes as well as habitual actions that might affect watershed quality. Furthermore, specific questions, most notably in the deforestation and health and sanitation sections, were explicitly developed to ascertain knowledge of the causal relationship between human activities and local water quality, with additional questions designed to reveal awareness of the relationship between degraded water quality and frequency of illness.

The survey was delivered to SYJAC in the summer of 2006 with the mutual understanding that it would be administered during the summer months with response analysis conducted in following weeks so that campaign implementation could commence in the fall. SYJAC, however, chose not to use the survey that this project developed and instead created an independent survey with different questions. And although the questions still aimed to gauge awareness of natural watershed processes and human actions that might affect watershed quality, the survey lacked a question that directly addressed the human health-water quality linkage. Furthermore, SYJAC did not produce a complete survey until the winter of 2006-2007 and had yet to complete its administration and analysis as of March 2006.

Fortunately for this project goal, ECOSUR was in possession of a water use analysis report conducted by two local organizations, Alianza Cívica and Comité Ciudadano Para la Defensa Popular (COCIDEP), during the summer of 2006 for the municipality of San Cristóbal de Las Casas (Appendix C.2). Despite the fact that the original questionnaire did not have the water quality-human health causal question that this project had initially designed, the analysis still covered the areas of personal data, water access, participation and organization, health, integrated knowledge of human activities and water quality.

The conclusions of the analysis indicated that 93% of the municipal population surveyed was aware that there is a problem with water quality, but that 41% still drink it untreated and 70% use it to wash their food. Based on these results, as well as the circumstantial knowledge that SYJAC possessed from years of working within the marginalized communities and the interest expressed in response to the initial BMP recommendations, the group was able to determine the principal gaps in knowledge that had to be addressed in order to ensure the creation of a successful education campaign that would empower the community to modify their behavior. The key areas of information that the campaign addressed were:

- Basic Water-Environment Processes
- Water Contamination
- Natural and Constructed Wetlands
- Water Filtration
- Rainwater Capture Systems
- Benefits of Using a Clothes Washing Station
- Health and Sanitation

Participatory development of the program content continued according to an informal action plan based on the interests of the community and schoolteachers, the resources available to both SYJAC and the Cinco de Marzo primary school, the most well-perceived strategies and approaches for implementation, and the overarching project objectives of environmental awareness and behavioral change.

Preliminary research for relevant educational content along with the formation of a series of lesson plans was completed by the UCSB students. The lesson plans and supplementary activities were revised to best reflect the needs indicated in the analysis conclusions. They were then sent to SYJAC in Mexico so that the education facilitators most familiar with the community and environment could tailor the materials to better reflect local conditions and resources.

Strategies and materials were then tailored to target groups according to their relationship with the environmental problem, their literacy rate, and the availability of resources in terms of budget, time, and facilitators. This resulted in the use of materials as a means to frame the message in different styles. For schoolchildren in the higher grades who had access to teachers, materials, classrooms, and a reserve of



time every day, detailed lesson plans with incorporated activities were deemed appropriate to explain complex environmental issues. Conversely, for schoolchildren in lower grades, and for community members with little or no education and limited free time, practical guides and informal meetings focused on how-to demonstrations and information sessions. The focus on several different audiences opens up several different pathways that can be followed to accomplish the projective objective and which consequently improves the probability of success.

One of the most critical aspects to the success of an educational campaign is the need to frame materials in a familiar context. The materials must be simple to teach and simple to learn in order to guarantee success. Working primarily with SYJAC, the main goal of the materials was established – the need to address the gap in knowledge between local water source quality and common illnesses and skin problems. Issues that promoted realistic and feasible practices, such as simple hygiene and sanitation measures to reduce the risk of waterborne diseases were emphasized. Straightforward guides for food handling and more interactive activities focusing on hand washing were created. Education materials regarding the implemented BMPs were also included in order to ensure community awareness and to encourage involvement.

The implementation process of the education campaign will be largely overseen by the educational facilitators at SYJAC. Their frequent and continuous contact with the community allows them to work efficiently within the parameters of successful preliminary training and implementation. During the trip to Chiapas in the winter of 2006-2007, the UCSB students were able to meet regularly with the community of Cinco de Marzo as well as with the members of SYJAC. During this time, the UCSB students held community meetings to promote participation and ownership on the part of the community members and facilitation on the part of SYJAC. In order for the project to progress successfully, however, SYJAC must adopt the role of a facilitator in two-way communication between the community and UCSB students.

Efficient communication among all the stakeholders is crucial in order to gauge responsiveness of the target groups and the adaptability of the program. This must be done, however, with the facilitators acting in a role that requires minimal supervision (Kindervatter 1987). If a primary objective of the campaign is to empower the community through the transfer of knowledge over time as a means to build decision-making capacity, then the local facilitators, rather than the UCSB researchers, must take ownership not just of the BMPs, but of the education campaign as well. Ownership instills a sense of responsibility and creates enthusiasm about the project that can only develop gradually.

Implementation of the education campaign does not signal the end of the project. Instead, monitoring and evaluation must continue so that the materials can be adapted to changing social norms and community needs. Monitoring is a systematic and ongoing effort to collect and analyze information to learn if a program is achieving the desired results. Carrying out periodic assessments while a program is in progress

allows mid-program changes to improve its effectiveness. Comprehensive evaluation may take place at a specific point in the program to verify that a program is on track, when there are significant issues or changes that affect the program's goals and objectives, or at the end of the program. Evaluation is discussed in more detail later in this chapter.

### 3.2 Education Campaign Characteristics

#### *3.2.1 Description of Target Groups*

Oftentimes, environmental education initiatives waste time and energy by directing education toward inappropriate target groups who have little or no impact on environmental management and decision-making. Rather, target groups should be made up of people whose practices directly affect the environment, such as primary water users and the people who influence them, for example community leaders or the consumer groups. There may, in fact, be several target group possibilities, with the most obvious not always being the most appropriate (United States Peace Corps 2005). For this reason, the project focused the education campaign on both women, who are the primary users of water on a daily basis, and schoolchildren, who act as vectors of sustainable management information within their households and who will grow up to become educated and informed participants in society. The campaign also aimed to involve other community members and successfully worked through community leaders on the *colonia's* directive board.

Each target group expressed different concerns and levels of education, from elementary school-aged children to community leaders. Though the message of the material is the same for all groups – explaining the need to protect water resources – the content and level of detail of the materials was tailored for each audience. Given the fact that educators at SYJAC chose which groups to target and how to divide them up, the campaign acts as an example of working within community-based development and empowerment and is a factor that should have an overall benefit to the longevity of the project.

#### *3.2.2 Formal Education Materials*

The curriculum developed by this group for use within the framework of a formal education system, specifically in the primary school of Cinco de Marzo, proposed to target the causal factors for the degraded watershed, and thus water quality, and the effect of such degradation on human health. Moreover, the curriculum sought to extend practicable and understandable actions that the learners could use themselves and then circulate throughout the greater community through dissemination within their household to family and friends who may not have access to schools. The materials were devised so that they represented a combination of complex lessons that reflect complex issues, and more straightforward activities that reinforced the lessons learned through actual implementation of the recommended practices.

Furthermore, supplemental BMP picture books were created by students at UCSB to reinforce the importance and benefits of using and maintaining the implemented BMPs. These picture books were hand-drawn with a focus on creating an easily recognizable and likeable character whose travels through the BMPs mimicked the path and quality of water through the BMPs. By creating a single character (“Gotita”) and using it in three separate books, the students are able to form an attachment with the character and its health and, subsequently, with the condition of the BMP technology. All the materials were developed for schoolchildren between the ages of about 6 and 12. They were largely visual in an effort to promote interest in and retention of the concepts (Appendix D). Group members recognized that while the content of the curriculum is intended to be simple, in order to reflect the everyday experiences and routine behaviors of the learners so that a link is recognized, the context in which they are presented must be exciting and fun so as not to intimidate or bore the learner (Payne 1997).

### *3.2.3 Informal Education Materials*

Government education programs may alienate those outside the influence of the traditional school system. Therefore, “a common feature of successful international development projects seems to be the occurrence of specific, behavioral change by a critical number of adults that continues beyond the length of the development project... [and that] is usually a consequence of a non-formal adult learning process” (Sinnott 1994).

In an effort to tap into this underrepresented group, the education campaign sought to include community members not just in the construction of BMPs, but also in the understanding of the reasons behind the recommendation for the BMPs. Several examples of international development projects exist wherein external actors came into a community, recommended and oversaw the construction of a technology, and then left. As long as there is no personal or community investment in the project, however, these types of projects will most likely fail in the long run (Bunch 1982). The community needs to understand what the motivations are for constructing a BMP, in terms of watershed and water quality protection. This allows them to understand the resultant benefits in terms of increased water security and improved health. The learning process must be participatory and responsive to the community’s needs. A community can only identify with a project for which it feels a need, or from which it appreciates the benefits. Only when the community identifies with the project will it take ownership of it and continue to manage it in a sustainable manner.

As mentioned earlier, materials developed reflect the informal education characteristics unique to San Cristóbal and the surrounding watershed (Figure 22). For example, in 2005, one in every four Chiapas residents spoke an indigenous language as his or her main dialect (Instituto Nacional de Estadística Geografía e Informática 2006). Cinco de Marzo community members speak several languages and

dialects and experience high levels of illiteracy. Educational materials describing the purpose and benefits of the community-based rainwater capture system and clothes washing station were therefore developed to be primarily visual, with the use of simple and minimal language, diagrams and illustrations in order to ensure widespread understanding across the community and, in the future, other communities with similar characteristics. Informal community meetings outlining watershed issues and BMP needs and benefits were conducted in uncomplicated language while using simple, largely visual brochures as accompaniments to reinforce the lessons learned. The use of various communications media such as visuals, discussion topics and interactive activities served as a cornerstone of informal education.



**Figure 22.** Informal community training to discuss the EcoLavadero in Cinco de Marzo

While there has been a great deal of study justifying the importance of visual aids in teaching, which concludes that vision is more important than hearing, it is important to note that this emphasis on visual representation is thought by some to be “a phenomenon which is rooted in the media-sophisticated West.” In many traditional societies there is a strong tradition of oral communication based on drama, song and story telling which [development] educators are only beginning to tap” (KiddandColletta 1980). Indeed, Hubley argues that the use of visual aids in development work can often result in confusion and misinterpretation due to differences in cultural and social norms (Hubley 1988). Although this is a valid

concern for any education campaign implementation project, repeated communication with SYJAC and continual revision of materials by educators in Mexico who were familiar with the community's exposure to visual media, assured us that the use of visuals in the education materials was not only acceptable, but encouraged. Only simple and recognizable characters and actions were depicted in the colorful pictures, a technique which, according to SYJAC, has proven to capture the attention and interest of children and minimally-educated adults in the region.

#### *3.2.4 Teaching Methodologies*

A successful educational program depends not just on the strength of the materials and the interest of the learners, but also on the techniques employed by teachers to engage and motivate the students. Traditional approaches to learning have often been criticized for their dependence on the rote method, or memorization and recall, and lack of creative thinking beyond the basic acquisition of facts. Alternative approaches that this education campaign has sought to incorporate "emphasize dialogue and problem-posing approaches which develop critical consciousness of social forces influencing behavior" (Freire 1972). The goal of this campaign was always to illuminate the link between the social forces of human action and their effects on the San Cristóbal watershed. Furthermore, the campaign seeks not only to raise awareness of the link, but also to instill skills intended to enable the learners to critically address that link. That ability to assess and address the link in light of the individual's and community's needs is an example of empowerment (Kindervatter 1979) through community participation that helps those involved to continue on the path of sustainable development.

### 3.3 Measuring Success

Success of this education campaign will ultimately depend on the assimilation of the knowledge into the community. As stated before, the intended purpose of the education materials and activities was to reveal the impact of human actions on environmental and human health, and to initiate behavioral change that would lessen that impact. The campaign, however, is not static. As there will always be improvements to be made in watershed management practices, the campaign must be able to adapt and respond to changes in community needs and interests. The success of the campaign may therefore "center on whether the principles of adult learning can be incorporated into the methodology and implementation of the development project," such that participants can effectively handle whatever change that may occur (Sinnott 1994).

#### *3.3.1 Survey (Findings and Future Needs)*

The most logical way to reveal changing interests and needs among the communities is to revisit the assessment survey that measured the initial level of environment and human health knowledge. Ideally, the same individuals who took the survey the first

time would answer the same series of questions a second time and, ideally, the answers would reveal an increase in the awareness of environmental problems and increased motivation to address them. Since learners are typically motivated to learn by the need to solve problems from life experiences, a failure of the learner to see the problem's relevance to life experiences would indicate that learning did not occur (Sinnott 1994). In this case, it would be clear that the curriculum was ineffectually structured and would require revision. The curriculum must always be structured around needs and interests of the learning individual if it purports to address the needs and gaps in knowledge for that individual.

This project team recommends using the original questionnaire that was prepared and delivered to SYJAC for use in a future follow-up survey that aims to evaluate the success and utility of the materials and that will be administered in Cinco de Marzo within six months of the initial campaign implementation date (Appendix C.1). Of course it is critical that the project members stress to SYJAC the importance of including a question that gauges knowledge of the environment-human health link in order to assess the effectiveness of the materials that were created and distributed to specifically address this linkage.

### 3.4 Education Materials

During this project, the project team and SYJAC prepared several lesson plans, classroom activities, posters, visual aids, and brochures first in English and then in Spanish and which were later reviewed with local educators during the site visits in September and December 2006.

#### *3.4.1 List of Deliverables:* (Appendix D)

The following items were printed and delivered to partners at SYJAC and elsewhere prior to June 2007:

##### A.) Family/Community Packets (120):

- 1) Rainwater Harvesting Brochure
- 2) Environmentally-Responsible Clothes Washing Station Brochure
- 3) Descriptive Flyer: Benefits of Practicing Good Health and Sanitation
- 4) Descriptive Flyer: Myths and Truths About Rainwater

Packets prepared for teachers contain all of the items listed above, along with the following items:

#### B.) Teacher Packets (9):

- 5) Seven lesson plans with activities covering Water Processes, Water Quality Influences, Natural and Constructed Wetlands, Health and Sanitation, Rainwater Capture Systems, Environmentally-Responsible Clothes Washing Station
- 6) San Cristóbal Watershed Overview
- 7) Classroom Activity: Which Behaviors Are Good? Which Behaviors Are Bad?
- 8) Three picture books for the nine teacher packets featuring the character “Gotita” on his adventures with the different BMPs
- 9) Three comic books focusing on safe water practices for six of the packets (lowest three grades will not use due to reading levels)

#### C.) Posters:

- 10) Maintenance of Environmentally Responsible Clothes-Washing Station
  - Three large posters: to be posted at the clothes washing site and around town
  - One small poster for a classroom
- 11) Structure of Environmentally Responsible Clothes-Washing Station
  - One small poster for a classroom
  - One large interactive poster with pull-away parts description pieces for use in a classroom.

### **4.0 Water Quality and Quantity Monitoring**

#### 4.1 Significance

Water quality and quantity monitoring represents a major step toward understanding watershed functions. The availability of water is interconnected with the development of prosperous societies, both in Mexico and around the world (Rose and Molloy 2007). Availability of water may be limited by quantity, quality, cost of extraction, and/or cost of treatment. The toll of poor water quality directly impacts a country's population. According to the United Nations (UN) Secretary-General, water-related diseases cause 80% of illnesses and deaths in the developing world. Yet water resources are typically poorly monitored and remain under the control of multiple non-congruous partners. Seldom do political entities conduct environmentally-appropriate or centralized oversight and management of water resources, since local management is more effective in most cases, due to dissimilarities in water supplies and demand even in nearby regions. For this reason, water quality is rarely well-characterized in even water-scarce regions.

Though the UN recognizes the pervasiveness of these conditions, the organization continues to strive toward a Millennium Development Goal aimed at increasing the number of people worldwide who have access to safe water sources and sanitation

(RoseandMolloy 2007). As part of this goal, watershed-wide protection is necessary, as is research into the sources, loading levels, transport, and fate of waterborne pathogens. Watershed monitoring provides information that can be used to outline actions toward achieving a secure, potable, and sustainable water supply, both in San Cristóbal de las Casas and further afield.

#### 4.2 Background

Water quality and quantity monitoring (WQQM) have played a pivotal role in this project since an understanding of the current state of water resources as well as observations of changes to this state are vital to prescribing effective water resources management programs. In the first San Cristóbal project, a partnership was established with ECOSUR so that significant surface water locations and water supply wells used by SAPAM could be monitored once every month. The partnership continued into this project, where both ECOSUR researchers and UCSB students have been highly involved in the oversight of the program's direction and the monitoring implementation.

A principal goal of this project was to improve the sophistication of sampling and analysis methods applied in the WQQM program. Methods that are inexpensive and highly portable are often the most inaccurate and this project therefore invested in improving the water quality testing capacities of ECOSUR's laboratory. As the project continues and new partnerships develop, additional parties such as SYJAC may begin to make use of the laboratory. This will allow the lab to augment its income and thus support technically-trained staff members, purchase the needed consumable supplies for monitoring, and intermittently upgrade testing equipment if it wears out or becomes obsolete.

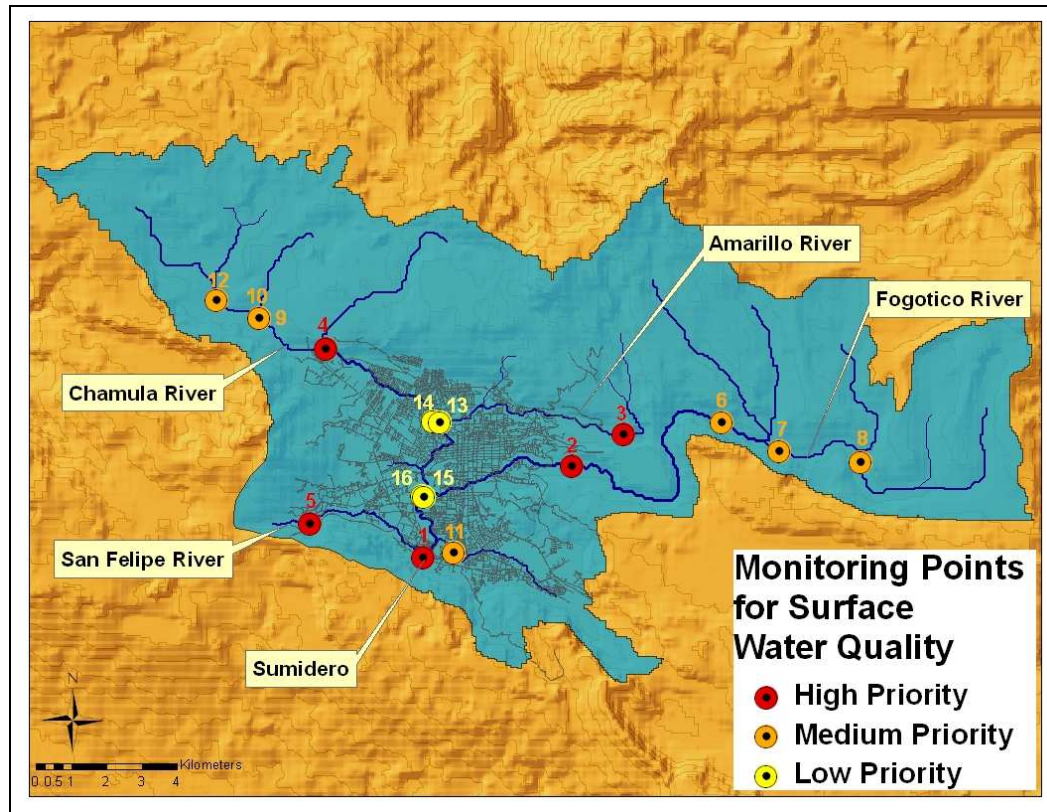
Baseline water quality data dated between June 2005 and February 2006 was provided by the first San Cristóbal project. ECOSUR's continuous monitoring program commenced in May 2006, and has been generally successful thus far. The water quality values gathered by ECOSUR were provided electronically to UCSB students, who then compiled the data for observation of trends over time. This information was also utilized in watershed modeling and, in some cases, for designing and measuring the success of BMPs.

#### 4.3 Monitoring Locations

In total, 16 surface water monitoring points were suggested by the first San Cristóbal project, with a ranking of high, medium, and low priority (Figure 23) (Bencala et al. 2006). High priority points often occur near confluences, so that the sources of pollutants among subwatersheds may be assessed. Locations were chosen to represent



the distribution of pristine water conditions, waters impacted by non-point source pollutants, and waters affected by urban point-source loading.



**Figure 23.** Locations prioritized for surface water monitoring by the first San Cristóbal Group Project (Bencala et al. 2006)

Of these 16 recommendations, ten surface water locations underwent monthly monitoring by ECOSUR (Figure 24). Furthermore, ECOSUR monitors eight of the water supply springs owned by SAPAM (Figure 25). The monitoring points used by ECOSUR were compared to the previous group's recommendations in Table 3. SAPAM utilizes four additional well locations as water sources, where groundwater is pumped from the underlying aquifer to supply parts of the town. In order to obtain the most critical information while working within the time and resource constraints of ECOSUR's researchers, the WQQM program focused on some of the existing monitoring points as well as two additional locations – the Intersección (where the Amarillo River passes beneath Calle José Morelos) and the Santa Maria spring. All of the water supply well locations, however, were dropped from the monitoring plan due to limitations in time and resources, as were the Salsipuedes and Ojo de Agua groundwater supply springs.



**Figure 24.** Juan Morales, a researcher at ECOSUR, taking a water sample in September 2006 at the surface water monitoring site Fogótico II



**Figure 25.** Juan Morales obtaining a sample in September 2006 from the KISST spring used by SAPAM for water supply

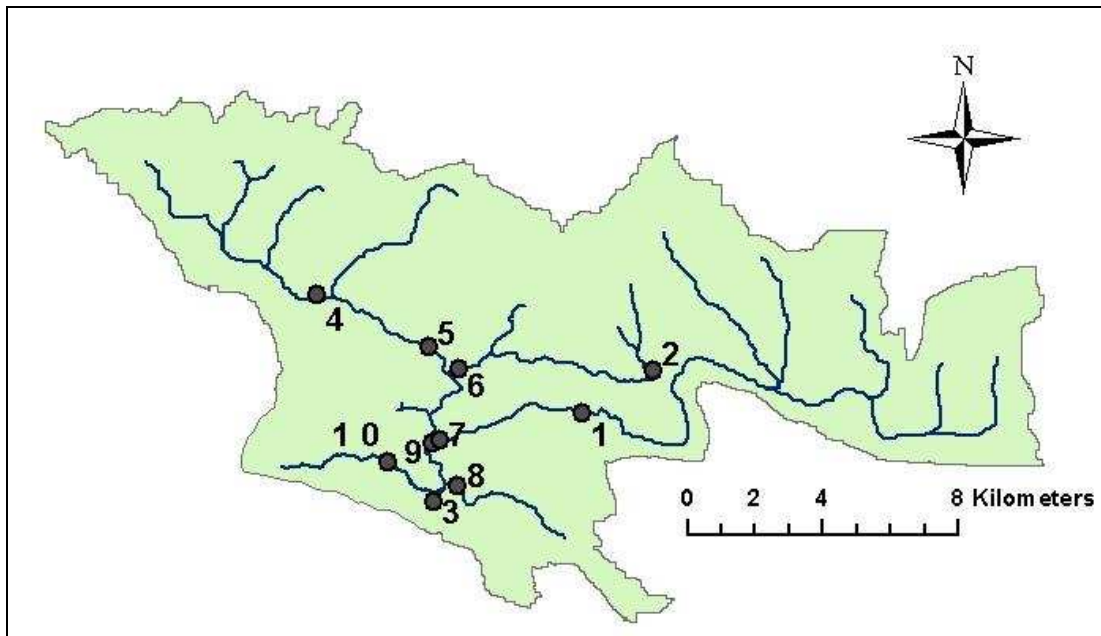
**Table 3.** Clarification of naming system for monitoring points used by ECOSUR through Feb. 2007

<b>Sampling Order</b>	<b>Description used by first San Cristóbal project</b>	<b>Description used by ECOSUR</b>
<b>Surface Waters</b>		
1	Fogotico – Above the city	Fogotico I
2	Amarillo – Near electrical plant	Amarillo I
3	Sumidero	El Túnel
4	Chamula – Outside the urban zone	Chamula I
5	Chumula above confluence with Amarillo	Chamula II
6	Amarillo above confluence with Chamula	Amarillo II (Puente Tlaxcala)
7	Fogotico above confluence with Amarillo	Fogotico II
8	Navajuelos	Navajuelos (Santuario)
9	(New Location)	Interseccion
10	San Felipe	San Felipe
<b>Water Supply Springs</b>		
1	Almolonga	Alomolonga
2	La Kisst	La Kisst
3	La Hormiga	La Hormiga
4	(New Location)	Santa Maria
5	Navajuelos	Navajuelos
6	San Juan de los Lagos	San Juan de Los Lagos
- N/A -	Salsipuedes	- N/A -
7	Campanario	Real de Monte
8	Peje de Oro	Peje de Oro
- N/A -	Ojo de Agua	- N/A -
<b>Water Supply Wells</b>		
- N/A -	Huitepec	- N/A -
- N/A -	Alcanfores	- N/A -
- N/A -	La Frontera	- N/A -
- N/A -	La Garita	- N/A -

Sampling locations were marked while in the field using a handheld GPS unit, so that precise spatial locations would be known for use in mapping utilities at UCSB. These latitudes and longitudes measured in September 2006 by UCSB students in San Cristóbal are listed in Table 4. Unfortunately, it was not possible to project these locations on a map of the watershed due to low accuracy of the GPS device and non-compatible spatial projections among layers. In place of this precise spatial information, a GIS map of the surface water monitoring locations provided by an ECOSUR researcher is shown in Figure 26, where the labels correspond in numbering to those in Table 3.

**Table 4.** GPS locations of each of the current monitoring points in decimal degrees taken with a WGS 1984 coordinate system

Surface Waters		X	Y
1	Fogotico I	-92.7569	16.73972
2	Amarillo I	-92.7175	16.87611
3	El Túnel	-92.8833	16.86972
4	Chamula I	-92.8753	16.99111
5	Chamula II	-92.6564	16.76639
6	Amarillo II (Puente Tlaxcala)	-92.7775	16.92972
7	Fogotico II	-92.8611	16.85972
8	Navajuelos (Santuario)	-92.7794	16.93556
9	Interseccion	-92.8947	16.84472
10	San Felipe	N/A	N/A
Water Supply Springs		X	Y
1	Alomolonga	-92.8269	16.93083
2	La Kisst	-92.9017	16.96194
3	La Hormiga	-92.8353	16.81444
4	Santa Maria	-92.7306	16.94417
5	Navajuelos	-92.6544	16.91306
6	San Juan de Los Lagos	-92.8822	16.73972
7	Real de Monte	-92.8258	16.88639
8	Peje de Oro	-92.6178	16.97139



**Figure 26.** Surface water monitoring locations tested by ECOSUR on a monthly basis; Numbering corresponds to Table 3.



## 4.4 Monitoring Tests

### *4.4.1 Materials*

The team transferred a limited supply of several Hach reagent kits for use with the Hach DR850 Portable Colorimeter provided to ECOSUR by the first San Cristóbal project. The Hach is capable of detecting up to 50 different water constituents, and the intent of the gift was to build the capacity of resources in ECOSUR's laboratory for the next year and into the future. The first San Cristóbal project from 2005-2006 had provided materials to conduct up to 200 tests of each parameter. Some additional reagents were transferred to ECOSUR by this project in June 2006. Among these were:

- Total Alkalinity, Nitrate and Nitrite, and 5-in-1 Test Strips;
- Calcium and Magnesium Indicator Solution, Alkali Solution for Calcium and Magnesium Test, 5.0 N Sodium Hydroxide Standard Solution, 1M EDTA Solution, and EGTA Solution for the Colorimeter's Hardness test;
- AmVer Diluent Reagent High Range Vials, Ammonia Salicylate Reagent Powder Pillows for 5 mL Sample, and Ammonia Cyanurate Reagent Powder Pillows for 5 mL Sample for the Ammonia test;
- NitraVer 6 Nitrate Reagent Powder Pillows and NitriVer 3 Nitrite Reagent Powder Pillows for the Nitrate test;
- Total Nitrogen Persulfate Powder Pillows, Total Nitrogen Hydroxide Reagent Vials, TN Reagent A Powder Pillows, TN Reagent B Powder Pillows, and TN Reagent C Vials for the Total Nitrogen test;
- Reactive Phosphorus Test 'N Tube Dilution Vials and PhosVer 3 Phosphate Powder Pillows for the Reactive Phosphorus test;
- Total and Acid Hydrolyzable Test Vials, Potassium Persulfate Powder Pillows for Phosphonate, 1.54N Sodium Hydroxide solution, and PhosVer 3 Phosphate Reagent Powder Pillows for measuring Total Phosphorus; and
- Several colorimeter vials, two glass eyedroppers, and a graduated cylinder for use in multiple tests.

This project purchased an IDEXX starter system, which included: a Quanti-Tray<sup>®</sup> Sealer, two Rubber Inserts, a package of 20 Quanti-Trays<sup>®</sup> and 20 Quanti-Tray<sup>®</sup>/2000s, a Colilert<sup>®</sup> and Colilert<sup>®</sup>-18 Quanti-Tray<sup>®</sup>/2000 Color Comparator, Colilert<sup>®</sup> Snap Packs of reagent for 100 mL water samples, UV-Absorbing Safety Goggles, and a UV Viewing Cabinet. The researchers obtained an electronic copy of a Most Probable Number (MPN) table for determining the amount of bacteria colony-forming units based on the number of positive wells, which was printed in Spanish. Finally, a practice session demonstrating the functionality of the equipment took place during the September 2006 visit to Chiapas. An online training video in Spanish available on the IDEXX website also became valuable in training, to review the analysis procedure and reinforce methods for proper use of this bacterial enumeration system.

The IDEXX method was first approved for various uses by the US Environmental Protection Agency in 1989 and re-approved in 1994, while the Mexican General Director of Environmental Health first recommended the method in 1999 (IDEXX 2007). It is still considered the current gold standard for bacteria monitoring in water systems in terms of cost-effectiveness. The tests are considered both simpler to prepare and to read, and provide a much larger range of detection than several other more labor-intensive methods (Table 5).

**Table 5.** Detection limits for other traditional bacteria enumeration methods as compared to the IDEXX technology (IDEXX 2007)

<b>Method</b>	<b>Lower Counting Range (MPN/100 mL)</b>	<b>Upper Counting Range (MPN/100 mL)</b>
<b>Quanti-Tray</b>	<1	200
<b>Quanti-Tray/2000</b>	<1	2419
<b>5-Tube Dilution and Plate Count</b>	<1.1	16
<b>10-Tube Dilution and Plate Count</b>	<1.1	23
<b>Membrane Filtration and Plate Count</b>	<1	80

Lastly, UCSB obtained a flow velocity meter for use by ECOSUR. This method is considered more accurate than performing the float calculation method, which extrapolates average water velocity from the surface velocity. The flow meter consists of a protected water turbo-prop propeller with a magnetic sensor, coupled with an expandable probe handle and a user-friendly digital readout display. The meter incorporates a positive displacement technique for measurement with running true velocity averaging of the readout value. The anodized aluminum handle is lightweight yet durable and extends from 3-6 feet in length. Researchers at ECOSUR were encouraged to use the flow meter whenever needed, for the WQQM program and other projects. It was requested that the meter remain available to UCSB researchers during trips to Chiapas.

#### *4.4.2 Methods*

Physical, chemical and biological parameters were incorporated in the recommended monitoring plan for ECOSUR. More detail regarding the significance of these tests and their description of water quality can be found in the first group project report “A Framework for Developing a Sustainable Watershed Management Plan for San Cristóbal de Las Casas, Chiapas, Mexico” (Bencala et al. 2006). The parameters recommended for implementation by the first San Cristóbal project and those actually being tested by ECOSUR as of March 2007 are compared in Table 6.

**Table 6.** Comparison of recommended and currently performed tests for the WQQM Program in San Cristóbal de las Casas

Category	Recommended	Performed
Physical	Color	No
	Temperature	No
	Turbidity	No
	Flow	No <sup>1</sup>
	Total Dissolved Solids	Yes
Chemical	pH	Yes
	Dissolved Oxygen	No
	Alkalinity	No
	Hardness	Yes
	Ammonia	Yes
	Nitrate/Nitrite	Yes
	Total Nitrogen	Yes
	Reactive Phosphorus	Yes
	Total Phosphorus	No
Biological	Total Coliform	Yes
	<i>E. coli</i>	Yes

Field collection is generally accomplished over a 2-day period around the middle of each month by 1-2 researchers from ECOSUR. Reusable plastic sampling bottles that have been sterilized by autoclaving are used for collection of a 1000 ml sample, and bottles are placed in an ice-filled cooler until they return to the laboratory. Aliquots of these grab samples are then used for all tests. Temperature and dissolved oxygen are not regularly measured in San Cristóbal because a field probe is not available for these tests and these measurements cannot be taken accurately once the samples are returned to the laboratory.

While in Santa Barbara, the UCSB project team was trained in water monitoring detection methods so that members could familiarize themselves with the various aspects of a monitoring program and provide technical support for any concerns that arose in San Cristóbal (Figure 27).

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<sup>1</sup> Depth, a component of flow, is sometimes measured.



**Figure 27.** Dayna Yocum, a member of the Group Project from UCSB, learned how to take a flow measurement in Santa Barbara, California prior to her trip to Chiapas.

For the purpose of training, analysis methods were simplified from traditional, more-complicated versions found in user manuals. These are meant to facilitate volunteer training for individuals with some prior background in science education. Methods and detection ranges are detailed in Appendix E.2 in the order listed in Table 6.

#### 4.5 Roles of Partners

ECOSUR graduate students, undergraduate trainees and laboratory staff have carried out the main month-to-month functions of the monitoring program from May 2006 to the present. They have provided:

- A revised sampling protocol;
- Vehicular access and transportation to monitoring locations;
- Reusable sampling bottles and sampling supplies;
- Laboratory space and some equipment for analysis; and
- Electronic data sheets.

UCSB students provided water testing supplies and training to partners at ECOSUR between December 2005 and December 2006. Roles of UCSB students have been to:

- Provide advisement on the overall direction of the monitoring program and specific problem areas;
- Fund and/or supply some testing equipment; and



- Give technical support for appropriate use of some equipment and analytical methods.

In terms of supplies, this project obtained funding to provide partners at ECOSUR with the equipment detailed above. Additional materials not listed above were obtained by other means. It has been communicated that disposable supplies for all of these devices will need to be purchased by ECOSUR after the end of this project.

Time and manpower are the most significant limiting factors in expanding the WQQM program at ECOSUR. Thus, UCSB students assisted with monitoring during trips to Chiapas, though a longer-term solution has not been found. It is possible that, through partnerships formed in this project, high school-aged volunteers at SYJAC could assist with monitoring when needed, although trained individuals with prior experience are preferable. Other UCSB contacts in San Cristóbal with water sampling experience include Stephen Zylstra and Greg Hewlett. Inquiries regarding their willingness to continue assisting ECOSUR with the WQQM program have been made, and are discussed under the “Follow-up and Future Actions” section of this report.

#### 4.6 Results

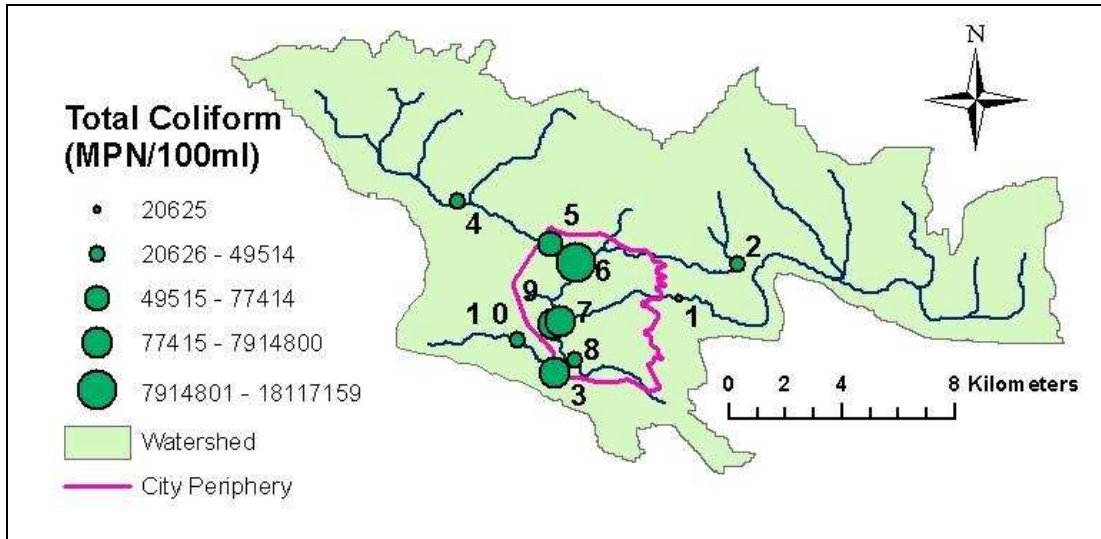
Monitoring results from May 2006 to December 2006, excluding October 2006, are detailed in Appendix E. As an indicator of baseline conditions, the average values found at each monitoring point are presented in Table 7.

**Table 7.** Average water quality indicator values for surface water sites measured May-Dec 2006 (n=7)

	<b>Fogotico I</b>	<b>Amarillo I</b>	<b>El Túnel</b>	<b>Chamula I</b>	<b>Chamula II</b>	<b>Amarillo II</b>	<b>Fogotico II</b>	<b>Navajuelos</b>	<b>San Felipe</b>	<b>Intersección</b>
<b>Nitrite (mg/L)</b>	0.00	0.01	0.04	0.16	0.02	0.05	0.02	0.02	0.03	0.03
<b>Nitrate (mg/L)</b>	0.70	0.68	1.87	1.57	1.18	0.73	0.59	0.66	1.18	0.70
<b>Phosphate (mg/L)</b>	0.15	0.70	1.93	0.61	0.39	1.75	0.44	1.17	0.25	0.77
<b>Total Coliform (MPN/100mL)</b>	20,625	39,196	18,117,159	77,414	49,514	6,663,956	6,082,177	48,246	44,275	7,914,800
<b>Fecal Coliform (MPN/100mL)</b>	14,344	28,101	12,236,523	40,763	22,583	15,061,087	4,666,440	36,836	28,492	5,355,946
<b>pH</b>	8.09	8.00	7.29	7.75	8.30	7.18	7.54	8.14	8.17	7.36
<b>Total Solids (g/L)</b>	0.07	0.09	0.21	0.16	0.16	0.22	0.11	0.25	0.21	0.15
<b>Ammonia (mg/L)</b>	0.00	0.28	2.97	0.32	0.01	3.10	0.27	0.12	0.16	0.67

All of the sites exhibit high contamination from fecal and total coliforms. Figure 28 illustrates the surface water locations' level of contamination, where the size of the

marker depends on the concentration of total coliform found at that site. The results for all of these sites indicates the presence of pathogens, including bacteria, viruses, and other microorganisms that can cause disease in humans. Thus, one can assume that the surface water surrounding San Cristóbal in general is not safe for human consumption or recreational contact (Table 8). High levels are most likely due to the regular practice of discharging raw wastewater into streams.

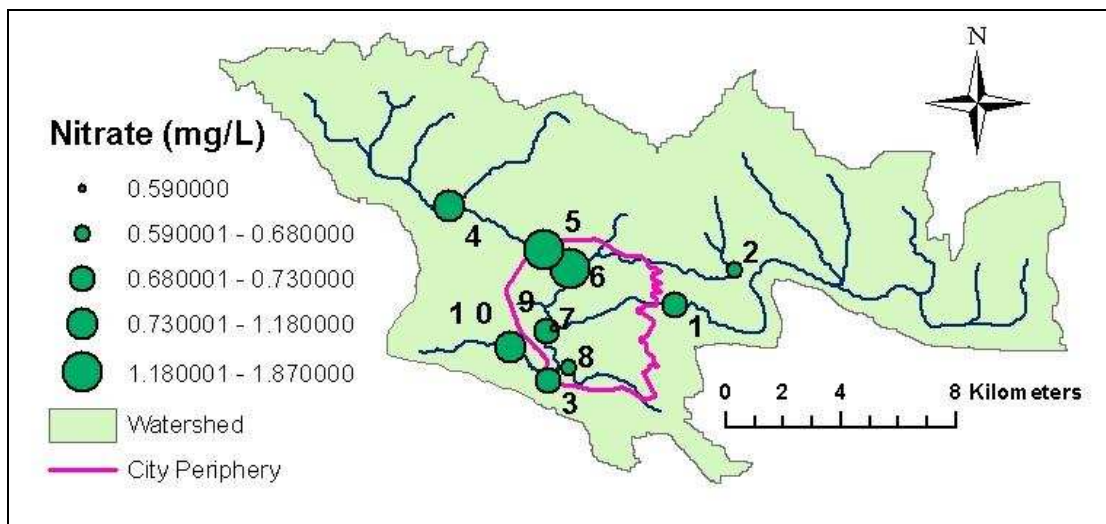


**Figure 28.** Gradation of low to high values found for average total coliform (MPN/100ml) at ten surface water monitoring sites in San Cristóbal's watershed; Location 7 (Fogótico II) overlaps the symbol for location 9 (Intersección)

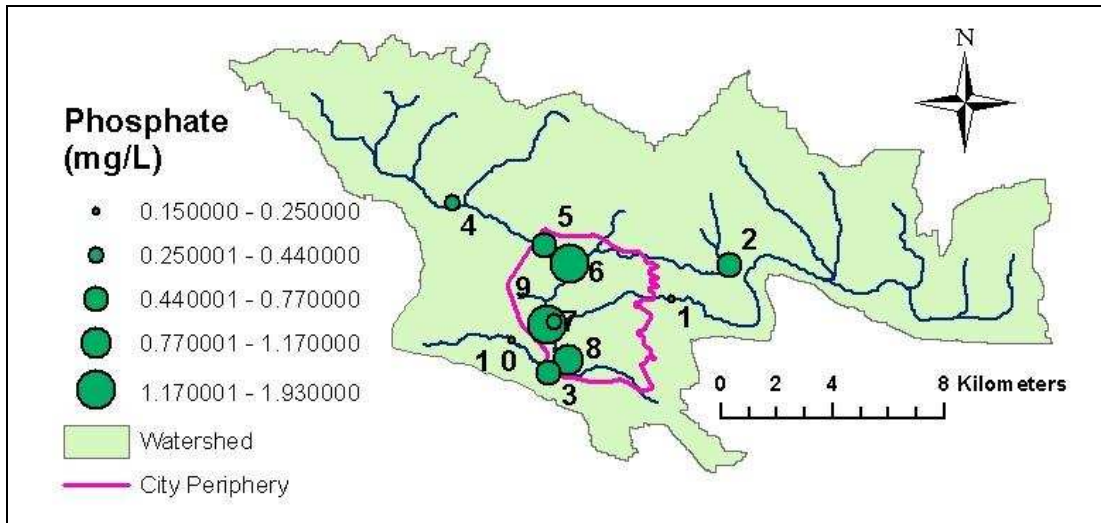
**Table 8.** Comparison of water quality parameters tested by ECOSUR with the related US and Mexican legal standards (Coutiño 1998; Lillo 1996; US Environmental Protection Agency 2007a; US Environmental Protection Agency, U. E. 2007b).

Parameters Tested by ECOSUR	Average Value for Surface Water Sites in San Cristobal	Mexico Primary Contact Standard for Rivers	US Primary Contact Standard	Average Value for Drinking Water Supply Sites in San Cristobal	Mexico Drinking Water Standard
Nitrite (mg/L)	0.04	40 (Total N)	(not specified)	0.006	1.00
Nitrate (mg/L)	0.96		(not specified)	0.02	10.00
Phosphate (mg/L)	0.88	20	(not specified)		
Total Coliform (MPN/100mL)	4,334,787	(not specified)	126	20	0
Fecal Coliform (MPN/100mL)	4,162,514	240	33	16	0
pH	7.74	(not specified)	6.5 - 9	7.36	6.5 - 8.5
Total Solids (g/L)	0.16	75 (Suspended Solids)	(not specified)	209	1,000
Ammonia (mg/L)	0.60	(not specified)	(not specified)		
Hardness (mg CaCO <sub>3</sub> /L)				253	500.00
Turbidity (FAU)				1	5
Free Chlorine (mg/L)				0.14	0.2 - 1.50
Total Chlorine (mg/L)				0.22	250.00

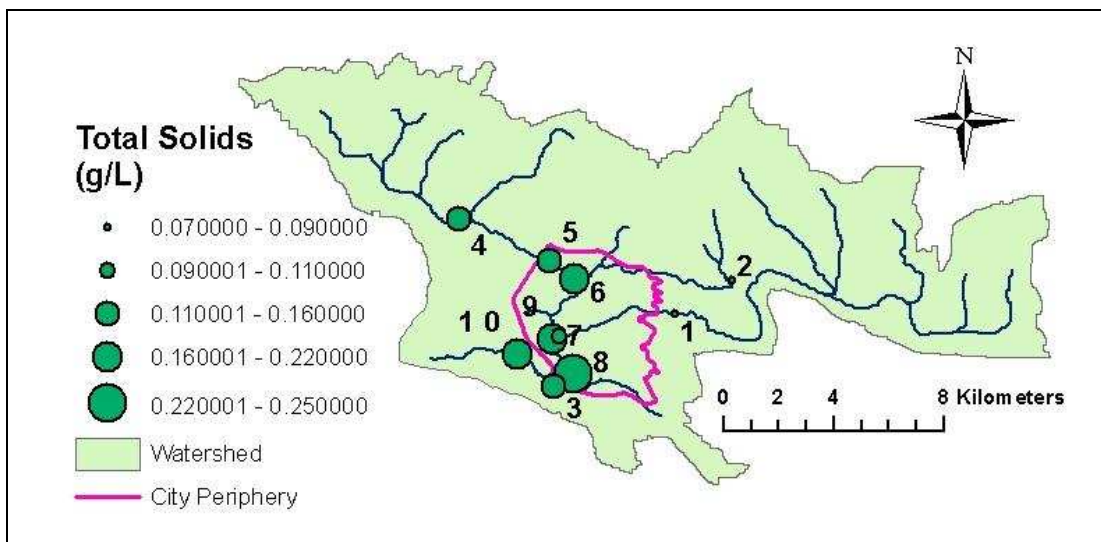
When analyzing the WQQM results, nutrient levels meet Mexican primary contact and drinking water standards, and pH is also within a normal range Table 8; Figure 29; Figure 30). Total solids are likewise acceptable (Figure 31). Finally, ammonia values are within a reasonable range for most monitoring sites, but are high for El Túnel (where the Sumidero River exits the watershed through a manmade tunnel) and Amarillo II locations (Figure 32; Figure 33). High ammonia values may occur due to a variety of factors, both natural and anthropogenic. Sources of ammonia include agricultural fertilizer, animal waste, household septic systems and cleaning products, in situ anaerobic degradation of wastewater, atmospheric deposition, or industrial point-source discharges. In San Cristóbal, the main culprits are most likely agriculture-related non-point source pollution for the Amarillo II and a combination of several of these sources for El Túnel, since it receives incoming waters from all of the watershed's tributaries.



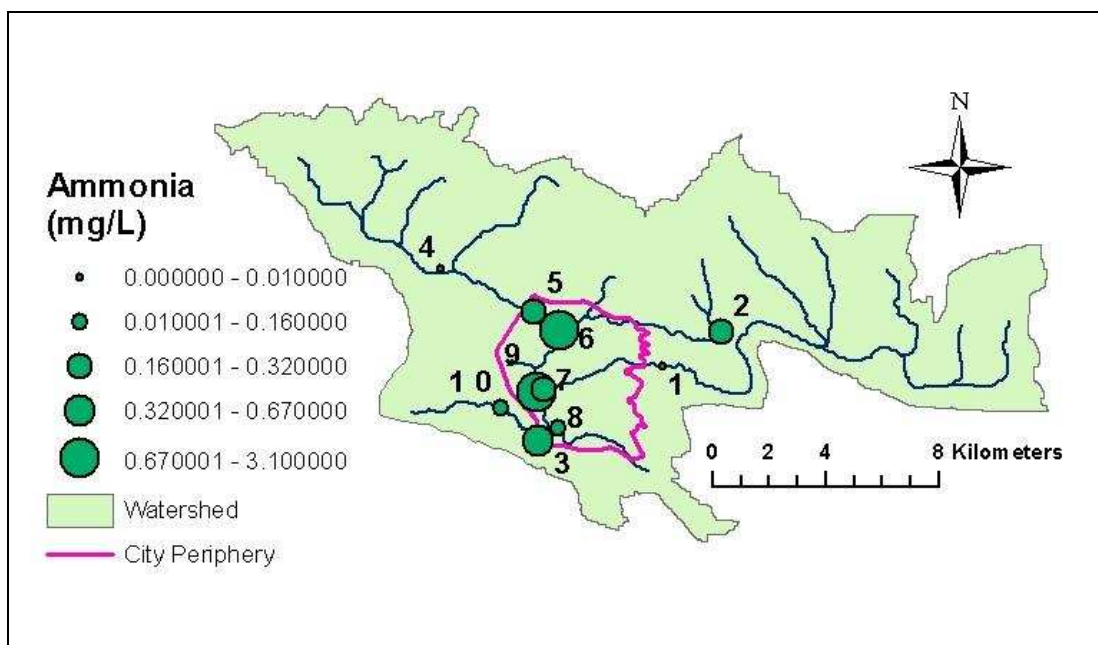
**Figure 29.** Average nitrate values in mg/L for the nine surface water monitoring locations; the value for site 7 (Fogótico II) is small and is overlaps the value for site 9 (Intersección).



**Figure 30.** Average phosphate measurements in mg/L at ten surface water monitoring locations in San Cristóbal's watershed from May-December 2006; The symbol for site 7 (Fogótico II) is overlapping the symbol for site 9 (Intersección).



**Figure 31.** Averaged values of total solids (g/L) found in water samples from the ten surface water monitoring locations between May and December 2006; the symbol for site 7 (Fogótico II) overlaps the symbol for site 9 (Intersección).



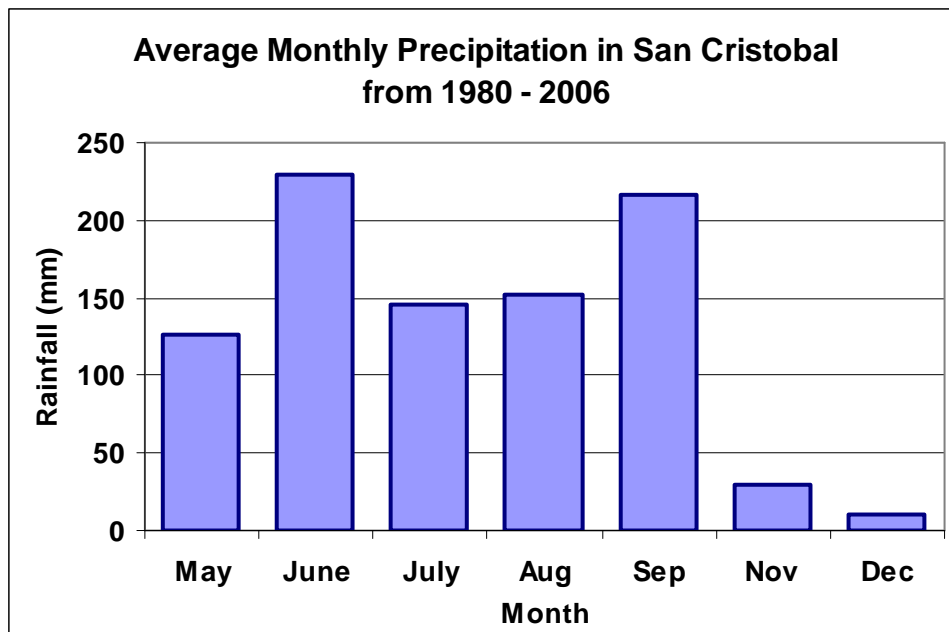
**Figure 32.** Ammonia averaged values (mg/L) for ten locations in San Cristóbal's watershed from May-December 2006; location 7 (Fogótico II) overlaps the symbol for location 9 (Intersección).



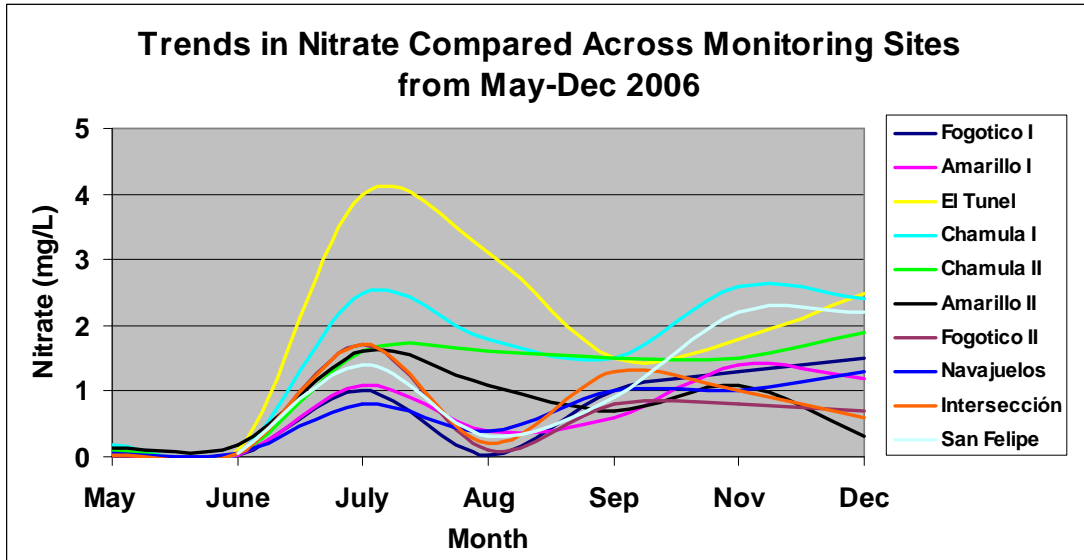
**Figure 33.** The entrance of the Sumidero tunnel (El Túnel); all water exits the watershed through this man-made tunnel drilled through the mountains. Therefore, this location collects waste and pollutants from all throughout the watershed.



To observe whether water quality is fluctuating throughout the year, values of each water quality indicator were compared across the nine different sites. First, nutrients do show some fluctuation. Nitrite ( $\text{NO}_2^-$ ) is not shown, since the values were minimal, and ammonia trends are also not displayed because results were only available from three months. Precipitation may influence the concentration of contaminants, either by having a dilution effect or by flushing pollutants from land into rivers. For this reason, a chart of the average monthly rainfall in San Cristóbal is shown for the monitoring period (Figure 34). Nitrate trends are shown in Figure 35. Here, it is clear that all sites experienced a dramatic increase in nitrate ( $\text{NO}_3^-$ ) from June to July 2006. This may be attributable to the application of crop fertilizers during this period. The highest values are seen for El Túnel and Chamula I sites. Chamula I collects overland runoff from a predominantly rural subwatershed, while El Túnel sees the combined effects of both point and non-point source runoff from the whole watershed.

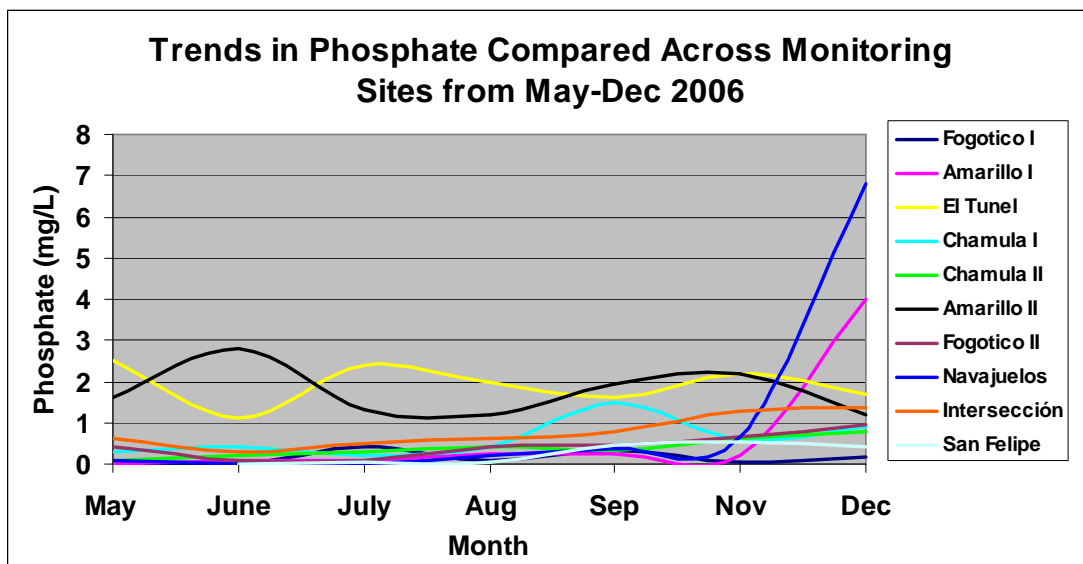


**Figure 34.** Average rainfall in mm for San Cristóbal (Comisión Nacional del Agua 2005)



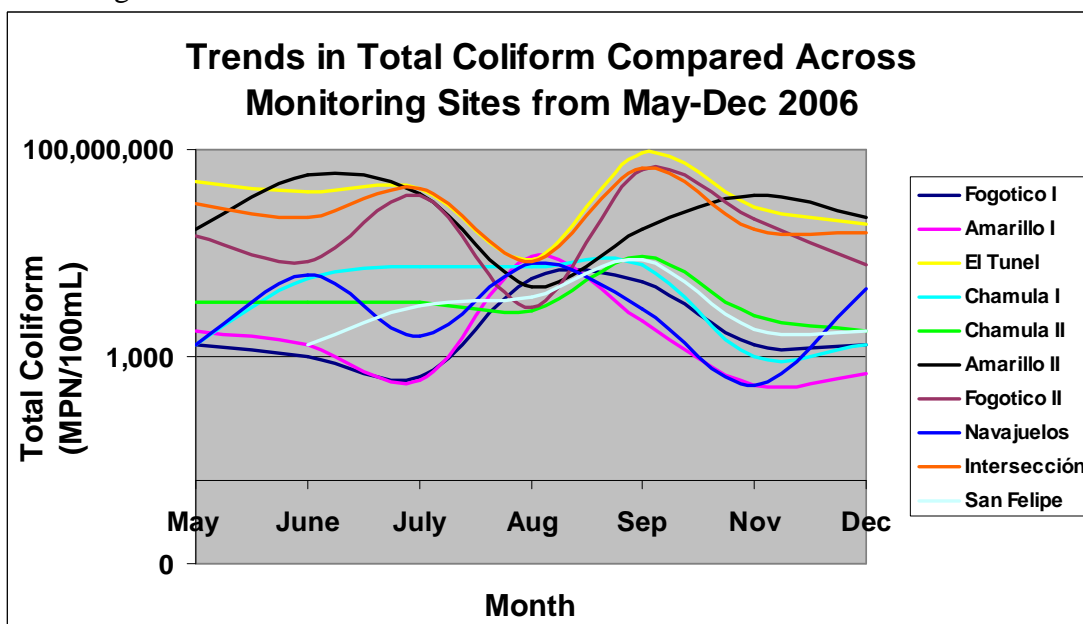
**Figure 35.** Comparison of monthly nitrate fluctuation across ten surface water monitoring sites starting in May 2006, until December 2006; the month of October is missing.

Phosphate, another major nutrient, shows a rather different trend than nitrate. The values may be lower than expected because the test was done for only reactive phosphate, a component of total phosphate. Figure 36 shows fairly low values for most sites, although spikes occur at the Navajuelos and Amarillo I monitoring sites in December 2006. Again, this is probably due to inputs from non-point sources such as agricultural fertilizers and animal waste, since these subwatersheds are located upstream from the urban area. Phosphate values are consistently higher for El Túnel and Amarillo II than the rest of the locations, as was the trend with ammonia. This could be explained by application in the watershed of combined agricultural fertilizers containing elements N (nitrogen), P (phosphorous), and K (potassium), a common mixture.



**Figure 36.** Phosphate fluctuation for ten surface water monitoring points in San Cristóbal's watershed from May-December 2006; Data for October is missing.

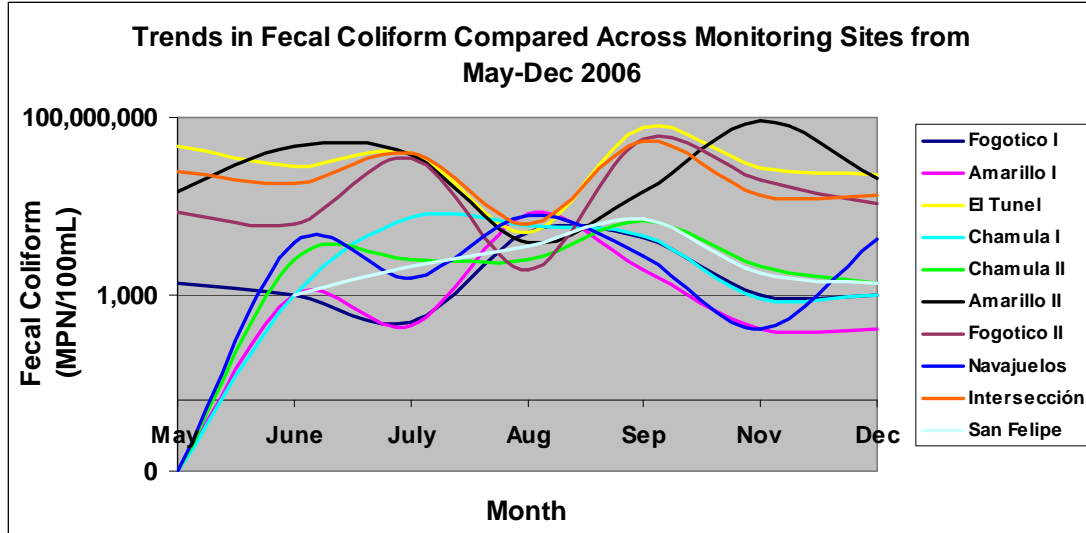
Total coliform values are displayed in Figure 37. As discussed above, the surface water is highly contaminated and this range of values signifies a hazard to human users. Total coliform counts are consistently higher at four points: El Túnel, Amarillo II, the Intersección, and the Fogótico II. Sources of coliform include both human and animal waste. In a rather strange pattern, the various sites appear to converge in August 2006, with normally high values being reduced and normally low values increasing.



**Figure 37.** Logarithmic display of total coliform MPN values found at ten surface water monitoring points from May to December 2006, excluding October 2006.

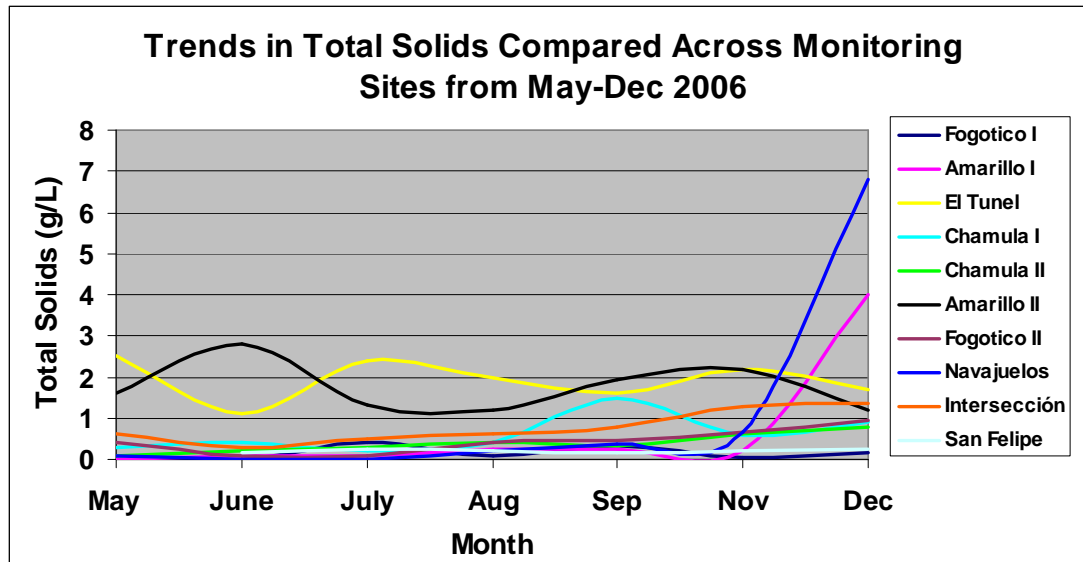


Fecal coliform trends are quite similar to total coliform, except that four locations (Navajuelos, Chamula I, Chamula II, and Amarillo I) actually test negative for the detection of fecal coliform in May 2006 (Figure 38). These locations also had consistently lower counts of total coliform, as mentioned above.



**Figure 38.** Fecal coliform results from May to September and November to December 2006 across ten different monitoring sites in San Cristóbal's watershed. MPN values are displayed on a logarithmic scale.

Lastly, total solids (the sum of total suspended solids and total dissolved solids) are not very high throughout most of the monitoring period, with values less than 7 g/L as compared to a maximum drinking water standard of 209 g/L and 1,000 g/L in the US and Mexico respectively (Table 8). Significant spikes are seen in December 2006 for the Navajuelos and Amarillo I monitoring points. This may be a function of the monitoring date directly following a major rain event, which can greatly increase turbidity and solids. Overall, higher solids levels are generally seen at the El Túnel and Amarillo II monitoring sites. To recap, these two sites also had high nutrient and bacteria levels. In general, solids are often correlated with bacteria levels, and thus are also a good indicator of pathogenic content. None of these values would render the water totally unusable, although higher solids levels can decrease the water's appeal for some uses.



**Figure 39.** Measurements of total solids from May to December 2006, excluding October 2006 at ten watershed locations

Complete results for monitoring done at water supply well locations can be found in Appendix E.3. Averages of these values are shown in Table 9. For comparison, standards for US and Mexican drinking water are located in Table 8. In these analyses of seven water supply locations from May 2006 to July 2006, Nitrite, Nitrate, Free Chlorine, Total Chlorine and Total Solids level were generally low and within an acceptable range for human consumption. Likewise, pH was within a safe range of values. Hardness was also typical, although the Peje de Oro spring had a low hardness as compared to most groundwater sources. This factor does not affect most uses of the water, though. Turbidity was always lower than the regulatory limitations, although it was higher for the month of June at the Peje de Oro and San Juan de los Lagos locations in comparison to the rest of the sites. As was mentioned earlier, higher turbidity is often, but not always, correlated with higher pathogen levels, and is sometimes used as an indicator of drinking water safety. In addition to the two locations mentioned above, La Almolonga and La KISST also showed moderately high bacteria counts. Any water supplied from these four wells should be disinfected before use.

**Table 9.** Average values of water quality constituents for spring locations monitored between May 2006 and July 2006

	Hardness (mg CaCO <sub>3</sub> /L)	Nitrite (mg/L)	Nitrate (mg/L)	Turbidity (FAU)	Free Chlorine (mg/L)	Total Chlorine (mg/L)	Total Coliform (MPN/100 mL)	Fecal Coliform (MPN/100 mL)	pH	Total Solids (mg/L)
<b>La Almolonga</b>	262	0.013	0.03	0	0.14	0.15	18	16	7.40	216
<b>La Hormiga</b>	255	0.007	0.05	1	0.14	0.50	1	0	7.44	217
<b>La KISST</b>	232	0.004	0.02	1	0.03	0.04	24	18	7.45	183
<b>Navajuelos</b>	294	0.004	0.01	1	0.36	0.46	0	0	7.28	240
<b>Peje de Oro</b>	131	0.006	0.01	1	0.05	0.07	53	41	7.31	118
<b>Real del monte</b>	280	0.004	0.02	0	0.25	0.31	0	0	7.30	221
<b>San Juan de los Lagos</b>	317	0.006	0.03	2	0.01	0.02	43	38	7.35	265

#### 4.7 Recommendations

This project recommends that all of the points shown in Figure 23 be monitored, provided that time and resources for more extensive monitoring become available in the future. Likewise, the monitoring program could be improved by capturing all of the parameters suggested in Table 6. Although some of the parameters or sites may not be at risk for non-compliance with water quality standards for recreational and consumptive use, it is important to establish at least baseline information for these parameters. Therefore, if some major disruption to the water source were to occur, it would be more easily detectable.

Flow is especially important to measure, since concentrations alone do not provide a clear picture of how much mass of the pollutants is moving through the system. Multiplying concentration values (usually mg/L) by flow values (m/s) will provide a mass flux value that can be input into the WARMF (Watershed Analysis Risk Management Framework) watershed model used for decision-making by ECOSUR and other partners, and also used in compliance mechanisms such as the Total Maximum Daily Load (TMDL) program which has been applied in some areas of the US. Researchers at ECOSUR have been encouraged to use the flow meter on loan from UCSB to obtain flow data for each of the monitoring locations.

In particular, capturing a representative sample of the water supplied to SAPAM customers could be useful in improving public health. Some of the springs and wells used to provide water to the city are disinfected prior to distribution: water from La KISST is treated with metered chlorine gas as it enters the distribution system, and La Hormiga, Navajuelos, and Real del Monte have chlorine tablets added as the water

passes through the pump. However, other water supply wells are not treated prior to distribution. The various water supplies' natural quality and usefulness may also vary quite a bit, depending mainly on whether the surrounding land is protected, or a source of contamination is located nearby. The source of water for a particular area of San Cristóbal depends on its proximity to one of these spring or well sources. Thus, the water source and treatment needed may vary widely from neighborhood to neighborhood. A general base water quality from each of the supplies might be made publicly available so that water utility customers could make informed decisions regarding investment in additional point-of-use water treatment devices.

Finally, an informed temporal distribution of monitoring dates might provide a clearer picture of the hydrologic processes in the watershed. Currently, the monitoring program was not planned to take place on a specified date each month. Nor does it adapt to monitor more often during periods of high importance for water quality, such as storm events or drought periods. This is partly due to scheduling difficulty, but a more flexible approach is possible in the future. Once sufficient data becomes available, it may be feasible to detect those times at which the water quality is fluctuating (either improving or declining) most. In an attempt to detect these types of events, monitoring could be done at differing times of month throughout the year to try to portray a representative spread of the full period. Then, once the high importance events are discovered, arrangements could be made ahead of time to try to capture these times during a flexible monthly sampling regime.

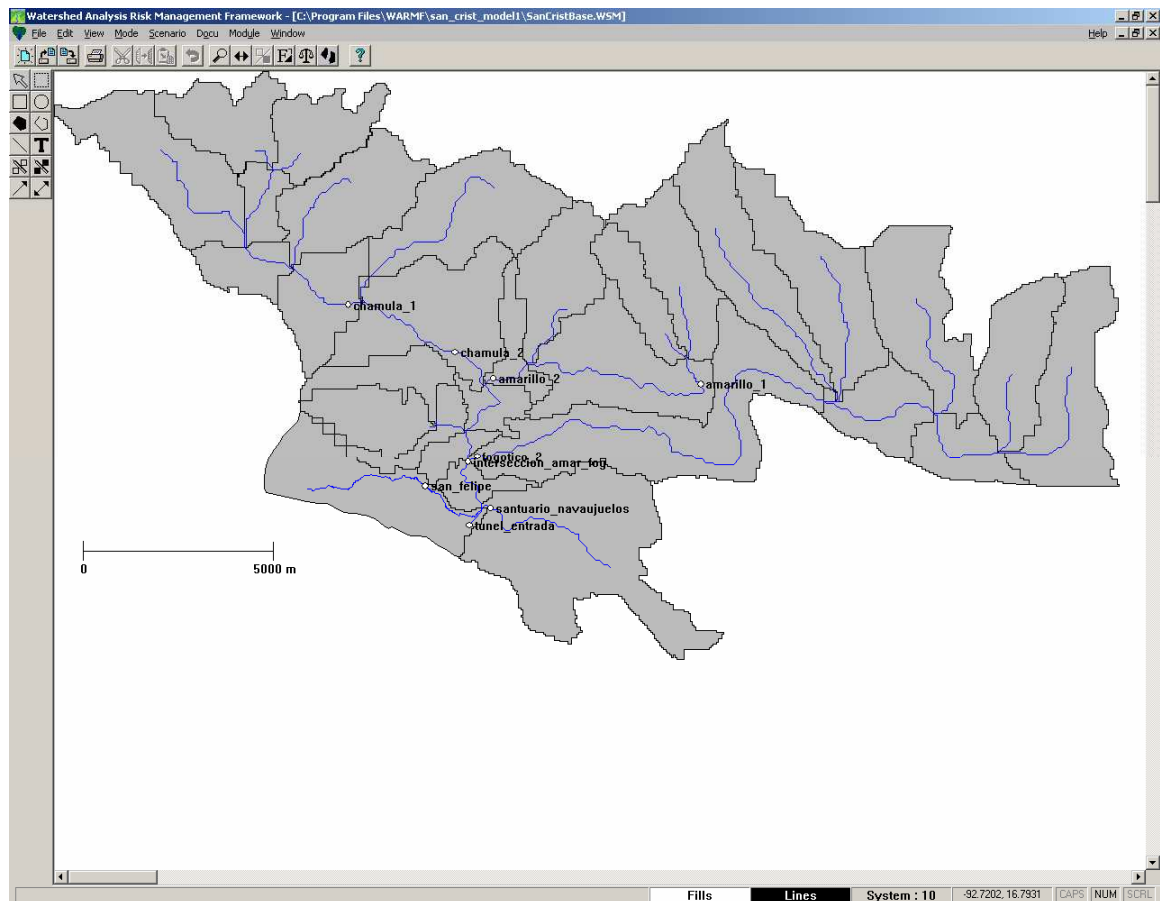
## **5.0 Modeling of the San Cristóbal de las Casas Watershed**

### **5.1 Approach and Justification**

Computer simulation models can serve as valuable tools to help understand current watershed processes and predict the watershed's response to future changes. To gain further insight into the watershed processes, this project used a model partially constructed by the first San Cristóbal Group Project members (denoted as 'initial model') in the EPA-recommended watershed modeling program: Watershed Analysis Risk Management Framework (WARMF). Project members increased the initial model's utility by calibrating it with water quality and quantity data measured from 2006 in San Cristóbal (updated model denoted as 'updated model'). To complete this project's goals toward researching and implementing effective BMPs, the watershed modeling program was used to simulate and analyze the potential effects of the recommended BMPs within the watershed.

WARMF is a cost-free, publicly available program that facilitates watershed planning and management for stakeholders. It is also compatible with other free data extraction and watershed delineation tools provided by the USEPA BASINS program. Its user-friendly Geographic Information System (GIS)-based interface makes it accessible for use by project partners in Chiapas, who are already equipped with the knowledge base necessary to run the program (Figure 40). Designed primarily for use in

determining Total Maximum Daily Load (TMDL) levels in impaired waterways, WARMF has the capacity to model the contribution of point and non-point sources of nutrients and pollutants to surface waterways and groundwater. More importantly, WARMF can model effects of anthropogenic forces that change the nutrient load or augment extraction of water resources. For instance, using estimates of pollutant removal rates for those BMPs recommended in this report, the nutrient load values can be modified to reflect the effects of widespread BMP implementation.



**Figure 40.** Screen shot of the WARMF interface.

Like any watershed model, the San Cristóbal model needs to be continuously updated with observed data, so as to accurately reflect the conditions in the watershed. Once calibrated, it will be able to guide management decisions towards watershed-wide attainment of water quality standards for coliform, Total Suspended Solids (TSS), Biological Oxygen Demand (BOD) and nutrients (N and P), and indicate areas in the watershed that need particular attention (US Environmental Protection Agency (EPA) 2006). Using the initial model, the project members input hydrology and water quality data collected in 2005-2006, then calibrated the model by changing appropriate parameters and used it to determine nutrient and pathogen fate and transport mechanisms for a number of future scenarios. This project's modeling goals focused on modeling the effects of BMP implementation on various regions of the

watershed. Scenarios modeled include wide-scale application of different recommended BMPs. Section 5.4 describes the scenarios run and output generated.

Continued water quality monitoring is crucial in support of the model, so that its calculations will represent the watershed's processes accurately. The single year of monitoring data currently available is not sufficient to calibrate the model to a point where environmental managers can rely on the model's output's accuracy. More observed data is necessary to improve the updated model's calibration and therefore the accuracy of the watershed's predicted responses to changes through time. However, the model does provide preliminary output results and an established scenario framework to update with future monitoring inputs.

## 5.2 WARMF Model Characteristics

Initial data collection and research performed by the first project provided a model that was fully functioning though not calibrated, and which served as a base for this project's watershed analysis. The initial model included meteorological data specific to San Cristóbal from 1989-1999, land use, municipal well pumping data, a rough subsurface soil profile, groundwater data, and estimates of point and non-point discharges into the waterways. This section of the report briefly describes the datasets and their modifications. Further information regarding how the datasets were obtained can be found in the first group's report (Bencala et al. 2006). To calibrate the model and employ it in making predictions, this project obtained up-to-date meteorological data and incorporated the observed water quality data obtained from the WQQM program performed by ECOSUR during 2005-2006. Parameters tested in this continuing program are pH, ammonium, nitrate, nitrite, bacteria, total nitrogen, total phosphorus, total solids, and flow.

### *5.2.1 Model Set-up and Function*

To construct the model, the San Cristóbal watershed was delineated and divided into a series of subbasins with EPA's BASINS program, then imported into WARMF (Bencala et al. 2006). This enabled WARMF to calculate surface water runoff and groundwater contributions to river reaches passing through each subbasin. Land use, vegetation cover, and precipitation data are used to characterize the subbasins, which allow the model to determine the speed and amount of water, nutrients, and pathogens that run off the land into surface waters. Water is routed through the watershed from reach to reach, intersecting with neighboring rivers that form the watershed.

In addition, WARMF completes the mass balance equation to determine the amount of pollutants that will flow into, through, and out of the watershed, incorporating point and non-source nutrient contributions from industry, agriculture, and septic systems. WARMF also can incorporate additions of pollutants from atmospheric deposition, though the initial and updated models for this project do not account for these values due to the lack of air quality data. However, atmospheric deposition is

unlikely to be a significant source of pollution, as there are very few polluting industries in San Cristóbal. In the updated model, sampled nutrients and coliform are targeted as water quality indicators, and are tracked throughout the system, incorporating their characteristics through the processes of infiltration, soil adsorption, exfiltration, and overland flow (Systech 2007).

#### *5.2.2 Initial Model Inputs*

##### Land Use

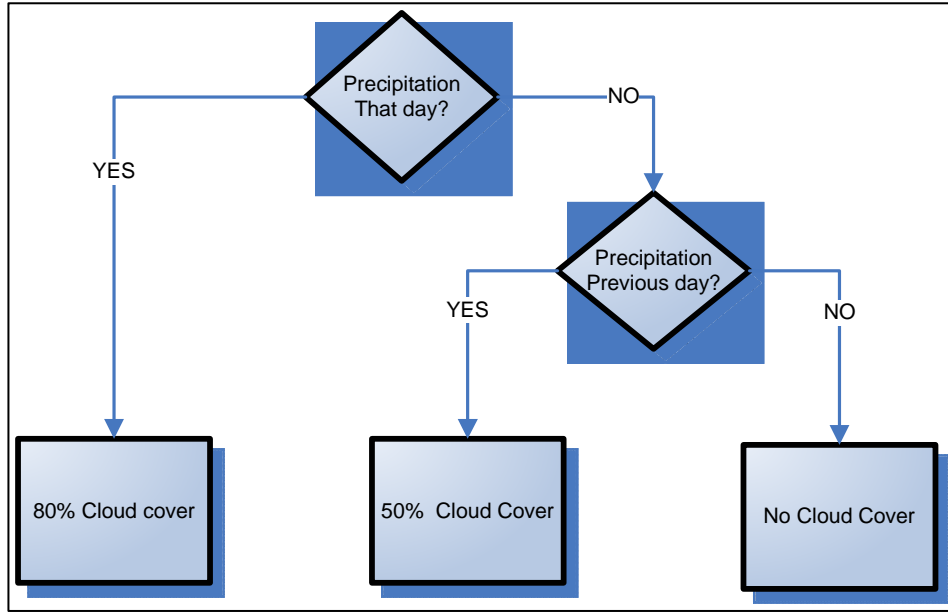
Land use data was acquired from a study performed by an ECOSUR researcher, in the form of a supervised classification algorithm associated with 30 meter LANDSAT TM data (Zermoglio 2005). The land use file was modified by UCSB researchers using heads-up digitizing to incorporate additional knowledge about the urban extent from a 2001 IKONOS image obtained from partners at LAIGE (Bencala et al. 2006).

##### Meteorological data

Meteorological data is required for WARMF simulations, which includes daily precipitation and air quality data. Precipitation and temperature data was obtained from Climate Computing Project (CLICOM) data records, a project of the World Climate Data and Monitoring Program. Data included records of several meteorological stations in the watershed, spanning 1951-2000. The updated model was required to run up through December 2006, so new data was requested and utilized.

Atmospheric deposition data is not available for this watershed, and a generic “dummy file” from another watershed was used to satisfy the model’s requirements. However, to ensure that bias was not introduced into the model, the atmospheric deposition multiplier was set to zero for all simulations, which forces the model to ignore atmospheric deposition altogether.

Additional data required includes cloud cover, dew point temperature, wind speed, and air pressure, which were also unavailable. To estimate cloud cover, a decision tree was employed that classified the percentage of cloud cover based on the precipitation records of the present and previous days, illustrated by Figure 41. This was developed by Dan Segán (Bencala et al. 2006) following the model developer’s instructions (Systech 2007).



**Figure 41.** Cloud cover decision tree, courtesy of (Bencala et al. 2006).

Daily dew-point temperatures were estimated using daily temperatures by first solving for saturation vapor pressure [Equation 2], then using this coefficient to solve for dew point temperature (Bras 1990), where  $E_s$  is saturation vapor pressure,  $T$  is average daily temperature, and  $T_d$  is dew point temperature [[Equation 3]. This equation produces dew point temperature in °F, which can be converted to °C with [Equation 4].

[Equation 2] 
$$E_s = 33.8639[(0.000738T + 0.8072)^8 - 0.000019|1.8T + 48| + 0.001316]$$

[Equation 3] 
$$T_{d(^{\circ}F)} = \frac{E_s - 6.11}{0.339} + 32$$

[Equation 4] 
$$T_{d(^{\circ}C)} = T_{d(^{\circ}F)} - 32 * \frac{9}{5}$$

Wind speed was estimated at 7 m/s based on the observed conditions of the watershed, and air pressure was calculated based on the mean elevation of the watershed. Both were held constant during the entire simulation period.

#### Subsurface Profile Depths

Due to the drastically changing elevation in the steep watershed, soil composition across the surface area is varied. However, this variability is not well captured in documented information and many soil characteristics were based on educated estimates from observations, elevation, and typical soil values obtained from literature. WARMF considers soil characteristics homogeneous for the entire subbasin, thus only the most typical conditions were considered when classifying soils.



All subbasins were classified as either having ‘Shallow Soil’ or ‘Typical Soil’ based on average slope. The nine subbasins with an average slope of 15% or greater were considered to have experienced heavy erosion, and were classified in the first group, and the 22 subbasins with an average slope of less than 15% were assigned to the second group. Values from a 2003 study of San Cristóbal’s soil resistivity provided limited information which was referred to when unit depths were assigned to the typical and shallow soil layer groups (Fuentes, Onofre, and Macías 2003). These values were modified somewhat in the updated model.

#### Soil Characteristics

WARMF divides the subterranean profile into five layers, for which the user must define thickness. The initial model divided the layers into two primary groups for estimation of the soil’s hydraulic conductivity: the topsoil layer (the top two layers) and the underlying soil units (the bottom three layers). Local data consisted of a rough soil classification map obtained from LAIGE at ECOSUR, which divided the topsoil into seven broad categories based on dominant regional topsoil. Literature values were used to define the hydraulic conductivity coefficients for each topsoil type and these were applied to each subbasin. During calibration by the first group, however, the values were significantly varied. Soil characteristics, including hydraulic conductivity and soil thickness, were a source of large uncertainty in the initial model.

#### Municipal Pumping and Industrial

The municipal water district provided the first San Cristóbal group with monthly pump rate data for 19 pumps in the watershed, from December 2004 to October 2005. These 19 locations were divided into five subgroups based on location. Pumping rates from all pumps in each subgroup were added together to determine the total extraction rate from each of the five primary locations, which was then input into the WARMF model. Estimates for November were set at the average pumping level for the 11 previous months in order to create a complete one-year dataset. This contiguous 12 month dataset was repeated throughout the entire course of the 11-year model (1989-1999) (Bencala et al. 2006).

The FEMSA Coca-Cola bottling plant represents the only major industrial water extractor in the watershed. Annual extraction rates from the plants two wells were obtained and then aggregated to estimate the total extraction rate. As in the first project, rates were assumed to be constant over the course of the year, and calculated accordingly (Bencala et al. 2006).

#### Fate of Extracted Groundwater

Following the assumptions in the first project, the research team assumed that the pumped groundwater returned to the river system in three different manners. It is important to take this into account because the river’s flow is attenuated by the groundwater extraction used for municipal water supply. To realistically model the system, the water “lost” to groundwater extraction must be returned to the river. In

this way, WARMF is able to model the stage (elevation) and velocity of the river's flow which can be compared with physical observations.

1. 40% is returned as point source discharges to the river reach in which it is consumed to represent wastewater.
2. 50% is lost to system leaks during the pumping process and is returned in an unpolluted state to the upper watershed subbasins. This value was based on government estimates, which report a 43% loss within the SAPAM system and additional losses in private pumping systems in the region (Arreguín, Ochoa Alejo, and Fernández Esparza 1997).
3. 10% is not returned to the system, based on an assumption that 10% of the pumped water is bottled within the region but consumed outside of the region.

#### Point discharges

The initial model incorporates untreated point source discharges to account for the untreated urban wastewater. A rough calculation of wastewater quantities for each subbasin was based on the proportion of total urban population (2005 population estimate) from that subbasin and multiplied by the 40% of water pumped from the watershed that is estimated to become domestic wastewater (Bencala et al. 2006). To obtain a conservative estimate, it was assumed that all urban dwellers contribute to the sewage conveyance systems of the urban center and that conveyance systems discharge into the rivers within the subbasin in which the wastewater originates.

The point source discharges contain measures of ammonia, phosphate, fecal coliform, and biological oxygen demand (BOD), which are commonly found in domestic sewage. The quantities reported as the Mexican standard per-person production rate by Crites and Tchobanoglous were multiplied by each subbasin's urban population to obtain the total subbasin load for each contaminant (Crites, R. and Tchobanoglous 1998).

#### Non-point discharges

Rural wastewater inputs into the system were estimated in a similar way, but were assumed to enter the model as non-point discharges because there are no known sewer systems in the rural areas of the watershed. Non-point pollution loads often differ greatly from point loads in that they are applied to the land surface, allowing for the soil and vegetation to absorb some of the nutrients before they enter the waterway. Using the 2005 estimated total rural population, a rough calculation of non-point loads for each subbasin was based on the proportion of total rural population for that subbasin and multiplied by the same Mexican standard per-person production rate for domestic sewage used above.

#### Additional Sources of Pollutant Load

Model default loading values were utilized to estimate loading from agricultural and livestock operations. In the future, these values could be improved by documenting

the type of crops grown and the ingredients in fertilizers applied around San Cristóbal to more accurately estimate nutrient loading from these sources.

### *5.2.3 Updated Model Inputs*

#### Water Quality and Quantity Observations

Since the commencement of the water quality and quantity monitoring program in May 2006, project partners at ECOSUR have sampled once each month (with the exception of October) from May to December 2006 at ten targeted locations in the watershed. Water quality parameters sampled include nitrate, pH, ammonium, nitrite, total coliform, fecal coliform, total nitrogen, total phosphorus, and total solids. Targeted locations include three monitoring points within the rural region, six monitoring points in urban areas, and one monitoring point located at the outlet (El Tunél) of the main river after all point and non-point discharges have been applied.

Water quality measurements are particularly important in the process of recognizing the major problem areas and nutrients in the watershed. Inputting this information into WARMF allows the user to calibrate the model by adjusting appropriate factors (nutrient inputs, effectiveness of septic systems, etc) in order to match the actual observed nutrient measurements. Additionally, the values can be compared from month to month to determine when the contaminant levels are at their worst and thus aid in identifying temporally-variable sources of pollution. Further, these water quality measurements can serve as a baseline for future comparison when examining the effects of BMPs. The data found for water quality is described and analyzed in section 4.6 of this report.

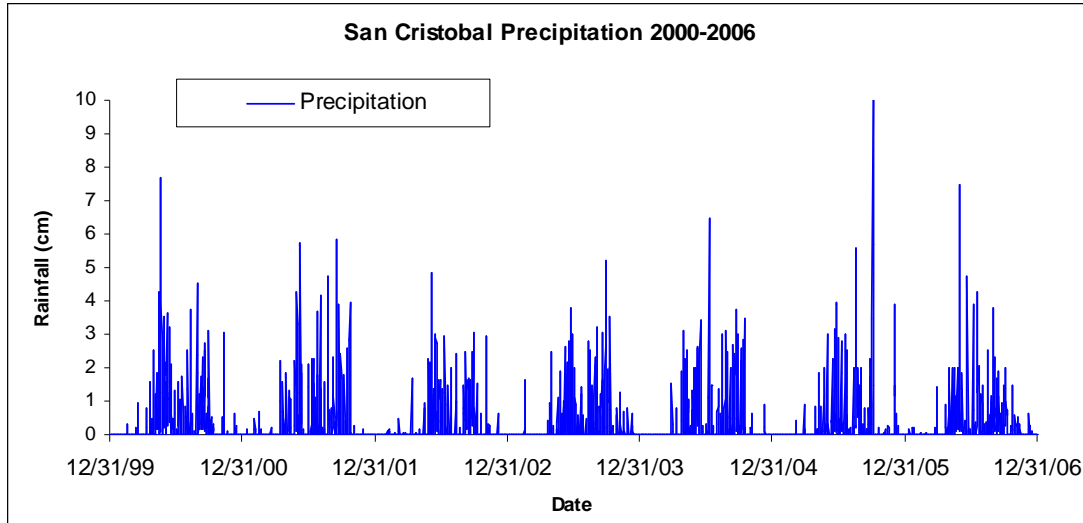
Water quantity measurements are equally as important as water quality values, because they enable analysis of total pollutant mass and flux. For instance, one can observe whether nutrient concentrations are increased at lower or higher flows, and conceptualize why this trend occurs in the watershed. Flow measurements should be made a priority as part of the WQQM program because it is necessary to have flow measurements to calibrate the WARMF model. The initial model was calibrated, though without any data points. The updated model incorporates water quality data taken as part of the water quality monitoring plan being implemented by ECOSUR, and a few flow measurements taken by project members in the late summer and early fall in 2006. To further improve this calibration, more frequent and long-term flow monitoring is needed. Using more data to calibrate the model improves its accuracy and makes the results more meaningful.

#### Updated Meteorological Data

It is important to match water quality and quantity data to actual conditions so that observations of high levels of nutrients or other contaminants can be associated with either high or low precipitation events. For instance, the initial model simulations suggest that in rural regions, runoff from storm events contributes a significant amount of the total nutrient load, while in urban regions the total nutrient load during

storms dramatically decreases, as the increased stormwater flow greatly dilutes the nutrient concentration. For this reason it is essential to have precipitation measurements for the days just prior to when the water sample was taken.

Data was solicited and collected from Comisión Nacional del Agua (CNA) for Station 7087 during the years 1951-2006 (Figure 42). The updated model focuses on the years 2000-2006, because monitoring data for this time frame was used to calibrate the model. Station 7087 is located within the city center of San Cristóbal. Gaps in the data set were filled in with average values for the day of the year.



**Figure 42.** Recorded precipitation in San Cristóbal de las Casas (Comisión Nacional del Agua 2005)

### 5.3 Calibration

#### *5.3.1 Flow Calibration*

Project members first focused on calibrating flow values because flow influences the concentration of constituents in the water quality observations. When observed hydrology values ( $n=6$ ) were input into the model and it was run with initial soil layer values (Table 10 and Table 11), simulations showed higher levels of flow than were reflected in observed values, so efforts were taken to decrease the flow. Group members adjusted field capacity, saturation moisture, initial moisture, and soil thickness values of the soil layers until the model output had the same range of values as that of the observed data.

**Table 10.** Initial soil layer values from the first San Cristóbal group project watershed model for shallow (<15%) sloped subcatchments

Soil Layer	Soil Thickness	Initial Moisture	Field Capacity	Saturation Moisture	Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity
1	100	0.20	0.40	0.50	6625	663
2	200	0.15	0.30	0.45	6625	663
3	1600	0.10	0.22	0.35	100	10
4	2750	0.20	0.20	0.35	750	150
5	3000	0.20	0.15	0.35	750	150

**Table 11.** Initial soil layer values from the first San Cristóbal group project watershed model for steep (<15%) sloped subcatchments

Soil Layer	Soil Thickness	Initial Moisture	Field Capacity	Saturation Moisture	Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity
1	50	0.20	0.40	0.50	6625	663
2	100	0.15	0.30	0.45	6625	663
3	800	0.10	0.22	0.35	100	10
4	150	0.20	0.20	0.35	750	150
5	100	0.20	0.15	0.35	750	150

Unfortunately, there are no extensive studies on soil layer depth and composition or groundwater movement in the San Cristóbal watershed; so much of this calibration was performed by inputting various combinations of likely values and attempting to adjust modeled flow to match observed flow. For example, the difference between field capacity and saturation moisture represents the capacity of the soil to store water. If this difference is decreased, the rate at which rainfall will saturate the soil layer increases, which, in turn, leads to exfiltration of groundwater to the streams. If the difference between these two values increases, then the soil has a greater ability to accumulate rain water in the soil without influencing the flow in the streams.

The initial moisture was higher than that of the modeled output conditions for observed data points, so initial moisture was lowered to remove the sharp drop in flow at the beginning of the six year modeled hydrograph. However, consistent with real-world values, the initial moisture was kept equal to or higher than field capacity (Table 12 and Table 13).

The initial model estimated soil layers 4 and 5 to be significantly thinner in watersheds with a slope >15%. During calibration, the thickness of soil layers four and five was increased from the model's original values in subcatchments with an average slope greater than 15% to be slightly thicker than values in the initial model. These additional 450cm increase the amount of water stored.

Calibration also involved varying the soil thicknesses. Final soil thickness values were chosen based on the scenario with the flow that best fit with observed values. Unfortunately, soil thickness data has not been studied in the region, and until further studies are undertaken, soil thickness will remain a source of uncertainty in the model.

Hydraulic conductivity in the flat and shallow sloped subcatchments was lowered to simulate slower movement through the soils. Horizontal conductivity was assumed to be one order of magnitude (ten times) more than vertical conductivity in the shallow sloped layers, following the recommendation of Yu et al (Yu, C. C., Lourerio, Cheng, Jones, Wang, and Faillace 1993). Steeper, thinner soils, however, were assigned a 5:1 horizontal to vertical conductivity ratio, as geologic movement characteristic of steeply sloped areas uplifts the soil layers, resulting in a sloped soil profile, thus creating a gradient within the soil layers and decreasing the soil structure's ability to slow vertical migration of water. To calculate the hydraulic conductivity values, the members used the assumptions of the first San Cristobal project, which developed the modeled the watershed soil with layers one and two as loosely packed soils, layer three as a clay layer, layer four as karst limestone, and layer five as volcanic rock. Conductivity values for layers three through five were adapted from the average of a range of values given these soil types by (Bencala et al. 2006; FreezeandCherry 1979).

**Table 12.** Final soil layer values for shallow (<15%) sloped subcatchments

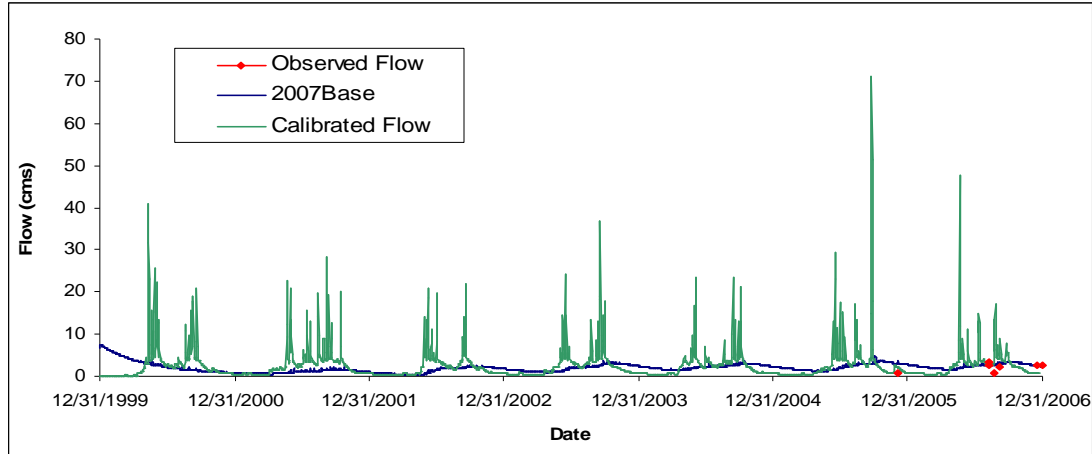
Soil Layer	Soil Thickness	Initial Moisture	Field Capacity	Saturation Moisture	Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity
1	50	0.43	0.43	0.50	2880	288
2	100	0.32	0.32	0.40	2880	288
3	800	0.27	0.27	0.29	1	0.1
4	2750	0.30	0.30	0.35	4320	432
5	3000	0.34	0.31	0.35	0.1	0.01

**Table 13.** Final soil layer values for steep (>15%) subcatchments

Soil Layer	Soil Thickness	Initial Moisture	Field Capacity	Saturation Moisture	Horizontal Hydraulic Conductivity	Vertical Hydraulic Conductivity
1	50	0.43	0.43	0.50	1440	288
2	100	0.32	0.32	0.40	1440	288
3	800	0.27	0.27	0.29	0.5	0.1
4	400	0.30	0.30	0.35	2160	432
5	300	0.34	0.31	0.35	0.05	0.01

To calibrate the model, project members chose to first calibrate the Fogótico River subwatershed, and then apply the input variables to the rest of the watershed. This approach was taken to save time in calibration. Fogótico was chosen because the observed flow measurements at the station were judged to be more robust than other

measurements (n=6). Observed flow measurements were taken atop a diversion dam. The constant profile provided the calculations with the most accuracy of all the sample locations. Figure 43 shows the modeled flows at Fogótico before and after the flow calibration. The blue 2007Base curve represents the simulate flow with updated and temporally extended precipitation and air temperature values with initial model soil coefficients. Simulations during the calibration process were compared to this initial curve with the goal of matching simulated values more closely to observed values in 2005 and 2006.

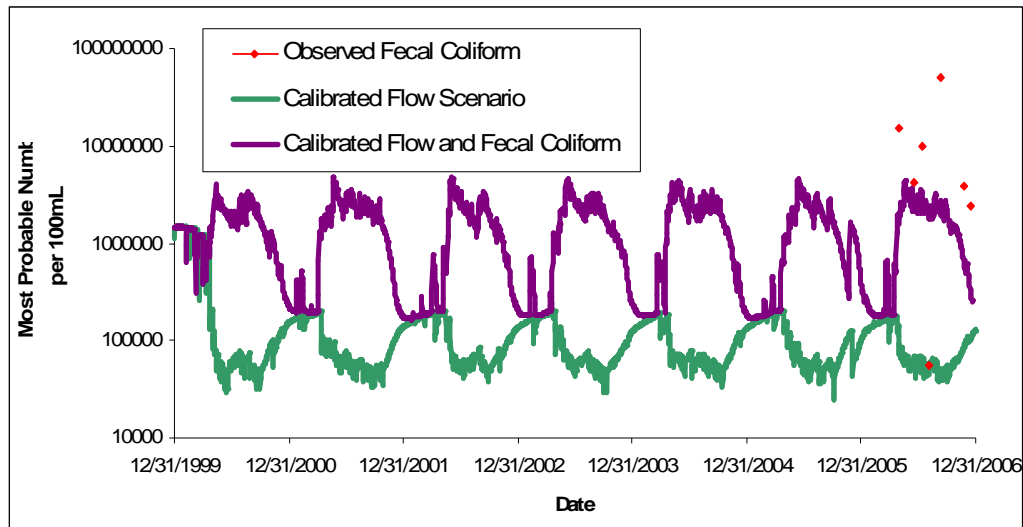


**Figure 43.** Flow at the Fogótico monitoring point before (blue) and after (green) calibration.

### 5.3.2. Fecal Coliform Calibration

Fecal Coliform concentrations were extremely low in the calibrated flow model even at the maximum septic system application rates of  $10^9$  fecal coliform bacteria per 100 mL water (Figure 44). As discussed in section 4.6, the observed extremely high levels of fecal coliform are due to raw sewage in the watershed. For this reason a scenario was created that does not include the urban point sources; this is further explained in the assumptions section in the composting latrines scenario. Attempts were made to improve the accuracy of the calibrated flow model by increasing the land application contribution in mixed forest, rangeland, and residential lands by a factor of ten. For the scenario modeling composting latrines, fecal coliform levels are explored at the Sumidero monitoring point because it represents a cumulative measure of fecal coliform levels from the entire watershed contribution.

The resulting calibrated flow and fecal coliform scenario mirrors the calibrate flow scenario with unadjusted fecal coliform concentrations because the septic systems discharge into the top soil layer. During high flow events, more of the bacteria is washed out of the soil. Precipitation events directly correspond to the higher simulated fecal coliform levels.



**Figure 44.** Fecal Coliform concentrations at the Sumidero monitoring point in the calibrated flow scenario with unadjusted fecal coliform concentrations (green) and the calibrated flow scenario with fecal coliform concentrations at maximum input level (purple)

#### 5.4 Scenario Descriptions: Watershed-Wide Scale of BMP Implementation

##### *5.4.1 Scenario Overview*

The BMPs that focus on reduction and attenuation of sediment, nutrients, and pathogens are summarized in Table 14. This analysis used the watershed model to test the response of the watershed to wide-scale implementation of one of the recommended BMPs, composting latrines. Additional scenarios that can be modeled are described following the analysis. Not all of the BMPs recommended in this report can be addressed through a WARMF analysis. For example, WARMF would not be able to model the effects of widespread rainwater harvesting systems because their purpose is not intended nor expected to minimize pollutant loading. The watershed model interface does not allow users to assign a given load reduction for a specific geographic location in the stream network. Rather, the user must identify which variables to change in the subwatersheds delineated by BASINS, and then apply a load reduction equal to the cumulative reduction attained by all implementations in that subwatershed.



**Table 14.** BMP implementation scenarios modeled using WARMF

<b>BMP Scenario</b>	<b>Contaminant Addressed by BMP</b>	<b>WARMF Tool used in Simulation</b>
Composting Toilets	Fecal Coliform, BOD, N and P	Septic System
Blackwater Wetland	Fecal, Coliform, BOD, N and P	Septic System
Contour Trenches	Sedimentation, N and P	Cropland Application for BOD, Septic System for N and P

On the ground, each BMP operates in different ways to address different, but overlapping, sources and loadings of pollutants. As expressed in the model, however, the load reduction can be addressed using the same input parameter for multiple BMPs. These descriptions identify the BMP, the contaminant it removes, how the cumulative load reduction was calculated, the model variable that was altered, and the subwatershed(s) that the scenario affected.

#### *5.4.2 Composting toilets (EcoSanitario)*

EcoSanitarios address loading of fecal coliform, BOD, N and P. This analysis focuses on fecal coliform levels because it affects human health most and it is a powerful indicator of waterway health. Furthermore, composting latrines specifically target a reduction in fecal coliform. WARMF modeling input fields are limited to those that would normally be associated with a watershed in a developed country, such as the United States. In the model calibrated for flow and fecal coliform (denoted in the below figures as “Fecal Coliform – No Latrines”), treatment output from the septic system in the rural areas were set at values that would mimic total failure of a septic system, which corresponds to a load level of  $10^9$  fecal coliform colonies per 100 mL of discharge, represented in Type 3 Septic System (Figure 45).

**System Coefficients**

Minerals | Sediment | Phytoplankton | Periphyton | Food Web | Parameters

Physical Data | Land Uses | Snow/Ice | Heat/Light | Canopy | Litter | **Septic Sys.**

Flow (L/cap/day)

Septic System Discharge Quality (mg/L)

	Type 1	Type 2	Type 3
Ammonia	5.8	5.8	58
Aluminum	0	0	0
Calcium	0	0	0
Magnesium	0	0	0
Potassium	0	0	0
Sodium	0	0	0
Sulfate	0	0	0
Nitrate	0	0	0
Chloride	0	0	0
Phosphate	0.98	0.98	9.8
Org. Carbon	0	0	0
Fecal Coliform	100000	1000	1000000000
BOD	1.7	1.7	170

OK Cancel Help

**Figure 45.** Septic system loads in rural areas per person per day. Type 3 represents a 100% failing system, Type 1 represents a system with a composting latrine which eliminates 4 log (99.99%) and Type 2 represents a system with a composting latrine which eliminates 6 log (99.9999%).

In order to model the effects of composting latrines, the group members updated the treatment type by adjusting these values with literature values for reduction rates of composting toilets in developing countries. Stenstrom (Stenstrom 2001) found that used correctly, composting toilets reduced fecal coliform levels by four to six log (orders of magnitude), or 99.99 and 99.9999 percent. Samples collected and analyzed in San Cristóbal revealed that surface water coliform levels are exceptionally high around the watershed, particularly at the entrance to the Sumidero tunnel that exits the watershed. The scenario calibrated for flow with maximized inputs of fecal coliform was used as basis for producing various scenarios predicting the fecal coliform levels with various levels of implementation. Table 15 describes these scenarios, which used a high rate of reduction (6 log) and a low rate of reduction (4 log), as estimated by Stenstrom. Scenarios of 100% implementation were run to see what effect the composting latrines would have if used infallibly in the rural areas. A more realistic composting latrine implementation program, though still difficult to accomplish,

would construct latrines in 50 percent of the homes in the rural area. As the levels of coliform did not drop significantly with the 50% implementation scenario, an implementation rate of 80% was also modeled to get an idea of how rigorous of an implementation program was necessary to yield satisfactory results.

To reflect a 100% implementation rate in the model, the septic system discharge quality was improved to Type 1 discharge quality to reflect a 4log reduction and with Type 2 discharge quality to reflect a 6log reduction of fecal coliform. To reflect an 80% (or 50%) implementation rate, 80% (or 50%) of the septic system discharge quality was set for Type 1 for the 4log reduction and Type 2 for the 6log reduction, and 20% (or 50%) was set for Type 3 reduction, to mimic the effects of having no septic system for those households.

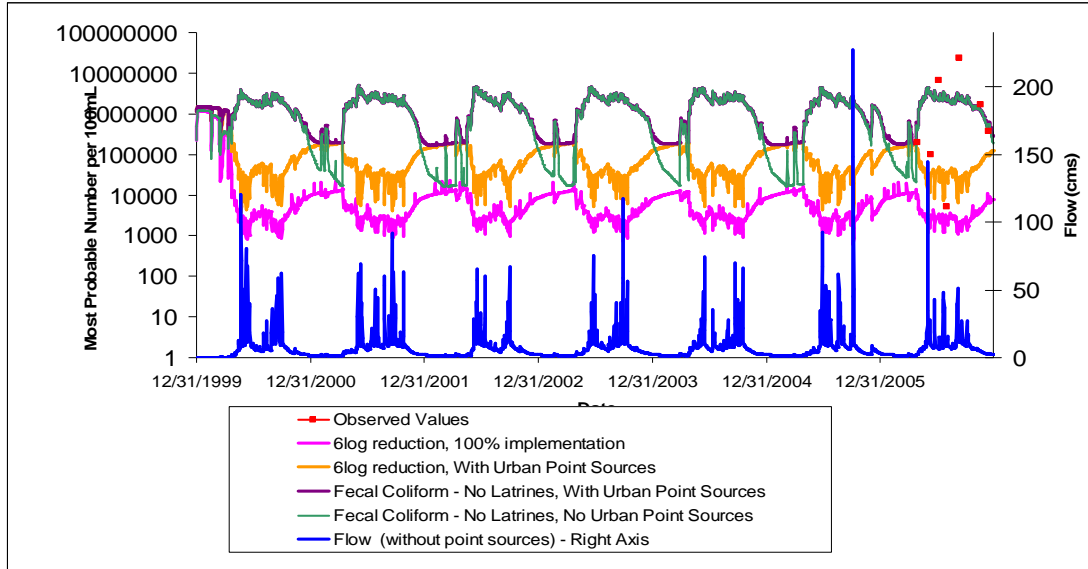
**Table 15.** Scenarios modeling fecal coliform reduction with composting latrines

Scenario	Scale of Reduction (Stenstrom 2002)	Percentage Reduction	Initial Fecal Coliform (MPN) per 100 mL	Fecal Coliform Reduction with Treatment (MPN) per 100mL	Fecal Coliform (MPN) per 100 mL
Composting Latrines - 4log fecal coliform reduction, 50% implementation	4log	99.99	10 <sup>9</sup> in 100% of households	10 <sup>4</sup> in 50% of households, 0 in 50% of households	10 <sup>5</sup> in 50% of households, 10 <sup>9</sup> in 50% of households
Composting Latrines - 4log fecal coliform reduction, 80% implementation				10 <sup>4</sup> in 80% of households, 0 in 20% of households	10 <sup>5</sup> in 80% of households, 10 <sup>9</sup> in 20% of households
Composting Latrines - 4log fecal coliform reduction, 100% implementation				10 <sup>4</sup> in 100% of households	10 <sup>5</sup> in 100% of households
Composting Latrines - 6log fecal coliform reduction, 50% implementation	6log	99.9999		10 <sup>6</sup> in 50% of households, 0 in 50% of households	10 <sup>3</sup> in 50% of households, 10 <sup>9</sup> in 50% of households
Composting Latrines - 6log fecal coliform reduction, 80% implementation				10 <sup>6</sup> in 80% of households, 0 in 20% of households	10 <sup>3</sup> in 80% of households, 10 <sup>9</sup> in 20% of households
Composting Latrines - 6log fecal coliform reduction, 100% implementation				10 <sup>6</sup> in 100% of households	10 <sup>3</sup> in 100% of households

## Assumptions

Since composting latrines are not likely to be implemented in urban households, it was assumed that the implementation area is limited to the rural regions. In all scenarios modeling composting latrine effectiveness, point source inputs from the urban center were considered negligible for two reasons. First, it is likely that SAPAM will construct a wastewater treatment plant in the next few years, as the utility is already considering plant designs (Bencala et al. 2006). This management practice will greatly improve urban waterway and human health, but it will not eliminate 100% of the urban point sources. For ease of simulation, though, urban point sources were eliminated for this analysis. Second, ignoring urban inputs makes it easier to analyze the cumulative effects of rural composting latrines, as the urban point source inputs from residential sewage overload the system, particularly in periods without precipitation.

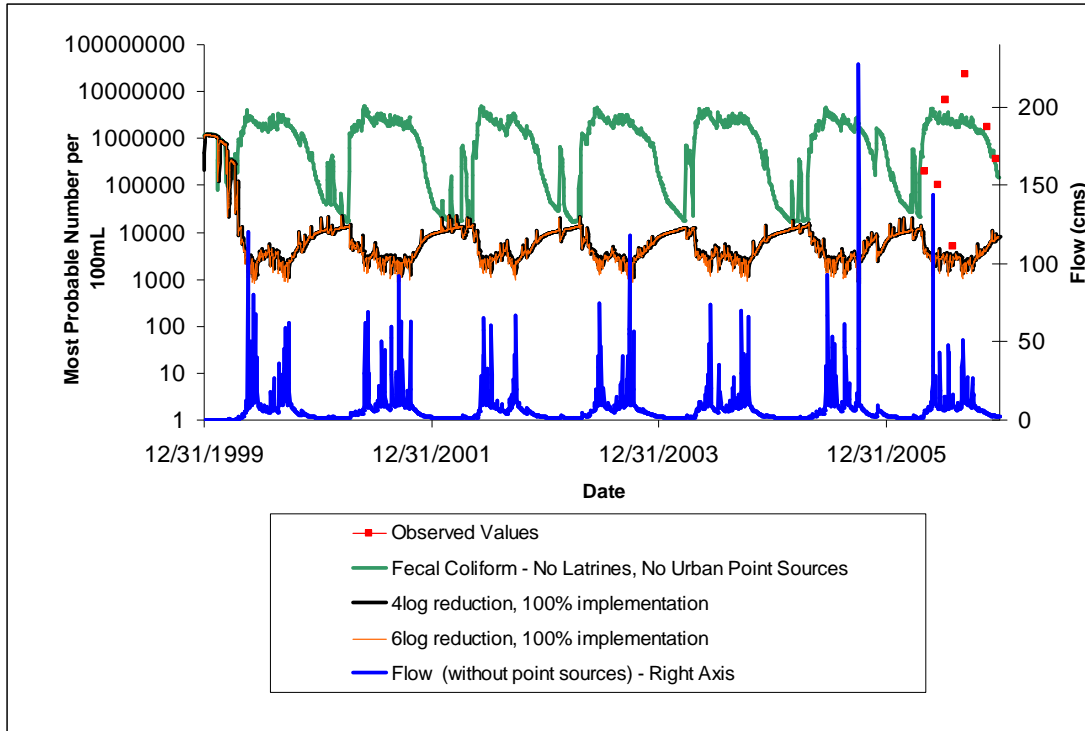
Figure 46 plots the modeled fecal coliform trends with point sources and no composting latrines (orange curve, which represents current conditions), without urban point sources or composting latrines (green curve), fecal coliform levels with a 100% implementation rate of composting latrines assuming a 99.9999% effectiveness (pink curve), and fecal coliform levels with a 100% implementation rate of latrines with the same effectiveness in the rural areas, but with urban point sources, assuming there is no wastewater treatment plant (blue curve). The model's simulated results show that during high flows (flows are represented by the dark blue curve), a large amount of groundwater contaminated by septic systems is mobilized in the top soil layer and enters surface waters (green curve). This relationship can be seen in all figures illustrating the scenarios, as flow is plotted on a secondary axis. The steep dip occurring during the dry season in the green curve is partially due to the lack of urban point sources in the scenario; the orange curve shows that the sewage system contributes to the system during all months of the year, regardless of precipitation.



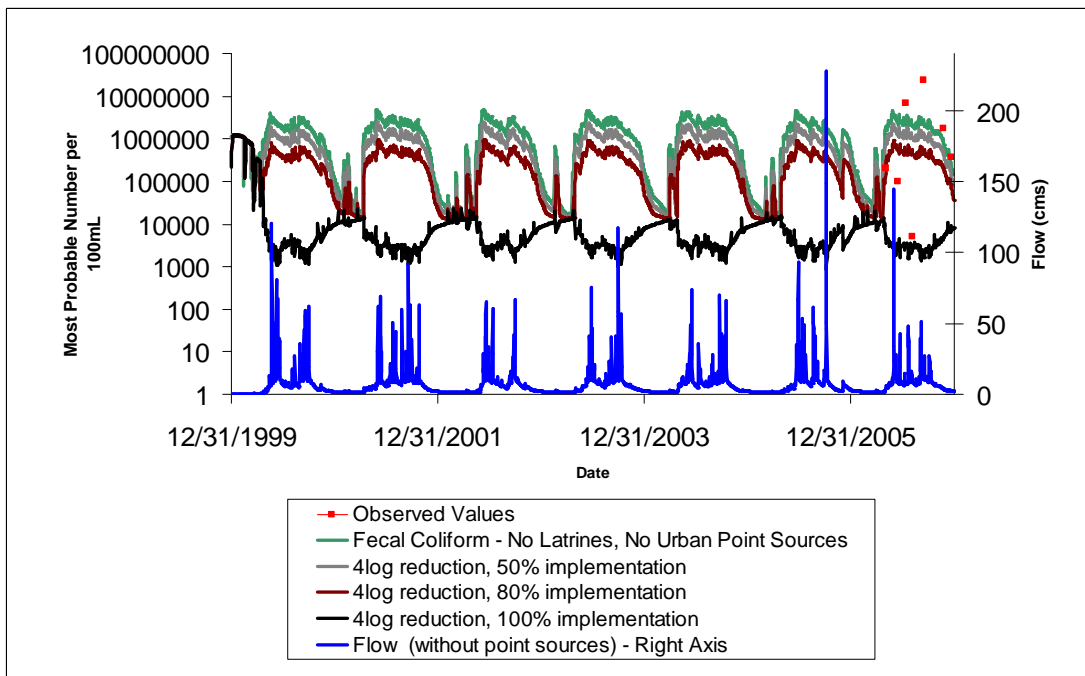
**Figure 46.** Comparison of Modeled Fecal Coliform with and without the use of Composting Latrines in Rural Areas at the Sumidero with a 6 log Reduction (99.9999%) at the Sumidero monitoring point

### Results

In accordance with literature values, these scenarios modeled a reduction in fecal coliform of four to six orders of magnitude. At the Sumidero monitoring point, where the entire watershed flow exits the system through an underground tunnel, the results yielded an average annual reduction of fecal coliform in the surface waters of 64%, with a 100% implementation rate. The rate of reduction changed dramatically during the periods of precipitation, fluctuating from a 99.7% reduction during precipitation periods to 0% during no rain periods. This is possibly due to the constant introduction of fecal coliform from animal feces through the soil column. Because the 4 log and 6 log reductions were so similar (Figure 47), only results for the 4 log reduction are shown in this report (Figure 48), as the percentage reductions were identical (Table 16).



**Figure 47.** Modeled Fecal Coliform with and without the use of Composting Latrines in Rural Areas at the Sumidero monitoring point, Comparison of 4 log Reduction (99.99%) and 6 log Reduction (99.9999%)



**Figure 48.** Modeled fecal coliform with and without the use of composting latrines in rural areas at the Sumidero monitoring point, 4 log reduction (99.99%). Various rates of implementation are compared.

**Table 16.** Percentage reductions for each scenario

<b>Composting Latrines Scenario</b>		
<b>Reduction in Fecal Coliform</b>	<b>Implementation Rate in Rural Areas</b>	<b>Total Watershed Reduction of Fecal Coliform (percent)</b>
4log (99.99%)	50%	32
	80%	51
	100%	64
6log (99.9999%)	50%	32
	80%	51
	100%	64

### Scenario Analysis

Pollutants from septic systems are discharged into soil layer 1. From there, pollutants are transported to the streams by the delayed water flow that travels through the soil column. Despite substantial reductions in septic contamination of the soil, the 4 log and 6 log treatment types do not provide 100% reduction, and do leak some fecal coliform into soil layer 1. This slow pollutant loading is a contaminant source that is carried to the streams by groundwater flow in the top layers of the soil. During rain events, the characteristics of the model's soil structure results in a high percentage of flow from soil being transported through layer 1 of the soil. This large volume of water dilutes the fecal coliform load in both the 4 log and 6 log scenarios, and so the concentration of coliform in these scenarios drops with the corresponding rise in rainfall.

The scenarios which modeled 50% implementation, 80% implementation, and no implementation of composting latrines deliver fecal coliform to soil layer 1 at a substantially higher rate than the 4 log and 6 log scenarios with 100% implementation. Group members posit that the low rate of groundwater flow in ambient conditions results in a bottleneck for coliform transport to the streams. With the arrival of the rainy season, the stockpile of coliform bacteria is mobilized by the high rate of surface and groundwater flow. The coliform concentrations in the river rise, and continue to be input into the rivers at a high rate until the tail end of the rainy season. Again, the effect of the septic systems on coliform contamination is determined by both the effectiveness of the treatment and the transport capabilities of layer 1, which has a high flow discharge rate in the model.

There does not appear to be much difference in the 4 log and 6 log scenarios in the reduction of fecal coliform concentrations in the water. This is true of both full and

partial implementation. There may be a control on these scenarios that prevents the difference in reduction, two orders of magnitude, from being expressed obviously in the results. One possible explanation is that in absolute numbers of fecal coliform colonies per 100 ml, the difference between these scenarios, in relation to the status quo of no treatment, is not substantial. Another possibility is that at such reduced numbers, the decay rate of the contaminant is a more significant downstream factor than that of the difference in reduction rates by the latrines.

### Findings

Figure 48 reveals that at a 100% implementation rate, composting latrines are extremely effective. However, even these major modeled reductions in fecal coliform are still out of reach of the Mexican standard for fecal coliform at 240 units/100mL (Table 8). It is a possibility that these standards are unnecessarily low; Blumenthal et al (Blumenthal, Mara, Peasey, Ruiz-Palacios, and Stott 2000) finds that the coliform guidelines for many developing countries may be too stringent for irrigation with surface water (which is much of the water's end use at the far end of the underground tunnel), and could be relaxed to a limit of  $\leq 100,000$  fecal coliform bacteria per 100mL. In this case, with a 100% implementation rate of composting latrines, Blumenthal's recommended guidelines for irrigation would be satisfied. However, it is highly unlikely that every household would implement this management practice, and if humans are exposed to the water during work or play, Blumenthal et al recommends a limit of  $\leq 1,000$  fecal coliform bacteria per 100 mL (Blumenthal et al. 2000).

It is clear from this analysis that the construction of a centralized conveyance system to a wastewater treatment plant for the urban areas would benefit the health of the watershed. Additionally, the construction of composting latrines in the rural regions of the watershed would greatly improve the levels of fecal coliform in the water and would likely reduce the amount of water-borne illnesses resulting from exposure to pathogens. Project members recommend the implementation of both these management practices to the largest extent possible.

#### *5.4.3 Additional Scenario Descriptions*

Partners at ECOSUR are interested in knowing the effects of widespread BMP implementation, and will continue to update this model to get more accurate results. A series of alternate scenarios are described below, to be modeled by partners in the future.

#### Blackwater wetland

Treatment of blackwater can be achieved by constructing artificial wetlands to harness natural processes (Section 2.3.6). Blackwater wetlands remove nitrogen and biological oxygen demand from the waste stream, as well as addressing fecal coliform. Load reduction for each watershed from blackwater wetland



implementation depends on the scale of implementation and the population served. Calculations based on census data were used to determine the population in each subwatershed of the model (Bencala et al. 2006). The average waste production of 114L per capita per day was multiplied per subbasin population to determine pollutant loading in each watershed (Bencala et al. 2006).

In the future, sewage from the urban center of San Cristóbal de las Casas will likely be treated at a wastewater plant. In addition, installation of blackwater wetland systems is land intensive, and the urban center is already densely developed. Because of these two factors, this scenario should analyze BMP implementation for the outskirts of the watershed only. As mentioned in the previous scenario, the model currently treats the waste stream outside the urban center as if the whole population used septic systems, and the septic systems have a failure rate of 100%.

Scenarios should model a decrease from the calibrated model to incorporate low levels of nutrients in the effluent in one scenario and high levels of nutrients in another scenario of each parameter. Similar to the composting latrines scenario, project members recommend modeling implementation rates of 50%, 80%, and 100%.

**Table 17.** Literature values for effluent from a constructed wetland system with a septic tank and surface water discharge (Henneck, Axler, McCarthy, Monson Geerts, Heger Christopherson, Anderson, and Crosby 2001)

BOD (mg/L)	TSS (mg/L)	Total Nitrogen (mg-N/L)	NO3 (converted from Total Nitrogen) (mg/L)	Total Phosphorus (mg-P/L)	Fecal Coliform (cfu/100mL)
9-44	8-16	16-60	70-265	0.4-11	35-1900

**System Coefficients**

Minerals | Sediment | Phytoplankton | Periphyton | Food Web | Parameters  
Physical Data | Land Uses | Snow/Ice | Heat/Light | Canopy | Litter | **Septic Sys.**

Flow (L/cap/day)

Septic System Discharge Quality (mg/L)

	Type 1	Type 2	Type 3
Ammonia	58	0	0
Aluminum	0	0	0
Calcium	0	0	0
Magnesium	0	0	0
Potassium	0	0	0
Sodium	0	0	0
Sulfate	0	0	0
Nitrate	0	70	265
Chloride	0	0	0
Phosphate	9.8	0.4	11
Org. Carbon	0	0	0
Fecal Coliform	1000000000	35	1900
BOD	170	9	44

OK Cancel Help

**Figure 49.** Septic System Coefficients for Blackwater Constructed Wetlands. Treatment Type 1 represents no septic treatment, Treatment Type 2 represents high levels of treatment in constructed wetlands, and Treatment Type 3 represents low levels of reduction for all available nutrient loads.

### Contour trenches

Contour trenches (Section 2.3.5) act by reducing loading from soil erosion from cultivated hill slopes. The main pollutants addressed are excess sediment load, and nitrogen and phosphorous from fertilizers. Literature suggests a potential runoff reduction of 75% and 70% for phosphorus and nitrogen, respectively (U.S. EPA 2006; US Environmental Protection Agency (EPA) 2006). Experiments indicate that contour trenches can reduce erosion by as much as 50% (IIRR 1998). An analysis should apply these reductions to the calibrated constituent levels for contribution from the cropland land use in WARMF.

Not all of the cropland in the watershed is on hill slopes. The constituent reduction should be calculated from the percent of total subwatershed cropland that is sloped, which should be determined as any land with a slope greater than 5%. To determine

the percent of the cropland in each subwatershed that is on a sloped hillside, partners can analyze the effects of contour trenches by combining a GIS land use layer with a hill slope layer, then overlaying it with a layer delineating the watershed into the subwatersheds used by the model. Finally, the reduction per subwatershed can be created from the ratio of sloped to level cropland and applied to the subwatersheds in the WARMF model.

#### 5.5 Recommendations

Project members strongly recommend continued monitoring of water quality and flow. It would be extremely helpful to have additional flow measurements, particularly during large rain events in order to gage the magnitude of the flow at the monitoring points. However, capturing these measurements can be dangerous, as high flows through the riverbed can have very strong currents. These measurements would be particularly helpful at the Sumidero monitoring point, as that site yields a cumulative measurement that is an indicator of watershed-wide health. With caution, the cross-section and flow can be measured at various levels of water surface elevation, and a rating curve, which serves to estimate flow by knowing the stage (water surface elevation) of the water surface, can be developed through a free modeling program like HEC-RAS, created by the United States Army Corps of Engineers. Once the rating curve is developed, a staff gage should be painted on the wall of a culvert or bridge structure to assist in visually determining stage. Knowing the approximate flow measurements for the monitoring points will affect the concentrations of nutrients and pollutants in the watershed model. More details can be found on this method in the first San Cristóbal group project report (Bencala et al. 2006) and in a HEC-RAS rating curve creation instruction manual (Rahmeyer 2002).

It is important that as project partners add new monitoring data, they continue to update other features of the model as well. Some model inputs are required to generate output, such as daily rainfall data, as this factor is the main control on river flow. Other parameters in the model remain constant, and the model will continue to generate output without further changes. However, improved data collected by geological studies for some of these parameters, like soil thicknesses and hydraulic conductivity, would greatly increase the accuracy of the simulations. Group members recommend that partners obtain more detailed data on the soils of the watershed through information sharing with governmental and non-governmental organizations in the region or through direct field studies.

#### 5.5 Conclusions

This model can be a useful tool to inform future management decisions. Partners will be able to use this model to help determine a range of management actions and estimate what effects the practices might have if implemented. With additional data to better calibrate this model, the accuracy of this watershed model will increase. One probable impact on the sedimentation rates of the watershed's waterways that this model so does not address currently is the effect of erosion from the pressures on the

forests that surround San Cristóbal. The following chapter addresses this issue, and provides strategies to lessen these impacts.

## **6.0 Reforestation**

As one aspect of this project, a site prioritization analysis was performed to inform reforestation efforts by local stakeholders. Because deforestation is widely suspected of a detrimental effect on water quality in Chiapas, according to the results of a survey done by ECOSUR, this portion of the project supports the goal of implementing programs that contribute to effective water resources management. The analysis incorporated geospatial information from a variety of sources, as well as review of other studies and communication with experts to formulate specific advice targeted to assist the reforestation campaign. Results of this analysis and recommendations were delivered to stakeholders, specifically Alejandro Ruiz Guzmán, a reforestation activist and campaign coordinator from San Cristóbal, and partners at ECOSUR.

### **6.1 Background**

The topography of Chiapas can be characterized by spreads of level land bordered by abruptly sloping mountains. Several decades ago, the landscape was covered by pine, oak, and pine-oak forests, where community composition varied by elevation (Figure 50) (González-Espinosa, Quintana-Ascencio, Ramírez-Marcial, and Gaytán-Guzmán 1991). Historically, though, at least some level of deforestation extends back for centuries due to traditional slash and burn agriculture and commercial logging, preferentially of oak *Quercus* species. Hillside patches known as *milpas* that are used for corn cultivation would often be abandoned following a few years of use, so that the natural succession of grassland and forest was allowed to occur (Figure 51). Primary succession often favors pine *Pinus* species. Unfortunately, the time scale of human-induced fragmentation is not normally long enough to allow tree populations to naturally reach a successional equilibrium (Cayuela, Golicher, Maria Rey Benayas, Gonzales-Espinosa, and Ramirez-Marcial 2006a). Thus, it is difficult to achieve restoration to the natural landscape.

Forest type	Environmental features	Characteristic species
Evergreen cloud	Altitude between 2000 and 2700 m. Permanent humid conditions as a result of high rainfall and/or fog interception	<i>Persea americana</i> , <i>Clethra macrophylla</i> , <i>Cleyera theoides</i> , <i>Prunus brachybotrya</i> , <i>Parathesis leptopa</i> , the arborescent fern <i>Cyathea fulva</i>
Pine-oak-liquidambar	Altitude between 1800 and 2100 m, high rainfall and low seasonality	<i>Quercus crispipilis</i> , <i>Pinus oocarpa</i> , <i>Liquidambar styraciflua</i> , <i>Clethra suaveolens</i> , <i>Rapanea myricoides</i> , <i>Saurauia scabrida</i>
Pine-oak	Altitude between 2100 and 2600 m, exposed to highly seasonal conditions	<i>Quercus crassifolia</i> , <i>Quercus laurina</i> , <i>Quercus rugosa</i> , <i>Pinus ayacahuite</i> , <i>Pinus pseudostrobus</i> , <i>Pinus tecunumanii</i> , <i>Garrya laurifolia</i> , <i>Arbutus xalapensis</i> , <i>Alnus acuminata</i> , <i>Cornus disciflora</i> , <i>Oreopanax xalapensis</i> , <i>Prunus serotina</i> , <i>Rapanea juergensentii</i>
Oak	Altitude between 1900 and 2100 m, dry climatic conditions	<i>Quercus segoviensis</i> , <i>Juniperus gamboxana</i>
Transitional	Altitude below 1700 m, warm temperatures and dry climatic conditions	<i>Ternstroemia oocarpa</i> , <i>Sebastiania cruenta</i> , <i>Eugenia capulioides</i> , <i>Parathesis belizensis</i> , <i>Xylosma flexuosum</i> , <i>Cupania dentata</i>

**Figure 50.** Five major categories of forest types distributed throughout the Highlands of Chiapas determined by (Cayuela et al. 2006a)

Successive fragmentation led to a more modern complex mosaic in the deforested areas evidencing past deforestation through the variety of successional stages. Stages visible today include fallowed fields, grassland, and shrubland used for grazing, alongside early-successional forest, mid-successional forest, and mature forest. Patches of old-growth forest are quite scarce (Cayuela et al. 2006a). Instead, much of the previously forested land consists of young secondary forests and permanently cleared grazing and cultivated areas (Cayuela, Maria Rey Benayas, and Echeverria 2006b). In observing the current landscape, the escalating need for resource management intervention is apparent.

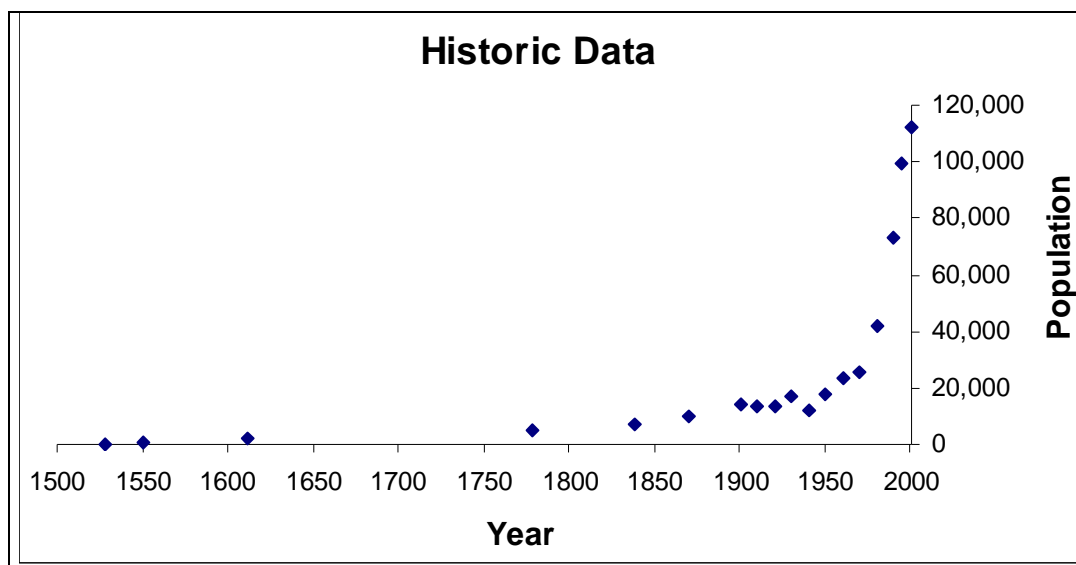


**Figure 51.** Section of forest cleared for corn production in the higher elevations surround San Cristóbal

A number of social and economic factors have contributed to the deforestation dilemma. The population has swelled dramatically in Chiapas over the last 30 years, leading to a combination of drivers that exacerbate deforestation effects (Figure 52). These include agricultural intensification, expansion of cultivated areas into forested lands, and a higher rate of forest product extraction (Cayuela et al. 2006b). Agriculture and other land uses tend to erode the top organic layer of soils, resulting in lower productivity levels (Chávez 2003). San Cristóbal has also seen an increase in livestock grazing on steep slopes, which easily erodes the thin fragile soils (Bencala et al. 2006).

Social unrest due to the 1994 Zapatista movement uprooted many of the indigenous populations in Southern Mexico (Bencala et al. 2006). Migration of displaced citizens to San Cristóbal is quite common given the city's long history as a cultural and economic center. Unfavorable labor and economic relationships between indigenous Mayan groups and the regional and national economy continue to distract stakeholders' attention away from conservation issues (Cayuela et al. 2006b).

As the urban center of San Cristóbal expands, more of the forested areas are cleared to obtain forest resources and increase alternative land uses, especially subsistence agriculture (Bencala et al. 2006). Lack of available low elevation lands forces subsistence and marginal farmers onto increasingly steeper areas (Cayuela et al. 2006b). Finally, the use of low technology farming methods by these individuals often neglects appropriate soil conservation measures.



**Figure 52.** The history of population change in San Cristóbal from 1528 (when the city was founded) until 2000 shows an overall exponential increase (Bencala et al. 2006).

The percentage of existing forests, both in San Cristóbal and Chiapas as a whole, has declined steadily since the 1950s (Bencala et al. 2006). Analysis over the state of Chiapas shows an increasing trend in deforestation rate, where up to 4.8% of the state's land area was deforested each year from 1990 to 2000 (Cayuela et al. 2006b). It is estimated that between 1975 and 2000, approximately 50% of the total forest cover in the Chiapas Highlands has been lost, while some of the remaining forests have been degraded by human use. Models have specifically detected high losses in transitional forests and evergreen cloud forest fragments, and a smaller loss in oak forest (Cayuela et al. 2006a). In the most recent analysis, the remaining forested land, ranging in age from primary and secondary forests to mixed pine and oak forests, comprised about 52% of the landscape (Figure 53).





**Figure 53.** Photograph of deforested hill slopes above San Cristóbal de Las Casas, taken in June 2006

As a result, many of the residual forest stands suffer from fragmentation and increased edge effects (Cayuela et al. 2006b). Fragmented forests and secondary forests that have re-grown after the land was cleared tend to suffer a reduced capacity to provide ecosystem services such as flood water amelioration, soil stability, pollutant filtering, and erosion control (Bencala et al. 2006) (Figure 54). Increased loss of soils from the land can increase turbidity and carry additional non-point pollutants into waterways, which impacts both aquatic life and the usability of the water. Reduced infiltration also decreases the potential for aquifer recharge. Flooding can have a detrimental effect on water quality by rapidly delivering untreated storm-water into rivers, or at an extreme level, by causing loss of life and property.





**Figure 54.** Secondary vegetation growth on a deforested hill slope in San Cristóbal

Aside from these direct impacts on water resources dynamics, deforestation also contributes to biodiversity loss, reduced carbon storage, disturbance of biogeochemical cycles, and reduction of a resource bank for pharmaceutical development (González-Espinosa et al. 1991). Deforestation similarly leaves lands with exposed soil more susceptible to natural disasters such as landslides, which creates a hazard for people living nearby (Chávez 2003). Habitat loss creates a significant concern for San Cristóbal's watershed in particular, a hotspot of biodiversity, because of the presence of two endangered species: the San Cristóbal Shrew *Sorex stizodon* and the San Cristóbal Pupfish *Profundulus hildebrandi* (Bencala et al. 2006). Similarly, ecosystem loss poses a concern since the watershed lies within two World Wildlife Ecoregion protected areas (World Wildlife Fund 2007). Lastly, climate change is expected to be heavily influenced by climate change, making the need for conservation even more pressing (Gómez-Mendoza, Vega-Pena, Ramirez, Palacio-Prieto, and Galicia 2006).

## 6.2 Approach

Scientists at ECOSUR initially recommended addressing the impact of deforestation on San Cristóbal's watershed as a part of this project. Recognizing the importance of watershed-wide land use management to healthy waterways, the UCSB students elected to adopt this task. There are a variety of ways to address the impacts of increasing deforestation, including farmer education for agricultural best management practices such as contour tillage and utilizing retention ponds for storm drainage. The

BMP how-to manuals, as well as the “Reforestation Strategies” section that follows, address some of these preventative approaches (Appendix A).

In order to improve land management where indiscriminant deforestation has already occurred, conservation of existing forest should be combined with extensive replanting of high-quality diverse forest species (Cayuela et al. 2006a). Added in with preventative measures, reparative efforts will speed restoration of a well-functioning landscape that provides ecosystem services related to water quality. Thus, the project chose to work within this context as well.

Through ECOSUR, the students were allied with a local reforestation organizer, Alejandro Ruiz Guzmán, who has previously worked in conjunction with San Cristóbal’s utility agency (SAPAM), schools, and other stakeholders to attempt to remedy the problems caused by deforestation (Guzmán 2007). Through the efforts of Guzmán and others, several locations for seedling cultivation, donation of project materials and many donors, volunteers and supporters have been found. The primary mission of the Reforestation Campaign was to educate community volunteers, schoolchildren, and indigenous farmers about the benefits of reforestation and enable them to plant donated seedlings. Although surrounding areas facing the same issues have undergone reforestation projects, this campaign represents the first such undertaking in San Cristóbal and the surrounding watershed.

The initial project received great support from people of all ages and social classes, where about 10,000 volunteers and more than 6,000 schoolchildren planted over 150,000 trees before October 2006. Radio stations, government organizations, private companies, and even sports teams were engaged to support the cause. The seedlings were spread over 41 distinct plots of land for which permission was obtained to do the planting (Figure 55). SAPAM was a major supporter, as they hoped to take action to recover, take care of and preserve the forests which help to recharge the water table. This groundwater supply feeds springs and wells that are pumped to supply the town’s 200,000 inhabitants. Through the reforestation campaign, SAPAM hopes to guarantee the usefulness of this water supply to future generations, and to conserve the diverse ecosystems of Chiapas.



**Figure 55.** A pine seedling planted during the first major reforestation effort in San Cristóbal

A second major effort is planned to run from June 1<sup>st</sup> to September 15<sup>th</sup>, 2007, backed by a donation of 100,000 seedlings from several local organizations, including Viveros de La Albarrada, Na Balom, Conafort, and Biocores. The new goal is to plant 400,000 seedlings. Organizers are also now working to establish a traditional breeding ground, where a large continuous plantation of the desired native species could be established. Though the campaign has been extremely successful so far, input was requested from project researchers regarding several areas where gaps in knowledge existed, in order to extend collaboration, improve research capacity, and benefit the long-term direction of the campaign. The project members were asked to:

- Calculate the total land area that has been deforested in the watershed using satellite imagery;
- Determine which areas to reforest in the watershed using spatial information datasets;
- Propose strategies for the second reforestation effort;
- Compare production costs of seed collection and sowing vs. collection and reproduction of trees by stakes with hormonal treatment for root induction, in order to lower the price of production costs and to guarantee a lower percentage loss;
- Propose strategies for collection of seeds and stakes;
- Propose a strategy to evaluate the success of the reforestation over time.

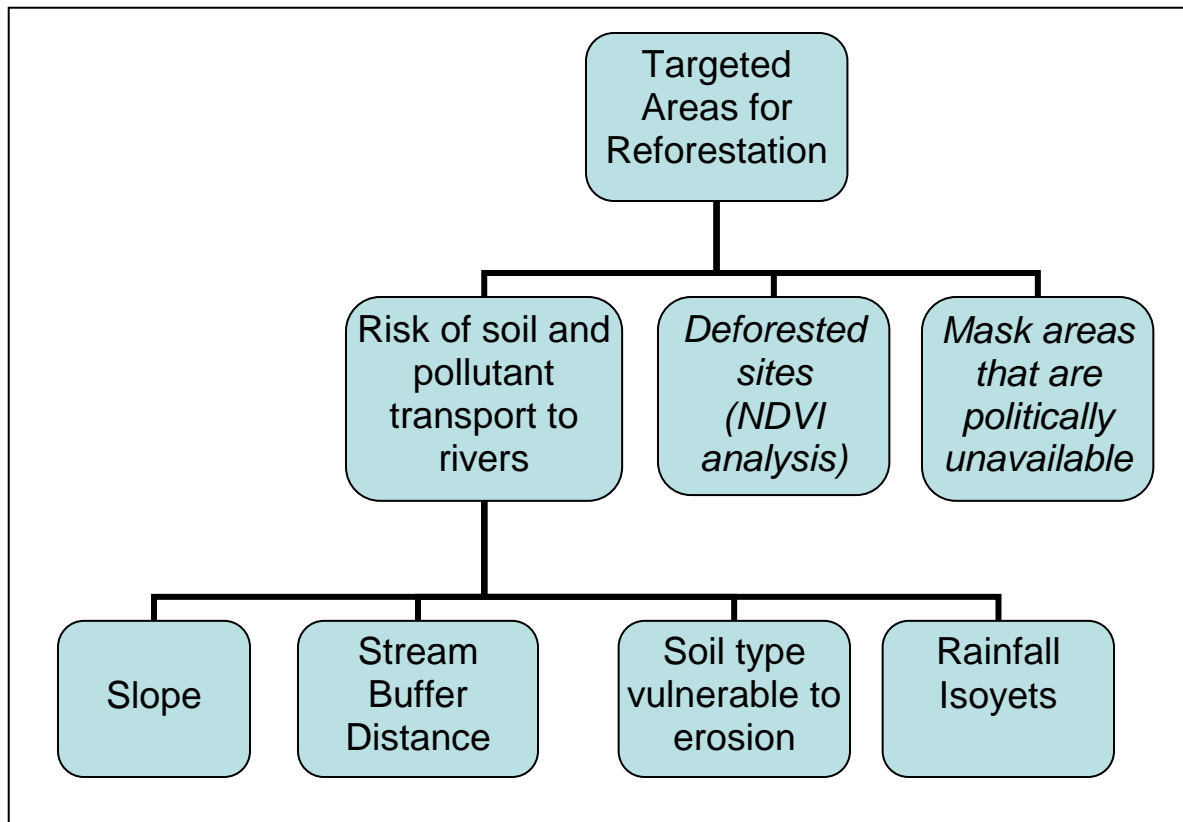
Given the available resources and timeframe, all of the above areas were focused on except a cost-benefit analysis of the various seedling production methods. The researchers worked closely with several experts at UCSB to gain perspective on how

the reforestation model should be aligned. The Laboratorio de Análisis de Información Geográfica y Estadística (LAIGE), an office specializing in geographical and statistical mapping applications at ECOSUR, assisted the effort (Laboratorio de Análisis de Información Geográfica y Estadística 2006). Finally, the group members collaborated with Trees for the Future, a United States-based NGO that works predominantly in developing countries (Trees For the Future 2007). This organization provides planting materials and technical knowledge on agroforestry and sustainable development, in order to help communities return their degraded forest lands and struggling farmlands to sustainable productivity. Trees for the Future assisted the project by helping to formulate strategical advice, donating seeds, and engaging in a partnership with the reforestation organizers in San Cristóbal that will continue after this project is completed.

### *6.2.1 Technical Approach*

Geographic Information Systems (GIS) files were obtained from LAIGE. These enabled a computerized multi-criteria analysis of areas that should be targeted for reforestation using ArcGIS 9.0 (ESRI 2007). In addition to assisting the reforestation campaign, identifying these areas can improve understanding of what impacts might be seen on the watershed as a whole if a successful long-term reforestation campaign were initiated. Quantification of the land area targeted, along with knowledge of the plans for reforestation, allow future scenario development that can be analyzed using the WARMF model.

Case studies of deforestation analysis were reviewed and individuals experienced in modeling, hydrology, and the effects of land use on water quality were consulted. This led to the formulation of a model outline specific to the goals of reforestation efforts in San Cristóbal's watershed (Figure 56). Complex statistical and spatial analyses and ground-truthing of the model were not accomplished within the scope of this project, as the main purpose was to provide a clear answer to stakeholders' questions within a limited timeframe. Nevertheless, many diverse factors were considered in the model, including a location's slope, soil type, and distance from a major waterway, as well as whether the area was previously deforested or under land use that would compromise the ability to extend a reforestation effort there.



**Figure 56.** Conceptual diagram for reforestation prioritization model Tasks in *italics* not utilized

One of the three main components of the model, the risk of an area contributing to degradation of the watershed, was estimated by combining several layers of information, which were chosen because of their inclusion as a variable in the Universal Soil Loss Equation [Equation 5] (Chávez 2003).

[Equation 5] 
$$A = R * K * LS * C * P$$

Where

A = estimated average soil loss in tons per acre per year

R = rainfall-runoff erosivity factor

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

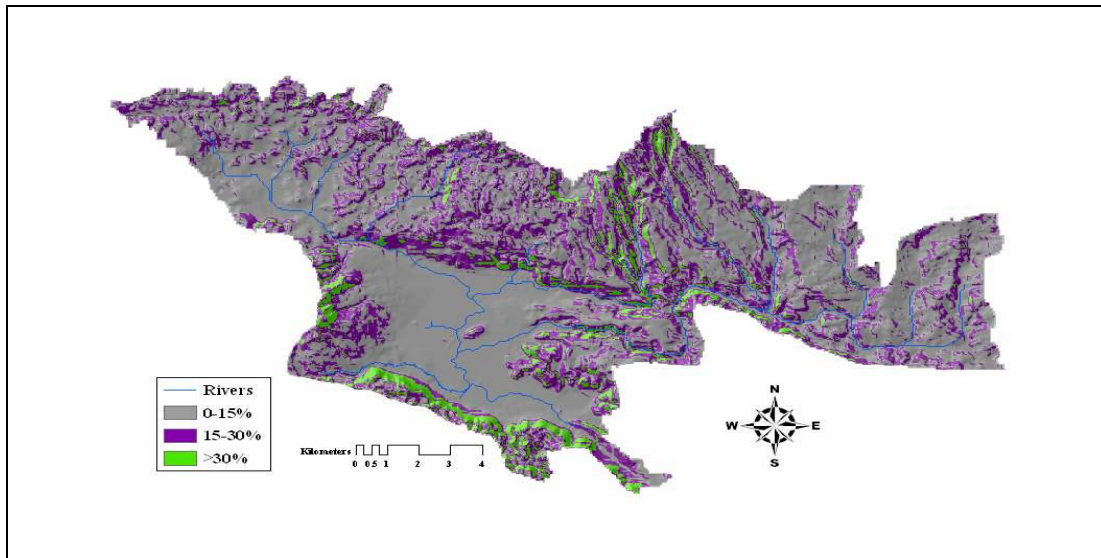
C = cover-management factor

P = support practice factor

These layers were each ranked on a simple number scale so that the highest values indicated the areas most susceptible to erosion. The four layers created described the spatial variability of slope, distance to rivers, vulnerability of soil to erosion, and rainy season precipitation. All layers were classified into three values so that no layer would be weighted more than any other.



The universal soil loss equation indicates that the slope of a patch of land affects the erosion from that area. To categorize steepness of slope, a digital elevation model (DEM) grid with 30 meter resolution was clipped to the size of the watershed. Hydrology tools were used to convert the raster elevation values to slope within each cell. The layer was then reclassified so that the slopes would fall into one of three categories: 0-15%, 15-30%, and greater than 30% (Chávez 2003). The datum now contained a value of “3” for the steepest slopes, “2” for moderate slopes, and “1” for fairly level ground (Figure 57Figure 1).

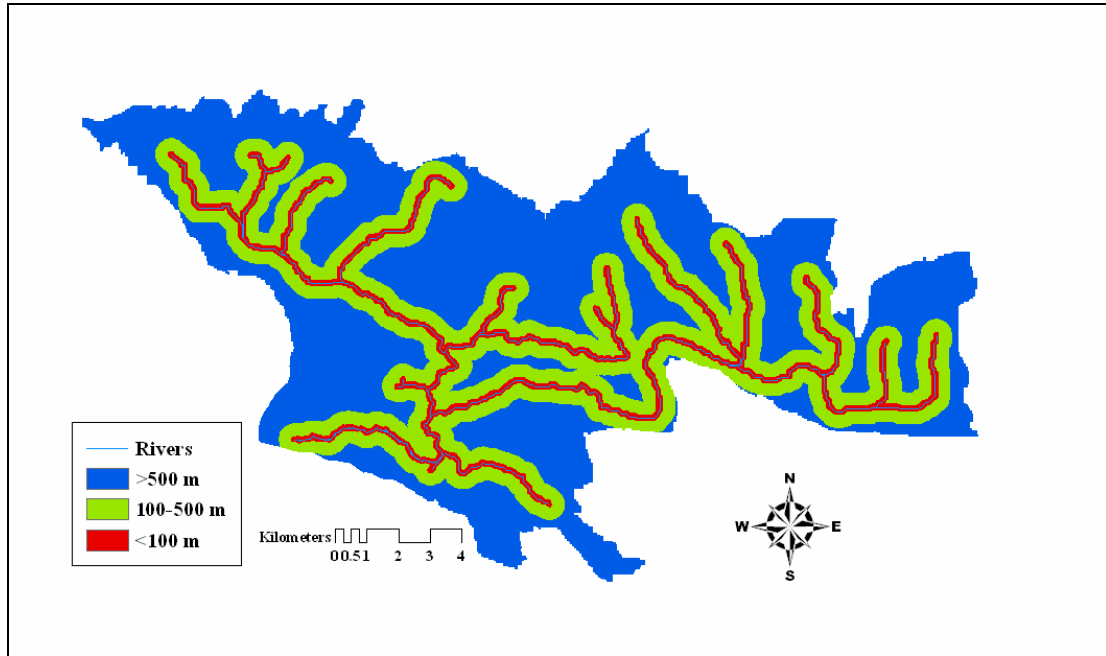


**Figure 57.** Hillslope in the mountains of San Cristóbal de las Casas

Second, to account for the potential for non-point pollution, distance to rivers was calculated for each location in the watershed using a multi-ring buffer tool in the “Coverage Tools” toolbox. The rivers layer was initially provided by LAIGE and processed during the first San Cristóbal project to show the major tributaries in the watershed: the Chamula, Amarillo, Fogótico, and Sumidero Rivers. Calculation of flow length along the paths of flow direction naturally created by topographical differences would provide a more accurate estimate of distance to rivers, but was not possible without excessive manipulation, since the Sumidero River exits the watershed through an artificial tunnel that is not reflected in the DEM.

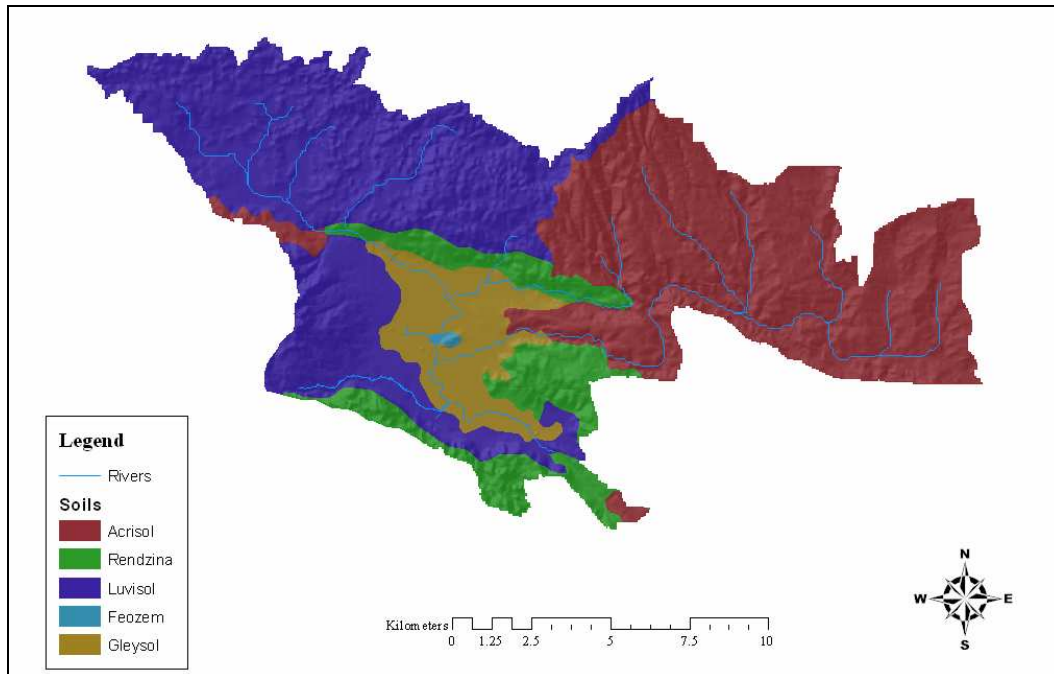
Buffer distances were set to 100, 500, and >500 meters (Figure 58). Areas within 100 meters of a major waterway were considered most critical, since much of the runoff that falls on riparian areas is delivered directly to the river without treatment. Thus, once the shapefile was converted to a raster, these areas were assigned a value of “3,” with areas at a greater distance from the rivers receiving corresponding lower values. In other words, the raster reclassification assigned a ranking from 1-3 that would

indicate how much land served as a buffer between the potentially eroding area and a river.



**Figure 58.** Distance from streams in San Cristóbal watershed

Third, soil types provided in digital maps by LAIGE were qualitatively assessed to determine the vulnerability to erosion. Information regarding each soil type and the appropriate management techniques for that type were considered (Food and Agriculture Organization of the United Nations 2006). The soil layer was converted to a raster and reclassified so that the cell received a higher ranking if it was naturally more easily subject to degradation following deforestation. Gleysol and Feozem were classified as “1,” since they have a low susceptibility to erosion. Likewise, Luvisol was classified as a “2” and Rendzina and Acrisols as a “3,” given their higher tendency towards land erosion and degradation following a deforestation episode. Table 18 summarizes the classification. Figure 60 shows the spatial distribution of the reclassified soils. The characteristics of each of these soil types are discussed in Table 19.

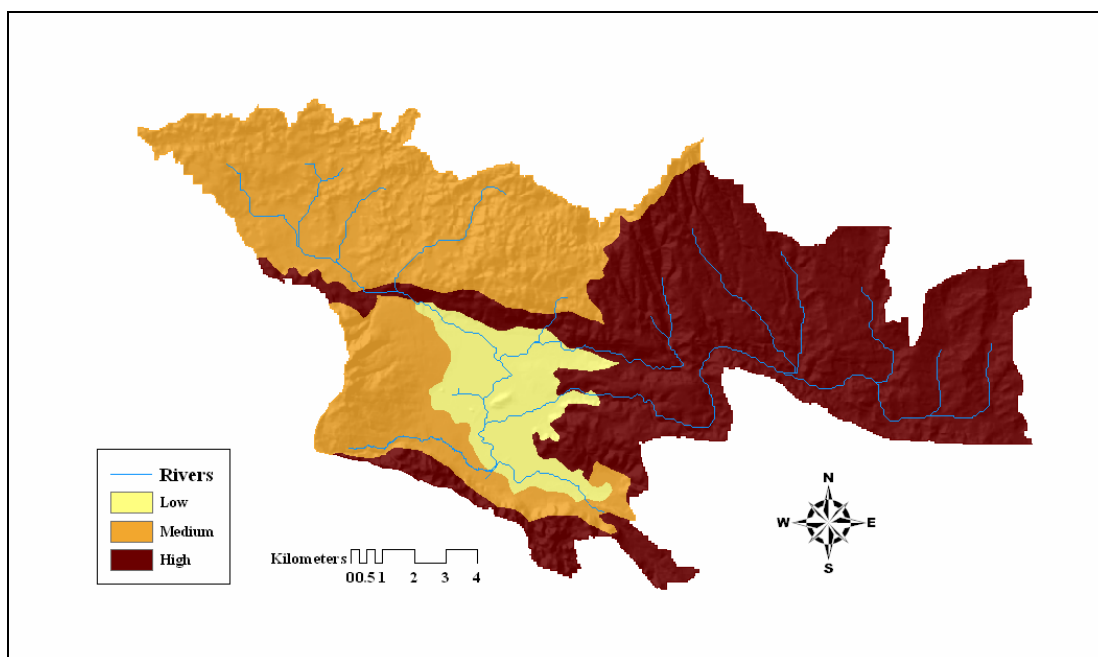


**Figure 59.** Soil Types in study area

**Table 18.** Extent and erodibility of each soil type in watershed, ranked from lowest to highest susceptibility to erosion.

Soil Type	Erodibility Rank	Area (Hectares)	% of Watershed
Gleysol	1	1,867	9.3
Feozem	1	35	0.2
Luvisol	2	8,092	40.3
Rendzina	3	2,148	10.7
Acrisol	3	7,914	39.5
Sum:		20,056	100





**Figure 60.** Soil erosion susceptibility ranking

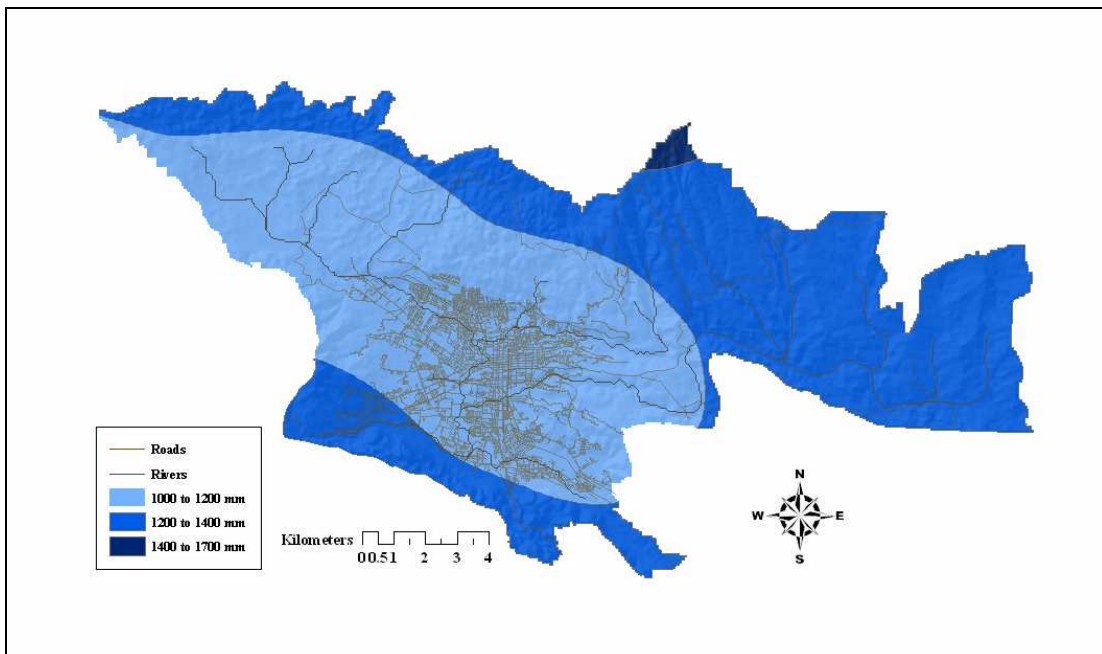
**Table 19.** Characteristics of soil types found in the watershed surrounding San Cristóbal de las Casas  
(Food and Agriculture Organization of the United Nations 2006)

Soil Type	Characteristics and Management Techniques	Problem for Erosion?	Problem for Tree Growth?
Acrisol	<p>Low base saturation, low-activity clay-enriched subsoil</p> <p>--</p> <p>Preservation of the soil surface organic matter and prevention of erosion are necessary when farming on Acrisols. Mechanical clearing of natural forest produces land that is largely sterile and where aluminum concentrations may reach toxic levels.</p> <p>Low-input farming on Acrisols is not worthwhile.</p>	Yes (major)	No
Feozem	<p>Deeply weathered, red or yellow soils of the humid tropics</p> <p>--</p> <p>Most have good physical properties, including soil depth, permeability, workability, and microstructure. They are well drained but may experience drought at times due to low available water storage capacity. These are less susceptible to erosion than most other intensely weathered tropical soils.</p>	No	No

Gleysol	<p>Wetland soils saturated with groundwater that develop a characteristic gley color</p> <p>--</p> <p>The main obstacle to utilization for agriculture is the need to install a drainage system. When adequately drained, Gleysols can be used for arable cropping, dairy farming and horticulture. However, soil structure will be destroyed if soils are cultivated when overly saturated. Undrained Gleysols are best kept under a permanent grass cover or swamp forest.</p>	No	Yes
Luvisol	<p>Experience clay migration from topsoil into subsoil, where the subsoil contains more clay, higher-activity clays and has a high base saturation</p> <p>--</p> <p>Most are fertile soils and suitable for a wide range of agricultural uses, but sometimes susceptible to structural deterioration if tilled when wet or with heavy machinery. On steep slopes, erosion control measures are required. Lower sloped areas are widely used for growing wheat and/or sugar beet while the often eroded upper slopes are used for extensive grazing or planting of tree crops.</p>	Yes	No
Rendzina	<p>Very shallow soils that are extremely gravelly and/or stony</p> <p>--</p> <p>Particularly common in mountainous regions, these have potential for wet-season grazing and as forest land. They are often naturally under coniferous forest. Erosion is a great threat, particularly in montane regions where high population pressure (tourism), overexploitation and pollution lead to forest deterioration. Leptosols on hill slopes are generally more fertile than their counterparts on more level land. Few good crops could be grown, and only at the price of severe erosion.</p>	Yes (major)	No

Fourth, a similar procedure was used, again based on the qualitative information in Table 19, to rank soils by suitability for tree growth. Low seedling survival rates can be attributed to poor soils or planting in the wrong season. The qualitative analysis of the soils did not reveal a stark difference in the soil suitability for tree growth, and so this element was not input into the model.

One consideration when reforesting is the timing of the rainfall. If trees are planted when there is not sufficient water to survive the adjustment of being transplanted, they are more likely to experience higher mortality rates. However, because the approach of this analysis focused on erosion prevention, the project focuses instead on the different precipitation amounts that fall during the rainy season, which lasts from May to October. Data from rainy season rainfall isoyets, obtained from LAIGE, was used for the fourth input layer. Rainy season precipitation in the region ranges from 1000 to 1700 mm. Monthly precipitation and monthly erosion are known to be linearly related (Chávez 2003). Because erosion is related to rainfall, the ranking of the watershed was classified with the areas that receive less precipitation being classified as a 1 (Figure 61).



**Figure 61.** Isoyets of the rainy season in the San Cristóbal de las Casas watershed.

With these four input layers prepared, the classified values were summed using the Raster Calculator tool so that the value for each cell in the new layer contained information from each of the four components. Calculated values ranged from 4, for low prioritization, to 11. One map was created showing the full range of values, and another was reclassified into High, Medium, and Low priorities using the equal interval classification system in ArcGIS. This enables a visual map to be created of where the highest priority areas in the watershed were located.

The second main model component, the Normalized Differential Vegetation Index (NDVI), was eventually discarded from the model due to technical difficulties. This measure indicates a location's relative biomass or greenness compared to other cells within a satellite image (University of Arizona RangeView 2002). The LandSat satellite images are made up of between three and seven different bands, depending on the model of the satellite and when it was launched. "Band" is the term used to

describe the range of wavelengths collected and analyzed for one (University of Arizona RangeView 2002). For example, band 3 collects light from wavelengths 3.55-3.93  $\mu\text{m}$ , which can show both forest fires and nighttime clouds. The NDVI index value is determined by applying a standard formula to a rasterized Landsat image [Equation 6].

[Equation 6] 
$$\text{NDVI} = (\text{Band 4} - \text{Band 3}) / (\text{Band 4} + \text{Band 3})$$

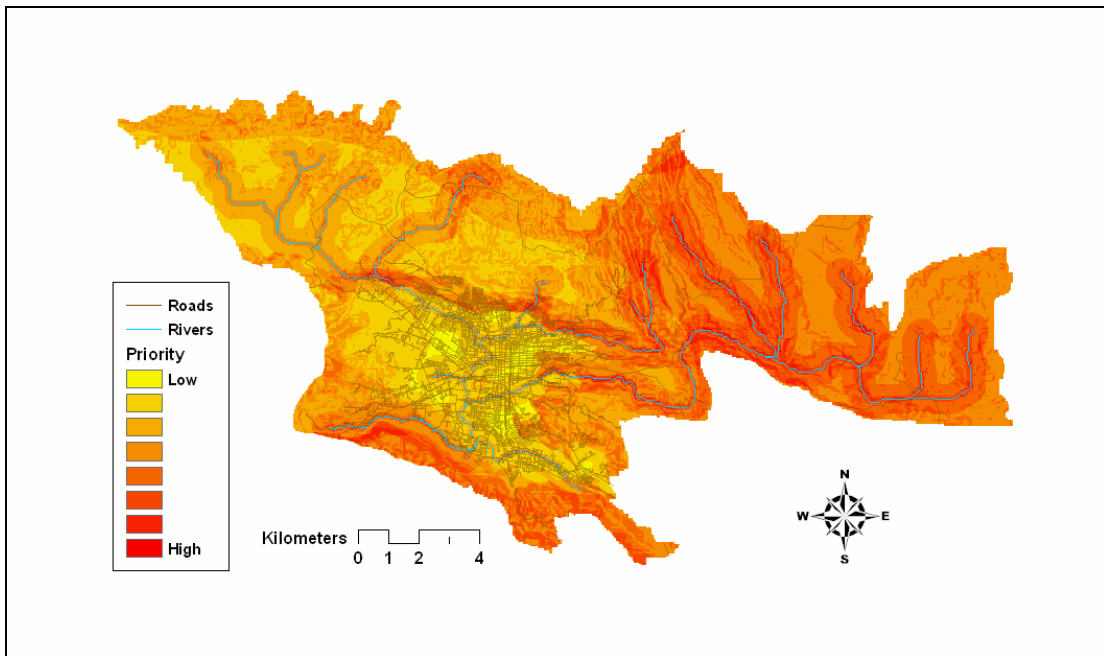
After the Landsat images were processed so that each raster cell had an NDVI value, three satellite images covering the watershed were compared to determine the difference in deforested area between 1991-2003 and 2000-2003, respectively. The first comparison gave information on a longer term and was expected to show a larger deforested area, while the second was expected to provide more evidence of more recent changes. A 1974 Landsat image was also available, but its use was not to be attempted for the purposes of the model because any deforested areas from this time period would already have undergone at least partial succession by the current year, 2007.

The NDVI calculation for 2003 was to be used to create a masking layer that would allow risk prioritization values to show only for those cells that were already deforested. This was accomplished by multiplying the combined risk raster discussed above by a reclassified binary raster where “0” represented the areas that were already forested or covered by a pre-existing land use such as commercial or residential land in the city. Likewise, “1” values were assigned to those areas that were found to have recently cleared vegetation. The NDVI calculations for the years 2003 and 2000 were calculated. However, as it turned out, the paths of the two flyovers did not overlap. In addition, qualitative observations indicated that the two flyovers may have been at different times of year, resulting in different growth conditions, which change the absorbance by the satellite image, increasing difficulty of the calculation. Due to these difficulties, in association with the low priority place on the reforestation analysis as it relates to the scope of this group project, NDVI analysis was not completed for this model.

### 6.3 Modeling Results

The reforestation analysis of the San Cristóbal de las Casas watershed used inputs of soil type, slope, and distance from river ways to develop a scaled classification to prioritize reforestation efforts in the watershed (Figure 62). No area in the watershed tested as high priority for all four input layers (Appendix F.1). As expected, the influence of the stream distance input is readily visible. However, though an area’s distance to streams is an influence on priority, the equal weighting of the four inputs returns a result where the influence of each layer is somewhat visible. The analysis also shows the high importance of the soil type input. The northeastern portion of the basin contains relatively few low priority lands, while Figure 60 concurrently shows

that this part of the watershed is almost entirely made up of soil types classified as high erosivity. For reference, soil types Rendzina and Acrisol were classified as most erodable (Table 18). It is also important to note the emphasis this analysis places on protecting the lands of the northeast portion of the watershed may be because this area is in close proximity to the Rio Fogótico, the largest of the main-stem waterways in San Cristóbal, both in area and in flow (Bencala et al. 2006).



**Figure 62.** Lands prioritized for reforestation as influenced by soil type, slope, and distance to streams. This map shows the full gradation of prioritization values calculated by the model.

In addition to the Fogótico subwatershed, the southern border of the watershed is also classified as High. Like the northeastern portion, this area is made up of erodable soils, but it also has many portions with a steep slope (Figure 57). Finally, the thin bands of mid-priority lands along the northern and southern mountain ranges coincide with the orographic effects on precipitation in the watershed (Figure 61).

Broken down into categories, the prioritized land that makes up the largest area is the medium priority classification, while only a relatively small area of land located on the steepest slopes surrounding San Cristóbal is classified as high priority (Table 20).

**Table 20.** Categories and extent of watershed lands as prioritized for reforestation; values may not add to 100% due to rounding.

	Hectares	% of Watershed Area
<b>High</b>	2,454	12.3%
<b>Medium</b>	9,547	47.8%
<b>Low</b>	7,955	39.9%
<b>Sum:</b>	19,956	100.0%

From visual examination of the individual layers, the result of the majority of locations being classified as mid- priority seems to be attributable mostly to two factors: the great amount of land made up of Rendzina and Acrisol soils (Table 18), and the distance from streams (Figure 58). The small difference in total area between Table 18 and Table 20 can be attributed to the difference in resolution between the two maps, the source data for one of which is a raster and the other is a shapefile.

One possible shortcoming of this analysis is that this stream layer used to quantify the distance to streams layer of this analysis focuses on the main stem and major tributaries of the four main rivers in San Cristóbal. Lower order streams in the basin are not taken into account by this analysis, though erosion can inhibit the quality of their waters and a portion of their contaminant load is still transported to the main stem rivers. If a more detailed map of the river systems of the watershed were available, it is likely that this analysis would categorize a greater percentage of the watershed lands as “high.”

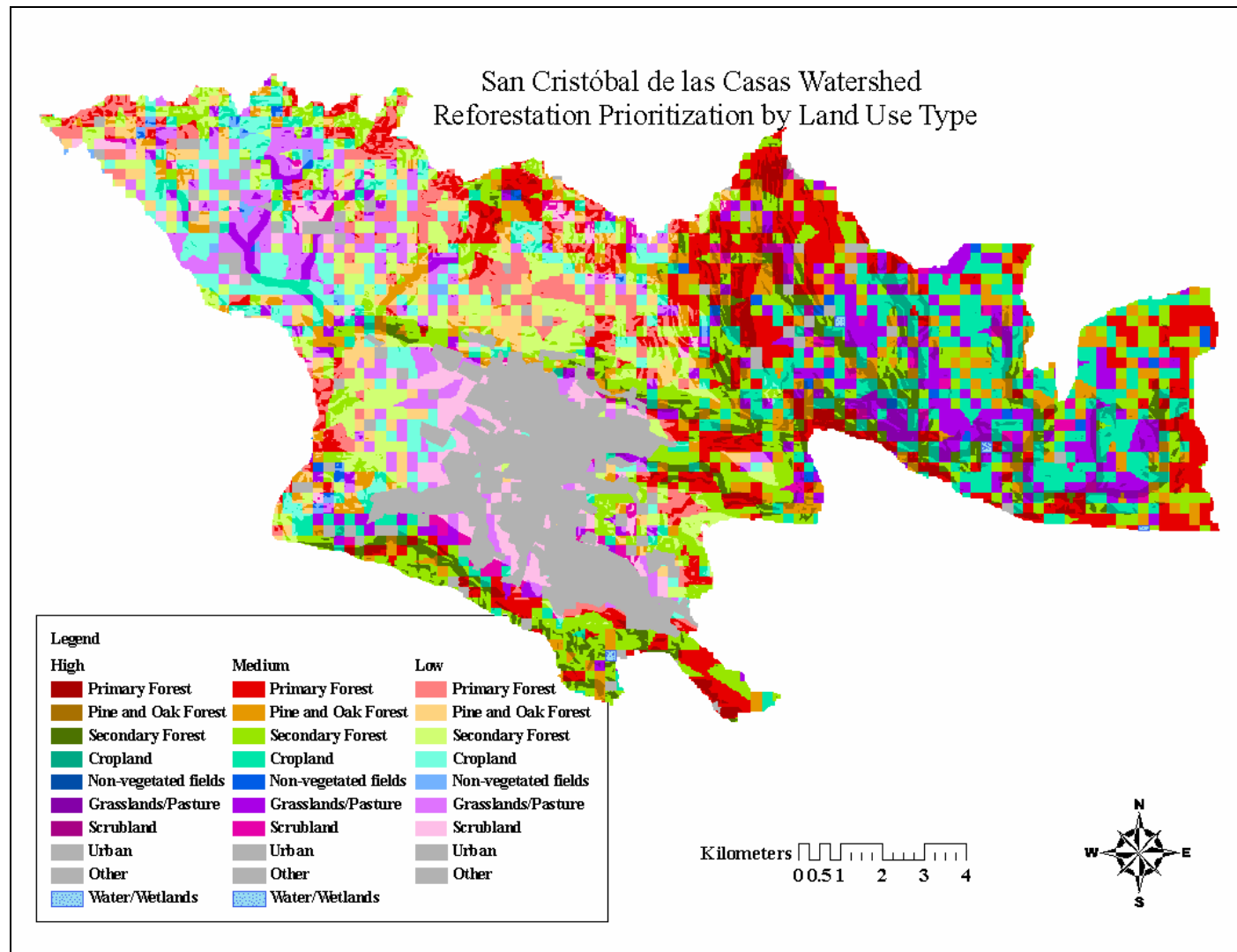
Additionally, the data displayed in Figure 58 represents stream buffer distance as applied to a two dimensional surface. A more accurate way of characterizing this input would model the overland flow distance from a given location in the watershed to its receiving water body. While attempted by group members, the resultant GIS layer was inaccurate due to the failure of ArcGIS to take into account that water drains through a tunnel in the mountain, and not over the border of the watershed with the lowest elevation.

The analysis displayed in Figure 62 does not take into account what type of land is represented by these categories, or what areas have recently been deforested. To address the first of these questions, this analysis added a coarse scale land use classification layer provided by partners at LAIGE. First, Figure 62 was reclassified into three priorities – high, medium and low – using the natural breaks method in ArcGIS. Using the Identify feature in the ArcToolbox, the land use layer was joined to the reclassified prioritization layer to assess which land uses were represented within these prioritization categories, and to identify the extent of each land use (Table 21, Figure 63Figure 64). In the table and figures that immediately follow this paragraph, all land use types are included for several reasons. First, the analysis employed a

rough land use layer, which is not accurate on a small scale. Therefore, some forest lands may overlap with croplands or fields. By including all land use types, our partners in Chiapas can see the rough distribution of land use in the watershed, and use this information to target their reforestation efforts. Finally, the analysis does not include a site specific survey of currently deforested areas, and at what rate they are being converted to cropland or non-vegetated fields. The below data gives them a baseline from which to proceed if they choose to monitor this conversion more closely.

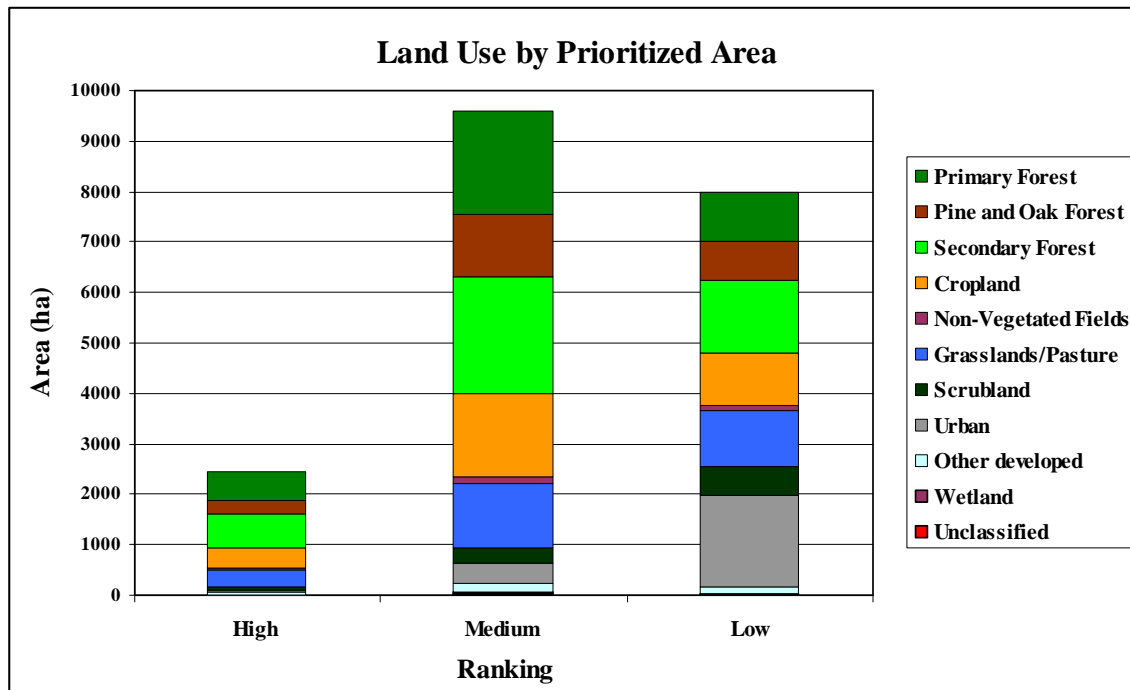
**Table 21.** Land use distribution for each priority class

Land Use	Priority Area (Hectares)		
	High	Medium	Low
Primary Forest	574	2036	971
Pine and Oak Forest	277	1235	771
Secondary Forest	659	2333	1450
Cropland	421	1652	1044
Non-vegetated fields	21	130	90
Grasslands/Pasture	341	1257	1101
Scrubland	73	301	589
Urban	29	418	1792
Other/Unclassified	54	169	148
Water/Wetlands	5	16	-



**Figure 63.** Combination of prioritization map and land use map, showing the categories of land use within each reforestation priority zone (high, medium, and low)





**Figure 64.** Land use distribution of reforestation prioritized areas

While Figure 62 and Figure 64 demonstrate a coarse scale analysis, an NDVI analysis would identify specific deforested sites which can be overlain on the land prioritization matrix of Figure 64. The nature of the deforestation in the San Cristóbal watershed is small scale. Clearing is done as a cottage logging industry and for relatively small plots of farmland (Bencala et al. 2006). The nature of these clearings being small in area, and often on steep lands, complicates their identification through NDVI analysis. This analysis was attempted, and NDVI rasters were created from LANDSAT images from 2000 and 2003, however, complications with overlaying layers from different LANDSAT projection sources, and the small scale widespread nature of the deforestation hampered completion of this aspect of the project.

Partners in Chiapas asked the group to perform a prioritization analysis, and also requested a suite of strategies to employ in the improvement and growth of their reforestation campaign. This element of the project follows.

#### 6.4 Strategies to Implement Technical Findings

The results of the GIS analysis performed by UCSB students, coupled with the data gleaned from a comprehensive literature review, illustrate a decades-long cycle of deforestation for economic growth followed by further erosion of the natural resource base as availability becomes scarcer (Cayuela et al. 2006b; De Jong and Montoya-Gomez 6–9 September 1994; Ochoa-Gaona 2004). Based on these conclusions, Guzmán

appealed to the UCSB group to provide the reforestation campaign in San Cristóbal with a series of possible strategies to ensure a successful project. This comprehensive reforestation initiative, as desired by stakeholders in Chiapas, is aimed at counteracting decades of human-induced deforestation that continues to detrimentally affect the San Cristóbal watershed to this day. The campaign compels implementation of technical strategies that target human influences on previously forested land, as well as institutional strategies that focus on the holistic management of the natural ecosystem.



**Figure 65.** Reforestation Project in Chiapas (SEMARNAT)

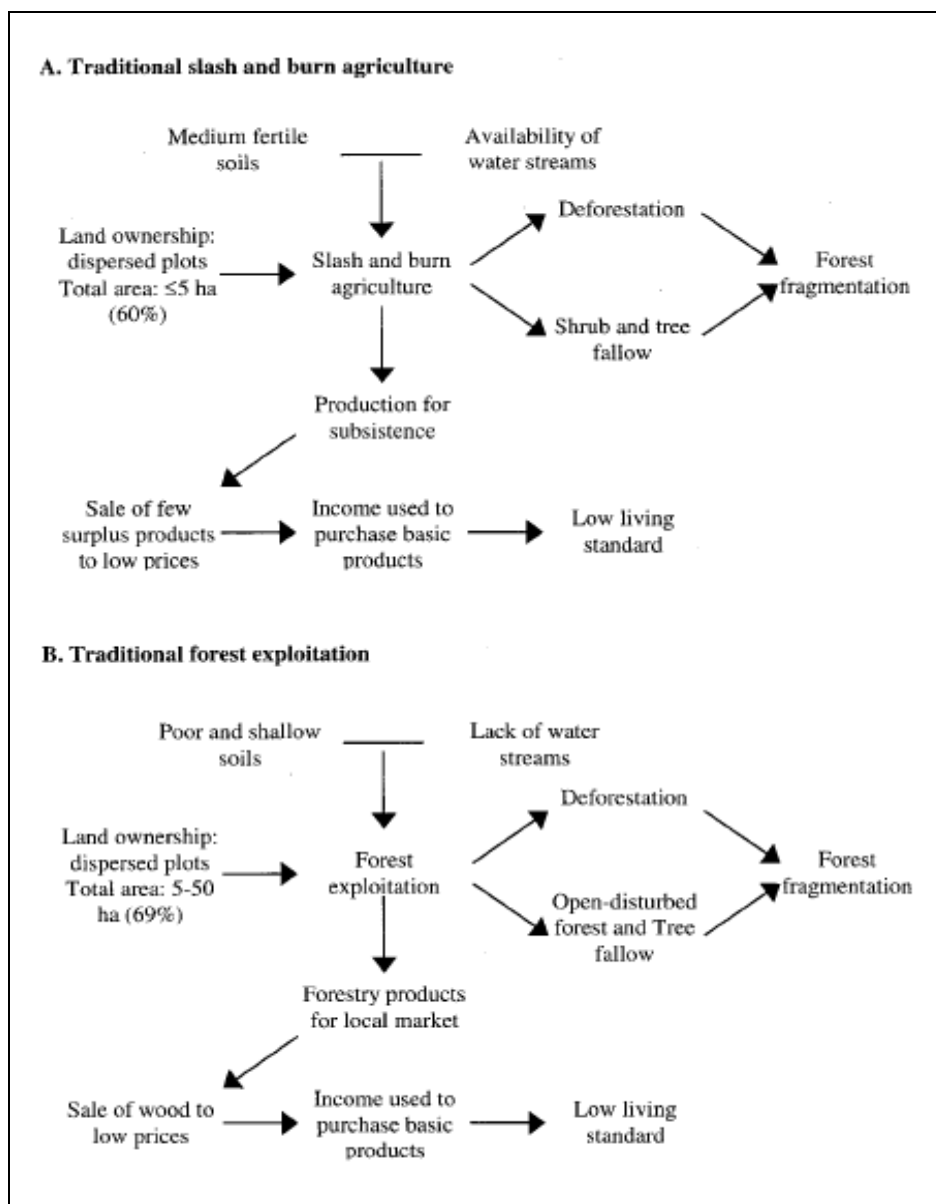
#### *6.4.1 Community-Based Strategies for Reforestation Initiatives*

Management of the external drivers on the natural system, particularly human-induced ones, is a critical component of any conservation strategy. Recent increases in population concentrations have affected the way in which farmers manage their agricultural land in Chiapas. The *ejidos* agricultural system, in which farmers own small pieces of land that are then divided into small, dispersed plots (most likely *milpas*, or cornfields, in Chiapas) that are tilled by individuals, has historically produced low yields and has proven to be commercially nonviable due to increasing economic pressure. Throughout the San Cristóbal watershed, farmers have eliminated forest vegetation in an effort to maximize economic yield (Ochoa-Gaona 2004). After the land is cleared, however, the ability of the fragmented forests and secondary forests that occupy the cleared area cannot provide the same level of ecosystem services, such as flood water amelioration, soil stability, pollutant filtering, and erosion control (Bencala et al. 2006). Soil fertility declines while population density continues to increase and land scarcity intensifies.

Any reforestation project that aims to put an end to the cycle of deforestation and land degradation must first tackle the issue of community motivation. Recent efforts on the part of Guzmán to extend reforestation efforts into the community have centered on the distribution of seedlings as investments which, when they reach maturity, will bring the farmers money in the form of a reward. Unfortunately, most of the farmers discontinue the project once payment is received (Guzmán 2007). The project team conducted an extensive literature review as well as personal interviews with forestry professionals in an effort to determine strategies that will build community motivation that is sustainable past the payment period. Based on the findings from both the research and the interviews, it was determined that incentives that are not based on direct monetary gains are the most successful.

Many programs that reward farmers with valuable trees such as hardwoods or grafted fruit trees upon the successful planting of a preset number of seeds or seedlings have been attempted. However, programs based on both a short-term strategy for sustainable livelihood, along with a long-term regional strategy for rehabilitation, will be most successful (Deppner 2007). The most promising means of implementing a successful two-phase reforestation project that encourages both income generation and resource sustainability is through the application of agroforestry, a land management system that combines agriculture, forestry, and occasionally grazing technologies to create more diverse, productive, and profitable land-use systems on nearby lands (Deppner 2007). Meanwhile, more marginal plots can be rehabilitated to forests through an assisted, albeit natural progression.

Traditionally, economic development objectives have resulted in the proliferation of plantation forestry – a short-rotation, high-yield timber system that is based upon the conversion of a species-rich natural ecosystem to a species-poor monoculture ecosystem (Ramakrishnann 2001). Alternatively, an agroforestry project relies on natural management that is grounded in traditional and integrated management approaches that address forest management in terms of silviculture (forest cultivation and harvesting), ecological knowledge and socio-economic and cultural factors (Figure 62). By shifting the focus away from timber or other commercial crops that are traditionally planted, which are primarily exported and of little benefit to the local community, preexisting ideas and behaviors can be exploited and incorporated into a design that can be successfully implemented and managed.



**Figure 66.** Two models of traditional land-use systems and their fragmentation patterns. (Source: (Ochoa-Gaona 2004)

Farmers in San Cristóbal currently “combine *milpas* production with minor livestock management and forest exploitation to cover their local needs for fuelwood, timber for construction, and other products, which gradually degrades forest stands (Ochoa-Gaona 2004). While this system was traditionally successful in the past, accelerated deforestation due to increasing land pressure makes it no longer sustainable. Still, by tapping into the traditional knowledge of shared land-use, a more sustainable agroforestry approach that promotes sustainable yet fast income-generating resources for sustainable livelihood in its first stage and increased diversification for longer term development in its second stage will more likely succeed.

The second stage of the implementation plan that focuses on species diversification will also address the issue of elevated soil acidity by correcting the current predominance of conifers such as pine and spruce. While these are the recommended tree species for primary succession in deforested lands, they should be modestly planted in the first stage so that soil can be rehabilitated, and then planted during the later phase once rehabilitation is accomplished. During the second stage, once soil is rehabilitated, spruce and pine can be planted in greater numbers as long as complementary, acidity lowering crops or trees continue to be interspersed. This shift from dominance of locally commercial species to a more balanced mix of commercially sustainable species with native pine and spruce species (whose success is based on the achieved and continued improvement of soil health and forest diversity) will increase participation in the reforestation campaign (Deppner 2007).

Other preexisting cultural and socio-economic norms that exist throughout Chiapas can be incorporated into a reforestation/watershed management plan as well. These include existing technologies such as rainwater harvesting systems and water catchment systems like bioswales, both of which increase soils' water retention and thereby improve soil fertility (Appendix A).

In order to guarantee the greatest probability of success from implementing a reforestation project, foresters at Trees for the Future advise that several seed collection techniques be followed. The first step in the reforestation process is seed collection during the planting downtime. High quality seeds of the same species should be collected directly from sites that are separated by more than 100 meters to insure species similarity while still encouraging adequate genetic variability to guard against inherent quality weaknesses. High quality seeds are those that come from trees with healthy trunk/branch formations, high growth rates, and high resistance to disease and pests. The seeds should also be collected from at least 30 different trees rather than one, and from all parts of the tree, in order to ensure a wide genetic base. It is also important that the seed be collected when it is mature since immature seed has low viability and storage life. Many seed species present maturity when they can longer be crushed between the thumb and forefinger, when the fruits begin to split open, or when the color of the seed changes. Seeds can also be cut open to check for the presence of a mature embryo and endosperm.

For future project reference, the species, origin, collector and date of collection should all be noted and shared with any individual to whom the seeds are distributed (Jaenicke 1999). Seeds can also be purchased from distributors such as Trees for the Future, which provides initial seed for multipurpose fast growing (MPFG) trees that can then be mixed with the seeds collected during the first few seasons of the reforestation initiative.

After collection, the husk of the seed should be removed and the seeds should be stored in dry, cool, dark environments. The lids of seed containers may need to be opened each month in order to expel excess moisture. Seed storage containers should also be sturdy enough to resist damage, but still be able to let in light – tightly sealed clear glass or plastic canisters are ideal. Damage from the chewing by rodents can be avoided by using

ash as an insecticide on the seeds. The containers should be kept away from walls and off of floors to avoid dampness and insects (Leary 2/9/2007).

Further reforestation techniques recommended by Trees for The Future for application in San Cristóbal are:

- Trees should be planted as seedlings between June and August in order to establish strong seedlings that will survive the coming dry season.
- Seedbeds or nurseries that can establish a large number of individual or small groups of seedlings in the same location where the trees will be transplanted provides many social benefits and also greatly increases survival rates.
- Fruit and hardwood species can be planted in the second phase of the project once highly productive, environmentally-beneficial trees that restore and protect the land are established.
- Widespread, but non-traditional and infrequently used tree species may be useful as starter species to improve soil conditions and therefore encourage rehabilitation of degraded systems. Of particular interest in soil rehabilitation is the success of *Leucaena leucocephala*, a fast-growing, self-pollinating, and multi-purpose tree species that is widely available in improved varieties, and therefore highly adaptable to variable weather conditions (Figure 67). The tree is also highly valued for use as live fencing, animal forage, and fuel. *Leucaena* leaves are high in nitrogen and therefore quite effective as natural fertilizers.
- Trees should be allowed to grow for at least 18 months before being harvested.



Figure 67. *Leucaena leucocephala* (Holmes)

Several agroforestry techniques that can be implemented in combination with tree-based reforestation initiatives in San Cristóbal were recommended in an interview by John Leary from Trees for the Future. These include:

- Contour planting: This technique, discussed in the BMP section, can be highly effective in the San Cristóbal highlands by guiding rainfall and other runoff into groundwater aquifers, which will minimize soil erosion during the rainy season. (Appendix A.5)
- Firebreaks: Because fire is recognized as a major disturbance in Chiapas that degrades habitats and reduces ecosystem services, barriers constructed of fire-tolerant tree species can help to protect more income-dependent trees or crops (Roman-Cuesta, Retana, and Gracia 2004). Fruit trees are usually fragile and are therefore particularly benefited by firebreaks.
- Live Fencing and Livestock Management & Forage Trees: San Cristóbal has experienced an increase in livestock grazing on steep slopes, which has led to erosion of the thin and fragile soils (Bencala et al. 2006). Several successful agroforestry projects rely on the use of a single tree species (i.e. *Leucaena*) to act as a free, sustainable source for an enclosure to protect sensitive species and also to serve as animal forage to beef up cattle.

Any community-based project should include an education component to supplement the technical implementation. It is important to recognize that adults living in Chiapas are the primary users, and therefore extractors, of the forest and its products and therefore have more urgent behaviors that must be targeted immediately. Section 3.0 outlines an education program aimed at both schoolchildren and community members in San Cristóbal that can be easily adapted to forestry issues and related back to watershed health.

#### *6.4.2 Institutional Strategies for Reforestation Initiatives*

In addition to bottom-up community-based initiatives, sustainable reforestation initiatives must also include strategies to modify current practices through top-down institutional mechanisms. Working within policy-making institutions to influence changes in land management and watershed health regulations can increase the legitimacy and ensure the enforcement of management proposals.

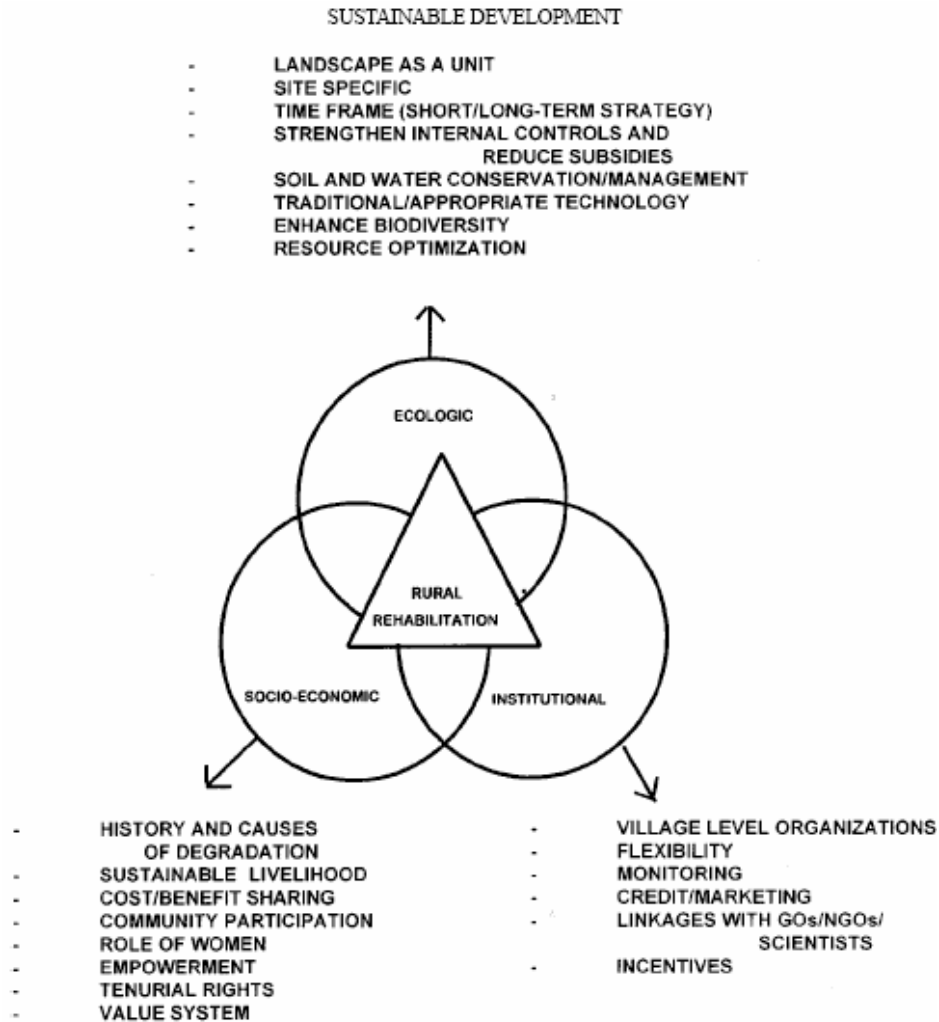
Mexican land tenure laws that govern the system of *milpas* agriculture only give farmers the right to use the land, not own it. Furthermore, the farmers have no real jurisdiction over the other resources that are inherently interconnected with the ecosystem such as water, fish, and minerals. Instead, these resources remain the property of the Mexican government and, as a result, the farmers have no incentive to use an integrated land-use approach (Ochoa-Gaona 2004). At the same time, the government has not crafted policies that support development of the marginal *milpas* lands, leaving the farmers apprehensive of land management alternatives (De Jong, Cairns, Haggerty, Ramirez- Marcial, Ochoa-Gaona, Mendoza-Vega, Gonzalez- Espinosa, and March-Mifsut 1999). It can therefore be



beneficial to both the marginalized farmers and the degraded ecosystems to make an effort to effect policy change as part of a reforestation effort.

Much of environmental policy regarding natural resource protection is based on forest conservation regulations. For a long time, ecosystem management policy focused on establishing reserves in areas prioritized for conservation or restoration. Recently, however, there has been a movement away from this method and towards integrated landscape management where conservation efforts are be focused on the detection of biodiversity hotspots, passive and active restoration sites, and sustainable forest exploitation by the local indigenous communities (Cayuela et al. 2006a). Designating communal forest ownership (a “commons”) often reduces pressure to clear land and is therefore lauded as a basis for a policy initiative. From such a policy comes a landscape management system that is based on shared traditional ecological knowledge. After all, when resources are jointly used by individuals with a common heritage, reforestation projects tend to be location-specific and highly participatory (Ramakrishnann 2001). The resulting integrated, human-manipulated ecosystem in such a traditional society remains in step with the ecological, socio-economic and cultural components of the environment (Gliessman 1989).





**Figure 68.** Interactive Factors in Ecological Rehabilitation (Ramakrishnann 2001)

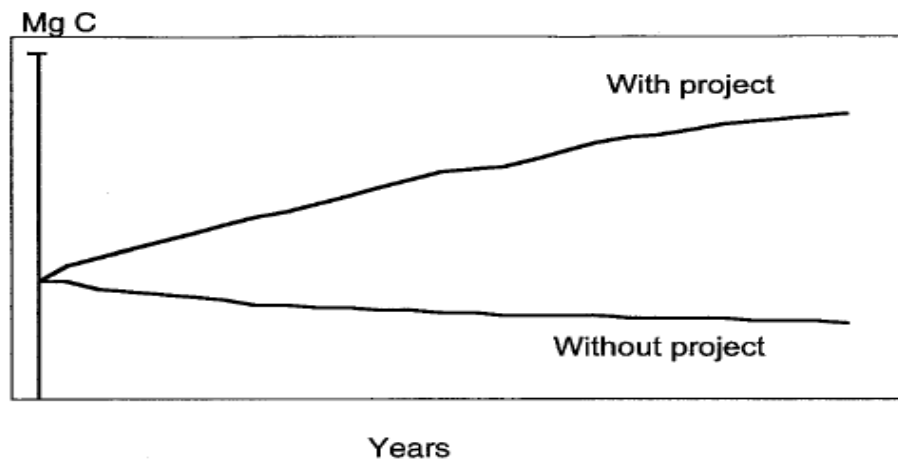
Perhaps the most prevalently successful policies regarding natural resource management at this time are those based on economic incentives. These various policies work to impose environmental taxes and subsidies to correct market distortions, create markets for forest ecosystem services, establish sustainable financing mechanisms, develop incentives for land managers, develop an institutional framework to match local conditions, and attempt to correct market failure through more equitable cost and benefit distribution (Pagiola 2005).

As an example, in “Tales of Dissemination in Small-Farm Agriculture,” Judith Tendler describes the success of a “good credit subsidies” program that was based on the principals of high subsidies and high discipline (Tendler 1994). Farmers first received credit at very low or even negative interest rates in order to buy certified items such as rootsock, seedlings, or fertilizer. The use of the issued credit to purchase the certified products was carefully monitored by the lending agencies and stakeholders. Because states like Mexico often hold a monopoly over forestry inputs, control over the supply and effective monitoring were already built in. Furthermore, the subsidy had automatic “sunset” provision that meant it would be discontinued once the initiative’s objective was

accomplished. The success of the program lay in the fact that it was specific and included performance demands.

Working independent of policy, microfinance has become a popular method of encouraging natural resource protection and economic development simultaneously by focusing on giving loans to women in poor communities to start small businesses so that they may generate income they would not otherwise have. Reforestation initiatives in Chiapas could integrate loans from microfinance institutions into projects that sell valuable hardwood or fruits from sustainable harvested trees.

Additionally, some economically-grounded policies are becoming more widespread. These are based on mitigating the effects of climate change through carbon sequestration projects (Figure 69). Due to the Joint Implementation program launched by the Intergovernmental Panel on Climate Change through the Kyoto Protocol in 1997, countries such as Mexico may transfer or receive emission reduction units resulting from projects aimed at reducing emissions or enhancing removals of human-induced greenhouse gases ("Kyoto Protocol" 1997). Again, the "crop tree" agroforestry approach is cited as being the best implementation option for carbon-sequestration policies because of the system's high biomass productivity and cost-effectiveness (De Jong, Soto-Pinto, Montoya-Gomez, Nelson, Taylor, and Tipper 1997a). The agroforestry for carbon sequestration approach is usually characterized by individuals and small groups involved in small-scale systems that reflect site-specific management and individual adaptation based on personal interest, local conditions, and previous experiences.



**Figure 69.** Hypothetical effect of a carbon sequestration farm forestry project compared to a non-sequestration project; in megagrams (Mg) of carbon per year (De Jong, Tipper, and Taylor 1997b)<sup>2</sup>

In Chiapas, efforts to develop new models for financing land improvements with carbon offsets as a source of investment capital have resulted in the Plan Vivo management model (De Jong et al. 1997b). The Plan Vivo system awards certified carbon offset credits to rural communities for completing activities to sustainably manage their natural resources. Carbon offsets acquired through the management plan are registered for sale in

<sup>2</sup> 1 megagram = 1 metric ton = 1000 kilograms

a carbon trust fund, providing a cost-effective and efficient framework through which rural communities and small-scale farmers can participate in emerging carbon markets. The revenue stream generated by carbon sales can also cover start-up costs associated with land use activities that would not otherwise be financially viable (Orego 2005).

The most effective policies for counteracting reforestation will aim to regulate land-use change so as to reduce further degradation while also limiting carbon emissions to the atmosphere over the short term. Policymakers and campaign organizers should, however, distinguish between these two effects, and focus the most time on managing short-term influences such as deforestation while allowing long-term influences such as climatic change to be addressed as an ancillary benefit of the policy (Gómez-Mendoza et al. 2006).

#### *6.4.3 Evaluation Strategies for Reforestation Initiatives*

Any reforestation project that is initiated must be monitored and evaluated in order to gauge its effectiveness. Pushing a strategy that proves ineffectual or even detrimental to the project goals wastes valuable time and resources when one could instead change tactics and modify content to design a better-suited project.

This report contains current GIS land cover and WQQM data that serve as a baseline indicator for any project that the Reforestation Campaign chooses to implement. Once implemented, the Reforestation Campaign should continue GIS forest cover and WQQM modeling in order to measure the success of the chosen approach. Other approaches to tracking forest health and trends over time are to conduct field surveys at reforested sites on a periodic basis and measure simple ecological indices of forest density and forest diversity. The appropriate evaluation mechanism depends strongly on the primary and secondary goals of the program, which might range from ecological improvement to social improvement within indigenous communities, increased public awareness, or recreational forest use. Some of these factors could be assessed by surveying the participants in the program or affected communities.

Monitoring systems for carbon sequestration projects must “track the stock of tree biomass through periodic inventories or surveys, and track the development of social, economic, and institutional structures...that [might] influence the long-term viability of carbon uptake and storage” (De Jong et al. 1997b). Evaluation for these types of projects should cover both the current performance of the project as well as the long-term prospects for storage and uptake of carbon.

## **7.0 Lessons Learned during Project Implementation**

In the spring of 2006, group members looked forward to the challenges of this project, and embraced them throughout. Still, one year later, there are aspects of the project that the group members wish they had been more knowledgeable about before starting the process. UCSB researchers engaged in this project for a variety of reasons: to gain more experience in water quality and quantity monitoring methods, to work on an

internationally-scoped project, to research and apply BMPs and watershed management strategies, and to expand capabilities to productively work in groups and benefit from other group members' knowledge. Most importantly, though, all group members wished to take part in a project that would have on-the-ground impacts and tangible benefits to communities in San Cristóbal de las Casas, Mexico.

Benefits were inherent in the project goals that included the design and implementation of a variety of BMPs that would improve sanitary conditions, the analysis of the San Cristóbal watershed to determine future management actions, the investigation of reforestation techniques and strategies to enhance water availability in the watershed, the development of personal and professional relationships with partners in Mexico, and the possibility of promoting the BMP designs in communities outside of San Cristóbal.

To a great extent, this project achieved the goals it initially set out, and project members and partners are satisfied with the experience. The approaches used to accomplish goals were based on past experiences, researched case studies, guidance from partners, documented methodologies, and trial-and-error actions. Although the project's span was only one year, the members sought to complete the project work within the framework of sustainable development. Members reasoned that only limited steps viewed as part of a much longer process of community development could occur within the project's timeline, and therefore attempted to approach the international work with this in mind. No amount of planning or application of researched methodologies, however, can dictate the success of a community implementation project, especially in the case of foreign development. This section addresses the lessons learned throughout the year-long process in terms of communicating and organizing with project partners and target community over international boundaries.

### 7.1 Broad Lessons Learned – Matching Project Goals with Project Possibilities

The goals of this project tackle issues of sustainable development, community and ecological health, and watershed-based management and planning in San Cristóbal de las Casas, Mexico. Additionally, the project aimed both to design and put into practice a number of BMPs as pilot projects, which would then be monitored for their effectiveness. Critical resources and time were applied to project preparations and implementation in order to accomplish these lofty goals. However, this project developed within the context of a Bren School group project, which has certain confining factors, such as a limited duration of one year, inability for students to dedicate full-time to the project because of the Bren School's requirements to enroll in classes each quarter, and the corresponding inability of students to spend a significant amount of time at the project site.

Members of this group project collectively spent about 20 weeks in San Cristóbal de las Casas working with partners and community members to determine the program plans, share ideas, convey design functions, design the education program, collaborate with implementing the water sampling program, and demonstrate construction of the BMPs. Progress was rapid and fluid during much of the time spent in San Cristóbal. Communication tended to rapidly break down, however, after UCSB project members

left the area, and at these times progress occurred much more slowly than expected. As project members realized what a significant difference in-person contact made, they attempted to spend as much time as possible in San Cristóbal to get to know partners better and to collaborate with them more frequently.

Still, more time spent in San Cristóbal would have been advantageous. This minimal amount of time available for travel to San Cristóbal was a chief limitation to the project's potential. Without substantial time on-site, it was very difficult to accomplish all project goals, specifically with regards to constructing pilot BMP projects. As a consideration in future projects of this type, the researchers recommend that development work should be initiated through an organizational framework that allows students to dedicate a great length of time at the project site, rather than within the Bren School Group Project framework, due to the program's course-based nature.

## 7.2 Lessons Learned – Working With International Partners

### *7.2.1 Communicating with Partners*

From the outset, UCSB project members have shared a common vision for the project's scope and goals. Members crafted a plan to accomplish these goals and communicated them to partners in the best Spanish possible. Each partner organization had a role in the project – for example, SYJAC was responsible for communicating and facilitating BMP construction with the target community, and ECOSUR committed to implement the recommended water quality and quantity monitoring plan. This division of responsibilities between partner groups proved to work well and efficiently. However, in many instances, the Mexican partners did not report results in a timely fashion, and UCSB students were not able to continue a portion of their work until those results were received. Partners in Mexico may have experienced the same limitation from UCSB researchers. In this manner, a time lag was infused into the project that inhibited the rapid progress necessary to accomplish stated goals within the short-term project timeline. The group learned a number of lessons from this experience:

- Ground rules should be agreed upon to ensure timely interaction between partner groups, who may conduct business on schedules that differ significantly from those that the facilitating group is used to. For instance, a weekly meeting could be established to report on each group's progress, or a rule that requires email response within three days could be initiated. Whatever agreement is reached, all parties should understand the importance of following through on their commitments. In winter 2007, the project members established a regular phone meeting with partners at SYJAC to administer efforts to construct the EcoLavadero. These meetings proved valuable in identifying issues as they arose, so that the group could respond to the challenges raised.
- Shared goals must be clearly defined across partner groups. If not, priorities for one group could poorly reflect the other group's priorities. For instance, UCSB project members suggested a number of survey questions specifically targeted at

assessing the water quality-human health relationship in Cinco de Marzo. Rather than using these questions, SYJAC created and administered alternate survey questions which had several questions touching upon both issues, but not one that specifically addressed the link the suggested questions targeted. As a result, UCSB researchers planned the education program without this first-hand data, and instead relied on data collected by partners.

- Consistent and clear communication is essential. This is a major stumbling block in many international relationships due to the language barrier. Although this project was equipped with several Spanish speakers, the language was not any member's first tongue. Nor were most project partners in Mexico able to converse fluently in English. Attention to improving language skills prior to the project is significant, since management work requires attention to detail, effective communication of ideas, and mutual comprehension. For instance, when details discussed in a telephone call with partners were not understood, project members did not always stop the conversation to clarify. This behavior can breed misunderstanding and confusion.
- In a new working relationship, patience and flexibility are key attributes. Project members found it frustrating that meetings in Mexico frequently lasted longer than expected, were cancelled or missed. The explanation for this confusion simply lay in recognizing the difference in the United States and Mexican cultures. Mexican culture tends to run on a more relaxed time schedule than the United States, which is likely to be a difference in many other countries as well. It is important to be able to work through this cultural difference and mutually agree upon the expected etiquette for timeliness and setting appointments.

### *7.2.2 Matching Work Ethic among Partners*

A second key piece of advice project group members would recommend for future work lies in getting to know partners and determining partner expectations and capabilities at the outset of project-based collaboration. Collaboratively defined goals should naturally fit within the objectives of all partners involved in order to ensure mutual motivation. Additionally, it is essential to define how much time and money each group is willing to spend on the project to avoid complications and financial misunderstandings that can lead to project delays. For instance, UCSB researchers found that the sense of urgency and rapid pace with which they worked due to the short time span of the project did not match the pace of the Mexican partners. Many circumstances necessitated multiple emails coupled with phone calls to receive a response that would enable the students to continue with research. This type of relationship breeds frustration, which must be pacified by recognizing that partner organizations are working on other programs simultaneously. To create an optimal working relationship and avoid this type of frustration altogether, it is recommended that a work ethic be more appropriately matched when committing to a partnership.

### *7.2.3 Ensuring Buy-In within the Community – Creating Factors for Successful Community Work*

It cannot be emphasized enough that buy-in from the community is paramount. That is, there must be a felt need within the community for the technology suggested and a sense of trust between all partners involved. There are certain factors that successfully came together in Cinco de Marzo that project members observed to have catalyzing effects. First, the project's partner organization, SYJAC, had a well-established relationship with community leaders before BMP implementation was suggested. Second, a group leader emerged that motivated other members to participate in group discussions and work days. Third, the financial collaboration between the groups circumvented the barriers that would have otherwise obstructed project initiation.

However, project members also discerned that when the community leader was unavailable, the level of motivation among community members plummeted. Community members were unwilling or unable to organize amongst themselves to advance construction. Thus, during lapses of leadership little progress occurred. Project members believe that having multiple leaders to continue member motivation would have increased the speed of the progress. Additional leaders would have been able to educate community members about the technology or practical solution, and would have been more available for questions concerning community activities.

### *7.2.4 Creating Trust and Working Relationships over International Boundaries*

Working internationally is inherently difficult. As mentioned, language barriers present misunderstandings, differing schedules impede successful meetings, and the lack of physical contact can limit understanding of shared program goals. More importantly, cultural differences can hinder mutual trust. In a community development project such as this one, where UCSB students lead very different lives than the community members with whom they are working, it is important that the students attempt to understand the community culture. One way to achieve this is to observe social norms: stand back and observe person-to-person interactions in the target community. Communicating in a similar manner and not creating tension through confrontation can help to create trust. Deferring to community leaders for advice also aids in building relationships, as does recognizing and respecting roles of various age or gender groups.

### *7.2.5 Utilizing Each Partners' Strengths*

Working in partnerships has the advantage of enabling each group to exploit each partner's strongest skills. In a partnership of groups where members have distinct skill sets, as is likely to occur when working across boundaries, each group should take on the appropriate roll to achieve the best results. This project effectively utilized the assets of each group to accomplish shared goals. To initiate planning for the demonstration of domestic rainwater harvesting system construction, SYJAC provided the first contact needed to unite the project members with the community group and facilitated communication between them. UCSB students provided the design and knowledge of how to construct the system, along with the necessary funding to construct a pilot project.

During the construction demonstration, community members provided additional labor for the system construction, and helped to provide community group members with lunch. SYJAC also aided in the educational component of the demonstration, stressing the benefits of the design and answering questions. Each group offered its strongest skill set to complete construction of the system.

#### *7.2.6 Defining an Appropriate Scope and Foreseeing Obstacles*

When defining the scope of a project, it is important to consider the availability input from all groups, and to envision outcomes realistically. In the case of the EcoLavadero, initial implementation goals set for this project exceeded the outcomes, primarily due to funding and scheduling restraints. Partner organizations agreed beforehand that UCSB researchers would provide the design, educational materials, and funding for the materials of the EcoLavadero. SYJAC would provide communication between the researchers and community members when researchers were in the United States, information about the potential projects and BMPs to the community members, and assistance and guidance in community group organization. The community of Cinco de Marzo committed to providing the labor for construction as well as to future maintenance of the EcoLavadero after construction.

Pledges by all groups were sincere, though the construction scheduling did not develop as planned. In many projects, particularly those in developing countries, unexpected barriers arise. In this case, the community group of Cinco de Marzo hesitated in initiating the EcoLavadero construction due to land ownership issues. Although this problem was not fully resolved, the group voted to carry on and begin construction while assuming that land ownership would be granted to the community in the near future. In this case, waiting for bureaucratic steps to be taken would simply take too long due to an inefficient municipal governance system. Land excavation began in December 2006, just before UCSB researchers arrived for the winter visit. It proceeded efficiently until mid-December when another obstacle presented itself – lack of funding for a mason. UCSB researchers waited for the group to reach an agreement until late January 2007. When no agreement was reached, researchers made funding available to contract a mason for only half the time necessary, hoping the group would together raise enough (\$275) to pay for the rest of the work. This step was taken partially to promote community buy-in, and also to spur the progress of construction within the project time period. The community hired a mason and construction advanced during February, but funds for services ran out again. To encourage financial contributions from community group members, project group members extended a “match” offer that promised the project group would provide matching funds for any funds provided by community members. Construction is moving forward slowly.

Although the completion of the EcoLavadero was initially viewed as a realistic accomplishment within the one year project span, the construction was not complete at the time of writing (March 2007). SYJAC and community members aim to complete construction by Summer of 2007. The limitations inherent to community-implemented construction were anticipated to a certain extent at the outset of the project, but there was still hope that large barriers would be avoided or would be resolved within a short



timeframe. Still, group project members are proud of the work accomplished on the EcoLavadero in Cinco de Marzo and are hopeful that upon completion, the system will provide the full range of benefits predicted.

## **8.0 Recommendations**

Recommendations from this project fall into five main categories:

- BMP Implementation
- Education
- Water Quality and Quantity Monitoring
- Watershed Modeling
- Reforestation

### **8.1 BMP Implementation**

This project recommended several specific BMP technologies that were found to be appropriate for San Cristóbal de las Casas according to a set of criteria that includes meeting the client's need, requiring only low-cost, locally available materials, and benefiting both human health and the ecological integrity of the watershed. The recommendations are as follows:

- In order to address the lack of a reliable and safe water supply in peripheral communities, rainwater harvesting systems are recommended for both the individual household and small community buildings that require water services.
- In order to reduce pollutant loading into surface waters, and to improve sanitary conditions, construction of wastewater treatment wetlands are suggested.
- In order to reduce loading of pathogens and organic material into surface water, as well as to produce a source of usable fertilizer for certain food crops, the project recommends the adoption of composting latrines in areas that are not connected to sewage infrastructure.
- In order to decrease stormwater flows and to prevent cross-contamination of surface waters from eroded soil, pesticides and fertilizers, the recently developed regions of the watershed beyond the city should utilize retention ponds, buffer zones, and bioswales along river corridors. This will also provide a source of valuable nutrient-rich topsoil for those attempting to farm in the steep regions of the watershed.
- In order to decrease the need for irrigation, prevent soil loss, and improve agricultural yields, the use of contour water retention trenches is recommended, especially for farmers in steep, recently clear-cut areas.
- In order to address the gap in knowledge surrounding the link between water quality and human health, this project recommends an educational campaign aimed both at preventing degradation of water resources as well as improving sanitation.

Encouraged by the creation of Spanish-language design manuals for each of these management practices, along with collaboration with several non-profit organizations, projects that utilize and implement BMP technology will most likely spread. These projects should be applied in both the peripheral communities just outside San Cristóbal's city limits, and in more remote communities that are still located within the watershed. It is likely that these projects can meet felt needs elsewhere in Mexico and even in other developing regions. In order to promote knowledge and technical assistance with the identified practical solutions, the design manuals will be made available in hard copies to partners in Chiapas, and in electronic form on the project website at <http://fiesta.bren.ucsb.edu/~chiapas2>. While these materials are tailored to address one specific watershed, modified copies should be shared through partner networks to solve cases of water access problems, sanitation issues and ecological degradation dilemmas in other areas.

Those BMP pilot projects that have been implemented in San Cristóbal during the span of this project, including the EcoLavadero and household rainwater harvesting system in the *colonia* Cinco de Marzo are serving as prototypes for other communities nearby who wish to visit the site and learn more about how these systems are constructed. It is the intention of this project that the effectiveness of the recommended BMPs be tested over time, and that extension of the technologies, if successful, be accomplished through both formal and informal social networking. If the pilot projects are applied on a larger scale, they can potentially greatly mitigate the environmental and human health problems experienced by residents of San Cristóbal.

The lessons learned over the course of this project, which are outlined in chapter 7.0, should be taken into account when implementing additional projects. Good communication among different communities will help to impart important messages regarding the best places to purchase certain BMP materials and how to best conduct maintenance of the system. Since some of these designs are original, such as the EcoLavadero, communication between past and future users is important in order to incorporate experiences shaped through trial and error into any necessary technological adjustments prior to BMP implementation. In order to facilitate this process, pilot projects are best kept to a small scale and built one at a time to observe effectiveness of the BMP before many large-scale projects are undertaken. Finally, partner nonprofit organizations should work to empower communities or individuals to complete these projects, rather than allowing them to passively participate as the sponsoring organization constructs the BMP. This will help to ensure success over the life of the structure.

## 8.2 Education

To meet the goal of increasing public awareness of environmental and watershed health, as well as personal health and sanitation issues that prevent disease, this project implemented an education campaign in San Cristóbal. Project members recommend that a survey incorporating questions regarding the link between water quality and human health is administered both prior to the use of educational materials, and within six

months to one year after implementation of the plan. The follow-up will help to assess whether the campaign is effectively addressing the targeted needs and knowledge gaps within the community.

Educational materials were intentionally created to be easily reproducible so that partner organizations could replicate and share them with others. Moreover, several of these materials will be freely and publicly accessible online, in both English and Spanish, on the project website (<http://fiesta.bren.ucsb.edu/~chiapas2>). This will encourage the spread of important messages both in San Cristóbal and throughout the wider region. Through communication with them towards this end, project members anticipate that SYJAC will continue to work with teachers and nonprofit educational groups around San Cristóbal.

It is very helpful for the educational materials to be administered in a way that is participatory rather than weighted towards one partner, because participation increases both interest and knowledge retention. Especially where BMP implementation is concerned, it is more useful to provide hands-on learning scenarios than to simply convey the information through rote methods of memorization and repetition.

We recommend that SYJAC work to affect some type of teacher training workshop, so that a greater number of individuals may administer the lesson plans and activities, and can then share this information with their peers. The integration of this project's educational goals into authorized school curriculum was not previously attempted, but is encouraged in the future. It would be helpful to interweave these lessons into the existing mandated curriculum for school-age students. The materials may satisfy requirements for science, environmental studies, or health education.

Materials tailored to the construction and operation of BMPs were designed to provide a simplistic yet complete overview of each type of project. These documents should be used as a valuable reference for individuals or communities who wish to implement a pilot project. Contact information for the author(s) was included in case any questions or confusion arises in future implementations. Partners at SYJAC, especially Miguel Peate-Martinez, were also taught the principals for each BMP's design, so that they might serve as resources for residents of San Cristóbal.

### 8.3 Water Quality and Quantity Monitoring

Recommendations for the WQQM program are continuation of monthly monitoring, while trying to integrate further tests, monitoring sites, and temporal flexibility into the program. Additional tests, especially flow readings and dissolved oxygen, should be incorporated into monitoring at all sites. If possible, staff gauges should be installed at sites to improve ease of measuring flow. These utilize past measurements of cross section morphology, traditional flow measurements, and stage (or water height) on the staff gauge to create a rating curve (graph). With this graph, which will need to be periodically updated in the channel shape changes, the field worker can simply observe water height next to the staff gauge and record a flow measurement. This will save valuable time and encourage the sampler to take this measurement on a regular basis.

Once a longer data set for flow data is available, the WARMF model can be calibrated more accurately, and total flux of various water pollutants can be more closely determined. Determination of mass flux is significant when attempting to assess the various sources, transport mechanisms and fate of pollutants. This information will allow managers to more efficiently address problem areas in the watershed, and to understand where BMP implementation is most needed. Individuals at ECOSUR will be trained in the calibration and use of the model, so that they may use it in future management applications.

Temporal flexibility in monitoring is helpful in capturing the degree of fluctuation of various water quality parameters. With monthly monitoring occurring at different times each month, especially upon expected perturbation events, such as heavy rainstorms or forest clear-cutting, the program will gradually begin to show when the greatest magnitude of change from baseline water quality conditions is taking place. Then, management actions and regulation can be tailored to fit the processes of that particular watershed. This information might also provide valuable data and an impetus toward construction of some BMPs, such as retention basins or bioswales, which reduce pollutant loading in stormwater from specific sections of land.

It is understood that time, manpower, and financial resources limit the ability of ECOSUR's water laboratory to complete the aforementioned suggestions at this time. Throughout this project, UCSB has attempted to help ECOSUR build their capacity by donating some monitoring equipment and by providing technical assistance regarding its use. Continued capacity building at ECOSUR is desired. The laboratory partners are working toward this goal by undergoing a certification process which will allow them to provide water quality testing services to outside entities for a fee. Income generated through this type of work should be reinvested in the laboratory, to build capacity both in terms of manpower and equipment availability. It has been suggested to the group's other project partners, including SYJAC, that they take advantage of ECOSUR's facilities to meet their water testing needs, as this will provide both higher quality data and some income generation for ECOSUR. In essence, the capacities of the laboratory will benefit the city as a whole, and even minimal resources will be shared efficiently.

#### 8.4 Watershed Modeling

As mentioned above, the project anticipates that the work done to begin calibrating the WARMF model during this past year will become useful to partners in San Cristóbal in finding the best watershed management solutions to problems that arise in the future. Some training will take place during a June 2007 trip to Chiapas, and the project advisor from UCSB, Arturo Keller, will be reachable at the Bren School to provide additional technical assistance in Spanish. This model should be utilized to determine the benefits of introducing BMP technology or other structures, such as water treatment plants, within San Cristóbal. In some cases, targeted implementation of BMPs can eliminate the need for more costly water treatment or remediation techniques. Quantitative results from the

model can be used in a cost-benefit analysis to determine the validity of implementing such a project.

### 8.5 Reforestation

The reforestation campaign in San Cristóbal has achieved several accomplishments thus far through its education and planting activities. Continuing these educational and planting activities is vital to sustaining watershed health. This project's recommendations, some donated seeds, and the results of the geospatial analysis will be delivered to Alejandro Ruiz Guzmán in Spring 2007. He will use these suggestions when designing and planning the second reforestation campaign, set to begin in May 2007.

Where all other factors are held the same, including accessibility to the land, reforestation projects ought to target the areas identified as high priority in this project's multi-criteria model that incorporates distance to waterways, slope and soil type. This project also recommends adaptation of agroforestry and microfinance principals to the campaign, in order to improve the livelihood of those people who farm the higher slopes surrounding the city for subsistence. Agroforestry principals recommend approaching reforestation initiatives in two stages. First, fast-growing, income-generating trees should be planted. Next, tree species that will improve ecological diversity should be planted as well. These two steps correlate well with the goals of the reforestation campaign. Microfinancing orchards could also meet the dual goals of providing forest cover and improving quality of life for residents.

An additional source of funding that can be implemented while waiting for trees mature and become cash crops is the utilization of programs that provide payment for tree planting to offset carbon emissions. These types of programs have recently proliferated with increasing concern regarding climate change, and some organizations work with communities in the developing world to reforest areas that will help to sequester excess carbon. This path might be considered as an additional incentive for tree-planting in San Cristóbal.

This project recommends that BMP education and other sustainable forestry practices also be considered throughout the campaign. Introduction of best management practices to these low-income populations would improve water and soil resources sustainability, while improving crop yields and quality of life. Some educational materials have been provided to Alejandro to this end. In addition, the researchers have established a connection between the Washington D.C.-based nonprofit organization "Trees for the Future" and the campaign organizers, so that they might provide additional educational information, technical assistance, and larger-scale collaboration toward meeting the San Cristóbal project's goals. Information sharing across partner networks is a valuable tool to increase the potential and success of this program in and around San Cristóbal.

## **9.0 Follow up and Future Actions**

### **9.1 Future Project Implementation Actions**

As this project evolved, it became clear that some of the initial objectives were difficult to fully achieve within the allotted timeframe. The enthusiastic reception of the initial pilot projects, however, has paved the way for the implementation of future projects. Had the group been less successful at developing these programs and designs, there would most likely not be any demand for future projects. Yet the project was able to strengthen relationships with its partners and clients in order to obtain the necessary assistance that larger-scale implementation requires.

The immediate future of the project involves continuation of the education program. An outline of how the educational program will be continued can be found in section 9.2 below.

Another specific future action for this project is the construction of additional domestic rainwater harvesting systems and, potentially, a second EcoLavadero in Cinco de Marzo. The rainwater harvesting demonstration conducted in January generated interest from many community families in this type of water storage system. Furthermore, a single EcoLavadero is not designed to service a community the size of Cinco de Marzo. This single unit will likely only meet the clothes washing needs of approximately 100 families. Should adequate levels of use and improved water discharge quality prove the EcoLavadero a success, a second EcoLavadero may be constructed in a different part of the community so as to serve families living farther from the current EcoLavadero.

The main obstacle to wider project implementation at this time is funding. While all group members have expressed willingness to remain involved in the project, the project has yet to obtain a large amount of additional funding. The project does have \$3,000 committed for future projects, and it is likely that \$7,000-\$10,000 can be raised. This amount of money could potentially fund either the construction of 25-30 additional domestic rainwater harvesting systems, or a second EcoLavadero and 10-15 additional rainwater harvesting systems. There is no implementation prioritization order as of yet. Any program will require additional resource input on the part of the end users in terms of financial support, volunteer organization and labor, or both. It is understood that outside subsidies might be necessary to complete RWH projects until widespread interest is sufficient to persuade greater personal investments in these systems. No system, however, will simply be given to a family or a community; rather, they will be required to bear some of the system costs themselves. This personal investment serves to ensure that systems are built only for those people who will take responsibility for their maintenance, upkeep, and overall function.

In the late fall or early winter of 2007, project member Matthew Elke plans to return to San Cristóbal to begin further project implementation. With the assistance of the other project members, he will also continue to develop the water quality and quantity monitoring program with ECOSUR and observe the progression of the education

program. The project partners will continue to maintain a collaborative relationship with Professor Arturo Keller of the Donald Bren School.

Further assistance will be provided by Greg Hewlett an American expatriate who makes San Cristóbal his permanent home. He is interested in cleaning up the San Cristóbal watershed. Greg has supported the project by providing information about the surroundings of Cinco de Marzo when the group project members were in the United States. There is potential for Greg to stay involved by disseminating the BMP designs to other communities that may benefit.

In addition to Mr. Hewlett there is American couple, Stephen and Laura Zylstra, who have provided assistance to the project. They too have expressed an interest in keeping the project going after our time frame has ended. Stephen has a strong background in the sciences and Laura has experience in development work and acquiring financing for projects. The potential success of any future actions will be greatly enhanced by the involvement of these three people and having them take the lead on some of the project development.

Proper assessment of the functionality and performance of the domestic rainwater harvesting system and EcoLavadero must be performed prior to further BMP construction. Constructing additional water resource management projects would be irresponsible and a waste of resources if they do not perform as intended. Through post project assessment, it should be possible to identify design modifications to further improve the BMPs.

Monitoring the performance of the pilot projects requires assistance from ECOSUR. The relationship that has been forged between the group and ECOSUR over the duration of the project ensures that a proper evaluation of the performance of the pilot projects will be conducted. Between spring 2006 and fall 2007, the project will call on ECOSUR's professional laboratory technicians to test the quality of the water supplied by the domestic rainwater harvesting system in Cinco de Marzo, as well as that discharged from the EcoLavadero. With this data, help from SYJAC, and assistance from other contacts within Cinco de Marzo, any necessary modifications to the design can be made prior to Mr. Elke's arrival. This will allow him to focus his limited time on further project implementation.

The maintenance of relationships with the group's clients allows for the possibility of future work and collaboration. While additional rainwater harvesting systems and perhaps another EcoLavadero would have a tangible impact, these efforts must be accompanied by the continuation and successful implementation of a comprehensive educational program. The group feels strongly that the water and sanitation education plans created in partnership with SYJAC will help to reinforce the understanding, acceptance of, and commitment to BMP projects.

## 9.2 Education Follow-Up and Future Actions

In order to ensure an effective education campaign that successfully achieves the initial objectives set out by the group to both reveal to the community the impact of human actions on environmental and human health, and to initiate behavioral change that would lessen that impact, the implementation and evaluation process must be continuous and participatory. SYJAC will act as the primary facilitator for the education component of this project both in Cinco de Marzo as well as throughout the San Cristóbal basin. The NGO's frequent interaction with the communities allows them to better gauge the success of the current educational materials, and to more capably revise materials so that they reflect the most current attitudes and practices.

SYJAC will partake in monitoring of educational achievements via an ongoing analysis of the level of comprehension in the communities regarding understanding of environmental and human health. These periodic assessments will take place during teacher and community meetings, as well as via informal community-based assessment conversations. They will then allow SYJAC to update materials in order to improve their effectiveness. This evaluation process is on the formal side, but still aims to measure the true assimilation of the knowledge into the community.

Evaluations will be conducted by SYJAC at six month intervals and will rely on the use of a survey created by this group. The first follow-up survey will take place within six months of the initial campaign initiation date, or by August, 2007. Though the evaluation would ideally use the same assessment survey that measured the initial level of environment and human health knowledge, this project will instead use a questionnaire prepared by the group that was not used in the initial rounds of interviews (Appendix C.1). The group believes that the assessment must include questions that gauge knowledge of the environment-human health link in order to assess the effectiveness of the materials that were created and distributed to specifically address this linkage. Because the assessment survey that was conducted by SYJAC did not include these questions, and because the follow-up assessment aims to evaluate the success and utility of the materials used in this project, the project team prepared this second questionnaire for SYJAC to use in the future. It will help to reveal changing interests and needs among the communities.

## **10.0 Conclusion**

This Group Project, "Design and Implementation of Sustainable Water Resources Programs in San Cristóbal de las Casas, Mexico," recognized a problem with the water resources dynamics in the watershed of San Cristóbal de las Casas and set out to provide solutions. The issues that confront the residents of San Cristóbal affect both human health and the environment. The goals on which this the project focused targeted both of these problem areas. The methods employed in addressing these problems encompassed both practical applications, such as creating BMP design manuals and improving ECOSUR's



water monitoring program, and theoretical research aimed at informing management of the watershed, such as modeling drivers and outcomes in reforestation GIS and WARMF.

Given the wide scope of this project's goals and taking into account the short time frame to complete these goals, this project is considered successful by the project team. A recount of the project's accomplishments:

- Constructed general how-to manuals for each of the recommended Best Management Practices (BMPs) for adaptation across a range of environmental conditions and regions
- Implemented 3 pilot projects, all of which currently require ongoing maintenance and monitoring.
- Produced 8 detailed design manuals outlining the objectives, functions, construction steps, and materials costs necessary for building selected BMPs
- Implemented an EcoLavadero pilot project that utilizes BMPs for water capture and treatment
- Strengthened a long-term water quality and quantity monitoring program, with a particular emphasis on increasing the accuracy and simplicity of pathogen monitoring
- Created a program to educate community members on the effects of poor sanitation and contaminated drinking water, and the benefits of watershed protection, with materials in both English and Spanish
- Updated and calibrated the WARMF watershed computer model to better predict impacts on water quality of widespread BMP implementation, and to identify priority sub-watersheds for BMP implementation
- Updated the watershed map with monitoring locations for water quality and water quantity data collection
- Performed a multi-criteria GIS analysis to prioritize reforestation sites within the watershed that will promote protection of the water supply, and developed strategies for a successful reforestation program

While these accomplishments satisfy the initial goals of the project members, the temporal scale of this success is less certain. The true efficacy of these projects will not be known for some time, and depends upon whether these actions effect measurable changes in human health indicators and sustainability of water resources in the basin.

In order for this project to be sustainable and successful over the long term, a number of actions are necessary. Perhaps first among these is confirmation that the goals of the project are in line with the goals of project partners in Chiapas. The components of this project were developed under the assumption that they would tailor the project to the goals and needs of the project partners. The members of this project worked hard to ensure that this was the case, meeting with partners when in San Cristóbal, identifying the concerns of Cinco de Marzo, the target community, and continuing the communication with partners at SYJAC and ECOSUR via email and telephone conversations when in the United States.

In order for the BMP implementations to remain successful, the people of the *colonia* Cinco de Marzo will truly have to take ownership of the pilot projects. Without this pride of ownership, the implemented projects will become just another failed development project, laying idle and going to waste. Even if the pilot projects are used and maintained, however, the success of their implementation will be considered limited if they do not inspire further replication. As time passes, a successful project will include the use of these pilot implementations as models for other communities and will be implemented repeatedly.

The BMP design manuals were created to aid this proliferation. They are intended to be a living document, refined by the user groups as according to relative conditions, and as unforeseen lessons are learned and design obstacles overcome. The success of these publications will be determined by the status of the manuals over time. If the individuals or communities who use them do not take ownership and update them periodically, then the relevance of the manuals will diminish.

Also key to the success of the project and the success of the BMPs specifically, is the education program. After producing and distributing the education materials, they were transferred to partners at SYJAC, ECOSUR, and Alianza Cívica. It remains the responsibility of these organizations to work with local schools or to establish an independent education program. To judge the future success of this campaign, interested parties, such as SYJAC, will need to determine if there has been an improvement among the target population in understanding the link between human and environmental health. Such knowledge can be obtained with future surveys, the results of which can be used in a continuous feedback loop to inform which aspects of the education program should be improved.

Transfer of ownership of the components of this project to partners in San Cristóbal is a recurring theme, and is paramount to the success of the project. At the completion of the project, ownership of the WARMF model will be transferred to project partners at ECOSUR. Once ECOSUR takes ownership of the model, the expectation is that they will continue to improve it. Providing data for the model is one of the reasons for the existence of the water monitoring program. In order to improve the model and its predictions, ECOSUR will need to improve the current WQQM program and implement the water quantity recommendations of the program as well.

With more complete and long-term data the WARMF model will improve. With the improvement of the model, the relevance of policy recommendations based on its predictions will increase. The same need for data is true of the reforestation prioritization model as well as the strategies recommended. The model provides the project's partners with a rough look at how to prioritize different areas in the watershed, but it will require ground-truthing in order to determine whether the areas listed as high priority are truly in current danger and whether they are accessible for reforestation efforts. As the program progresses, partners will be able to evaluate the success of different recommended strategies. Further, it will take years to determine successful reforestation results as a measurable improvement to the groundwater infiltration rate in San Cristóbal's

watershed. Even if an improvement is shown, it will be difficult to isolate effects attributable to reforestation as opposed to the other contributing factors, such as above average precipitation years.

Moving forward, it will be up to project partners, the target communities, and the actions planned by this group as a whole, including Mr. Elke, to continue working toward the goals set out by this project. Development work is not easy, but the group has hope that the contribution made in the past year will aid in positive progress towards the achievement of long-term improvements in watershed and human health. Currently, no plans exist for a third group project from the Donald Bren School of Environmental Science and Management to follow-up the work accomplished over the past two years. Group members and their advisor, Dr. Keller, however, do intend to stay involved in the welfare of the watershed and its communities, as mentioned earlier.

The central focus of this project is not the UCSB research team, but rather the health of the people and ecosystem within the study area. The chief accomplishment of this project is the provision of additional tools that project partners can utilize as they continue to better the condition of both human and environmental health in the San Cristóbal de las Casas watershed in Chiapas, Mexico. In the short-term, this project is a success. Project members are confident that the work that this project accomplished produced a strong framework from which project partners can advance their work.

## 11.0 References

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## **12.0 Appendices**

### **Appendix A: Design Manuals and Pilot Projects – English**

- Appendix A.1: Rainwater Harvesting and Storage
- Appendix A.2: Composting Latrines
- Appendix A.3: Retention Basins
- Appendix A.4: Buffers/Bioswales
- Appendix A.5: Contour Trenches
- Appendix A.4: Blackwater Constructed Wetlands
- Appendix A.5: Greywater Treatment Constructed Wetlands
- Appendix A.6: EcoLavadero

### **Appendix B: Pilot Project Proposals – English**

- Appendix B.1: ECOSUR RWH
- Appendix B.2: Cinco de Marzo School Building RWH
- Appendix B.3: Blackwater Constructed Wetlands

### **Appendix C: Surveys**

- Appendix C.1: San Cristobal Education Questionnaire
- Appendix C.2: ECOSUR Survey
- Appendix C.3: Water Use Analysis (Alianza Civica, etc.)

### **Appendix D: Education Materials – English**

- Appendix D.1: Lesson Plans, Posters, Brochures
- Appendix D.2: Cartoons

### **Appendix E: WQQM Data**

- Appendix E.1: Testing Methods
- Appendix E.2: Surface Water Quality Data
- Appendix E.3: Spring and Well Water Quality Data

### **Appendix F: Reforestation**

- Appendix F.1: Raster Value Combinations
- Appendix F.2: Raster Calculation Possibilities

## Appendix A: Design Manuals and Pilot Projects – English

## Appendix B: Pilot Project Proposals – English

## Appendix C: Surveys

## Appendix D: Education Materials – English

## Appendix E: WQQM Data

## Appendix F: Reforestation