A Framework for Developing a Sustainable Watershed Management Plan for San Cristóbal de Las Casas, Chiapas, Mexico

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Donald Bren School of Environmental Science and Management
Master's Thesis

May 2006

UNIVERSITY OF CALIFORNIA
SANTA BARBARA

A Framework for Developing a Sustainable Watershed Management Plan for San Cristóbal de Las Casas, Chiapas, Mexico

A Group Project submitted in partial satisfaction of the requirements for the degree of Master of Environmental Science and Management for the Donald Bren School of Environmental Science & Management

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The Group Project is required of all students in the Master's of Environmental Science and Management (MESM) Program. It is a four-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Final Group Project Report is authored by MESM students and has been reviewed and approved by:

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May 2006

Abstract
San Cristóbal de Las Casas, located in the central highlands of Chiapas, Mexico, is a cultural and economic center of the region. The future of San Cristóbal's water resources are threatened by rapid population growth, land use change, potential over-extraction of groundwater resources, a lack of sanitation services and wastewater treatment, and the resulting degradation of surface and groundwater quality.

To address these concerns, the project took a watershed based approach to assessing the problems that face the city. The project collected physical, social, economic, and political information about the area in order to begin developing an integrated watershed management plan. Furthermore, the project built a partnership between research and community based institutions in San Cristóbal and the University of California-Santa Barbara, laying the foundation for future cooperative research initiatives. This partnership has provided the region's stakeholders with a review of best management practices (BMP), a surface water quality monitoring plan, an analysis of wastewater treatment options, and a watershed model through which different management alternatives can be evaluated.

The final recommendations to our partners include: 1) Implementation of the specially designed water quality monitoring plan; 2) Establish pilot BMP projects to determine their effectiveness and local cost; 3) Use preliminary design considerations to explore large scale wastewater treatment options; and 4) Implementation of a water resources educational campaign.

Acknowledgements
We would like to thank our faculty advisors Arturo Keller and Bob Wilkinson of the Bren School and Jordan Clark from the Department of Earth Sciences at UCSB for their guidance and feedback throughout this project. We extend a special thank you to UCMEXUS and ERM for providing funding, without which this project would not have been possible. We also give many thanks to our partners in San Cristóbal who provided us with a wealth of information about the region including Jesús Carmona, Juan Morales, and Duncan Goliche of ECOSUR; Alejandro Flamenco Sandoval, Diego Martin Diaz Bonifaz, and Emmanuel Valencia of LAIGE; and Sabás Cruz García, Hilda Guadalupe Macias Samano, and Jesús Miguel Peate Martineaz of SYJAC. Finally, we would like to acknowledge and thank Brice Loose for creating this project and facilitating what has become a lasting partnership between the Bren School and the project stakeholders in San Cristóbal de Las Casas.

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Executive Summary

The historic city of San Cristóbal de Las Casas, located in the central highlands of Chiapas, Mexico, is an important cultural and economic center, rich in Mayan tradition. The region is also one of the poorest in Mexico, trailing the nation in most quality of life and economic indicators. During the last two decades, the city has experienced rapid population growth as political upheaval and persecution have forced peasants living in the surrounding communities into the city center. As a result of the influx of refugees, the city's population expanded from 42,000 in 1980 to over 130,000 today. The city's rapid growth is expected to continue for the foreseeable future and most estimates project the city's population to double again by 2030.

This growth has placed the city's already insufficient infrastructure under increased pressure. Sewage infrastructure exists within the urban center of the city, but the infrastructure exists solely to convey waste out of the city's center. After the waste is conveyed out of the downtown area it is discharged untreated into the river system traversing the city. As the primary receptor of the city's untreated domestic sewage, the river leaving the city has become increasingly polluted and no longer meets national surface water quality standards. As a result, the municipality currently owes several million U.S. dollars to the Mexican National Water Commission and will continue to accrue fines as long as they remain out of compliance.

In addition to the city's poor surface water quality, population growth has also strained the region's water delivery network. Despite being one of the wettest regions in Mexico, many people within the watershed still lack reliable access to potable water. There is no water delivery infrastructure outside of the urban area of San Cristóbal, and the delivery network within the city experiences frequent service disruptions. Operators routinely turn off wells for fear that the regional groundwater supplies are being overtaxed. There is anecdotal evidence to suggest that these fears are not without merit.

At the present time the city has no unified vision or plan for how it will deal with the current challenges or the greater challenges that await it. The city recognizes this shortcoming and realizes that it needs a management plan that incorporates an understanding of both the environmental factors governing the watershed and the social needs of the communities living inside the watershed. To this end, This project formed a partnership between ECOSUR (El Colegio de la Frontera Sur), a graduate university located in San Cristóbal, SYJAC (Skolta'el Yu'un Jlumaltic, A.C.), a non-governmental organization principally concerned with improving the lives of people of the region, and the University of California, Santa Barbara to address these concerns.

This project does not attempt to solve all of the problems of the watershed or to deliver a unified plan for future management. Instead, the project seeks to provide the stakeholders with a framework for solving the problems and a toolset that will aid them in making informed decisions. To that aim, our deliverables to our partners in San Cristóbal include a watershed model, a water quality monitoring plan, a summary of best management practices (BMPs) to address the various concerns in the watershed, and a set of wastewater treatment options to be considered. A summary of each deliverable is provided below.

Watershed Model: To gain insight into local watershed processes and explore the potential impacts of various management scenarios, a watershed model (WARMF) was implemented. The limited set of existing data did not allow for calibration, but the model allowed us to integrate the available data to form a conceptual understanding of the hydrological processes within the watershed. The model allowed us to estimate surface water flow, as well as the movement of pollutants within the watershed. We were also able to simulate watershed response to a variety of management scenarios including population growth, BMP implementation, and the maintenance of the status-quo. We are delivering this model to our partners not as a finished product, but as a tool to be updated and utilized as additional data is collected or new management strategies are suggested.

Water Quality Monitoring Program: Although the surface water is known to be contaminated with urban and agricultural loads, no significant data has been collected to characterize the conditions. In order to fill this information gap, a surface water quality monitoring program was designed to provide a better understanding of the sources, amounts, movement, and fluxes of contaminants within the region. The monitoring program presents a protocol and methods for data collection and analysis, sampling locations organized by priority, suggested sampling frequency, and the estimated costs of resources needed to carry out the plan. This plan was designed to offer flexibility in implementation schedule given the potential timing and cost constraints of ECOSUR, who has committed to implementing the plan.

Review of Best Management Practices (BMP): This project explored alternatives to solving San Cristóbal's myriad of water related problems including stormwater runoff, soil erosion, nitrogen and phosphorus loading, sedimentation, surface water contamination, aquifer depletion, and shortages of drinking water. The criteria used to evaluate these strategies include their ability to address multiple concerns, potential pollutant load reductions, physical land requirements, and cost. To aid our partners in the future selection of management strategies, we suggest a methodology for evaluating each option based on situation specific feasibility and effectiveness criteria.

In addition to suggesting an evaluation framework, we also conducted an initial review and suggested the establishment of the following as pilot projects:

- rainwater capture and collection systems
- composting latrines
- retention basins
- contour water retention trenches
- buffer zones and bioswales
- educational campaigns

Wastewater Treatment Options: Given the size of the city, the water leaving San Cristóbal will not meet national standards without the implementation of a large scale treatment system. The treatment options considered in this analysis include a variety of lagoon systems, constructed wetlands, intermittent filtration systems, and conventional wastewater treatment plants. To help the municipality assess the feasibility of these options, we answered several important questions: 1) How much wastewater is produced; 2) What is the pollutant load of the wastewater; 3) What future population should be planned for; and 4) Where is the most suitable location for a treatment facility?

Evaluation of each treatment option considered was based on the amount of land required to accommodate the facility. The size required for the facility was estimated based on current and future pollutant load projections. The analysis also considered the feasibility of locating the facility both within and outside the watershed, given four additional characteristics: slope of the land, soil permeability, land availability, and length of required sewage infrastructure. Consideration of different placement possibilities led to consideration of five different treatment flow regimes. To determine the range of possible wastewater flows and pollutant loads requiring treatment, both high and low population growth scenarios were considered given a 25 year planning horizon.

Based on the preliminary analysis of treatment options, there are three options that warrant additional consideration. All three options minimize projected space requirements for the project, provide high levels of constituent removal, and are scaleable to deliver the necessary treatment capacity to serve the city's estimated future population. The three options are:

- Advanced integrated treatment lagoons
- Multi-pass intermittent filtration system
- Modular wastewater treatment plant

To maximize the benefit to the city of San Cristóbal, it is imperative that the sewage is conveyed directly to the treatment facility, and no longer discharged into the surface waters of the watershed. The analysis also suggests that the city's currently planned dual stormwater and wastewater sewage conveyance system may not be the most cost effective strategy from a treatment standpoint. Combining municipal wastewater with stormwater flow significantly increases the volume of water requiring treatment, leading to increased land requirements and higher treatment costs. We therefore recommend further consideration of separate wastewater and stormwater flow systems.

The deliverables outlined above are only the first step toward developing a watershed management plan that addresses all the concerns of San Cristóbal de Las Casas. We are handing these items over to our partners as the building blocks for the development of a framework. We are also providing our partners with recommendations for the critical next steps towards meeting their long term goals.

1) Implement the water quality monitoring plan. This cannot be stressed enough, without reliable data about the region, planning for the future is impossible.
2) Establish pilot BMP projects to determine local costs and effectiveness. Success of BMPs are historically site specific, thus it is important to determine how effective each practice is locally and how much each will cost to operate, prior to recommending larger scale implementation.
3) Use preliminary design considerations to further explore advanced treatment lagoons, intermittent filtration systems, or modular treatment plants to treat the city's wastewater. Cost of construction of non-traditional wastewater treatment systems are driven by land acquisition costs, thus our analysis focused on the amount of land required. Further analysis should focus on quantifying these costs for the proposed project sites and comparing them to the cost of a modular treatment plant.

4) Explore opportunities for a water resources educational campaign. There appears to be an opportunity to realize immediate environmental and human health benefits through the implementation of targeted educational campaigns. Likely focus areas include watershed processes, how human behavior affects these processes, and sanitation as it relates to water use and human health.

1.0 Introduction

1.1 Problem Statement

The colonial city of San Cristóbal de Las Casas, in the central highlands of Chiapas, Mexico, is the cultural and economic center for the indigenous Mayan population of southern Mexico. The region is also one of the poorest in Mexico, trailing the nation in most quality of life and economic indicators. Despite being one of the wettest regions in Mexico, it continues to rank below the national average in access to potable water and sanitation services.

Socio-political upheaval of the last two decades has brought many rural peasants into the city, more than doubling the population of the urban center. The current population estimation puts the urban center at 138,000 people. The city's population continues to grow at a rapid rate and is expected to double again by 2030. This explosion in population has placed the city's water supply infrastructure under increased pressure. The current infrastructure in San Cristóbal is insufficient to meet the basic needs of a large portion of the population. Further, there is anecdotal evidence that basin storage and recharge has diminished from historic levels and will continue to decline if proper management and planning strategies are not implemented to relieve the increased stress on the aquifer.

Sanitation services in San Cristóbal are in even greater disarray. While sewerage infrastructure exists to convey wastewater out of the urban center of the city, none of the waste is treated before being discharged into the surface water system. The surface waters of the region have become increasing polluted as the primary receptor of this untreated domestic sewage. Sewage input has increased in accordance with population growth and as a result, the water leaving San Cristóbal no longer meets the national surface water quality standards. As such, the municipality currently owes several million U.S. dollars to the Mexican National Water Commission and will continue to accrue fines as long as they remain out of compliance.

The future of San Cristóbal's water resources are threatened by population growth, changing land use, and a lack of sanitation and wastewater treatment. Unfortunately, there has been a shortage of data collection and research within the watershed to help frame a water management plan for the city. The city's plight is not unique; sustainable watershed management is a major issue for many communities, particularly in areas experiencing rapid population growth. This project has built a partnership between research and community based institutions in San Cristóbal and the University of California, Santa Barbara. The aim of this partnership is to provide our partners in San Cristóbal with scientific and economic information that will guide them in making informed decisions about the future of their watershed.

1.2 Project Approach

When we first embarked on our project, the goal was to create a watershed management plan for the city of San Cristóbal. It quickly became apparent that there was inadequate information to develop a comprehensive management plan. We also understood that many decisions could not be made by us as to how the water utility should manage the local water resources. Because of these limitations we decided not to search for a single solution, but to develop a set of possible solutions and tools for use by local decision makers. The final deliverables of the project provide information and suggestions for future action to the decision makers in San Cristóbal so that they can create and, ultimately implement, a comprehensive watershed management plan.

The basic approach to our project was to 1. Identify the problem, 2. Collect the available data and derive information, 3. Determine the management options, 4. Evaluate these options, and 5. Deliver management recommendations and a decision making framework to our partners (Figure 1.1).

Our preliminary problem identification methods relied heavily on local knowledge of poor water quality and of diminishing water supply from natural springs. From this we determined that we would need the following data in order to assess the extent of these problems:

- Climate: temperature, cloud cover, precipitation, and evapotranspiration
- Water quality: pH, biochemical oxygen demand, fecal coliform, nutrient concentrations (pesticides and fertilizers), and the major sources of these pollutants
- Water use: number and location of wells, pumping rates, and human consumption rates
- Spatial data: land cover, land use, geology, topography, and hydrology
- Demographic: population, projected population growth, and socio-economic and political conditions
- Mexican water quality standards
- Water supply and sanitation conditions, including the current water and wastewater conveyance network

Once we determined this target list of data, our next step was to determine what was readily available and what was not. For the most part, we were able to obtain at least a subset of the data that we wanted.

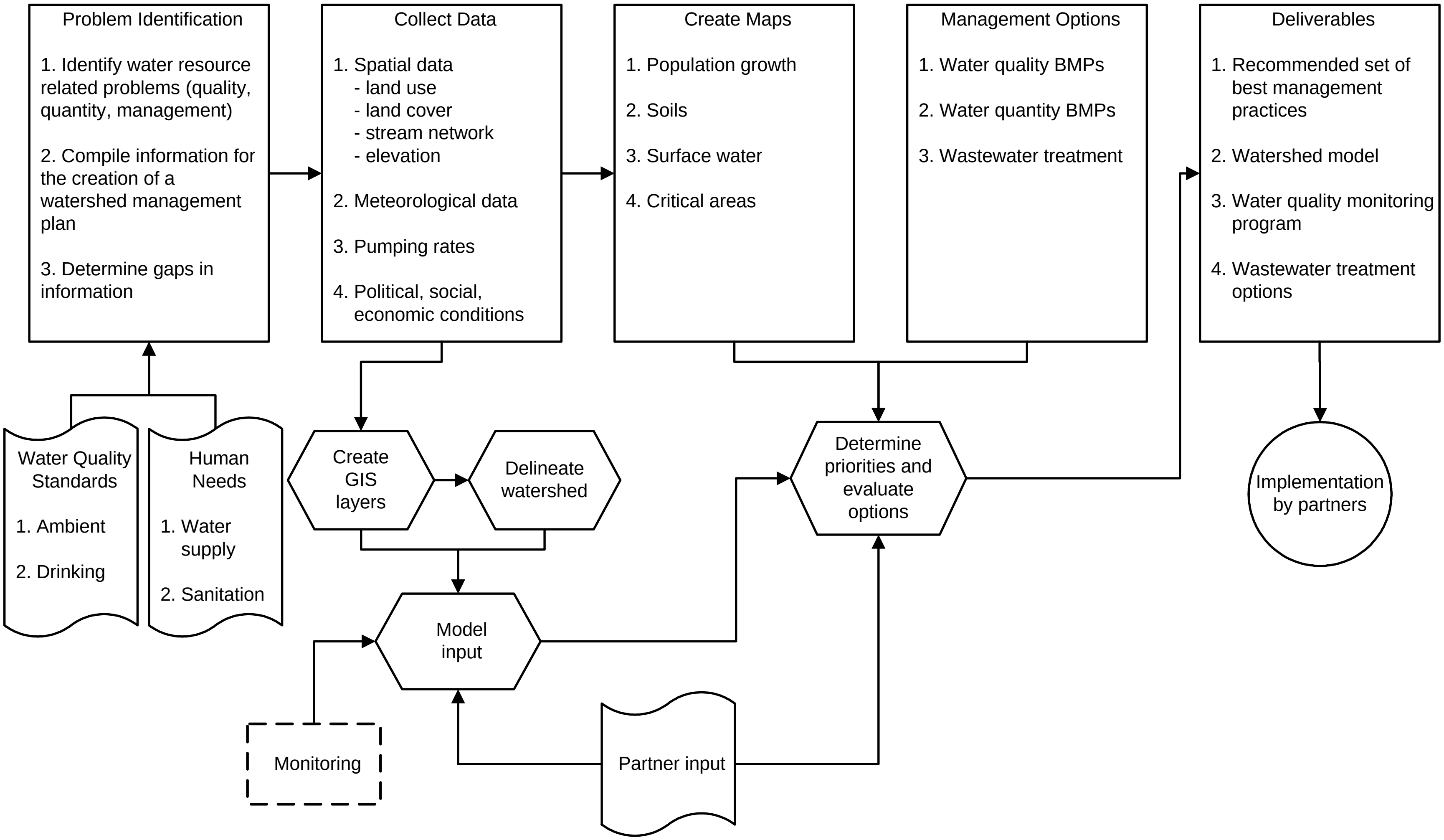
Using the data we were able to collect, the watershed was delineated (see Appendix 8.1) and data was input into a watershed model in order to gain a better understanding of the dynamics of the watershed (see Section 6.4). Setting up the model required making several assumptions about the characteristics of the watershed, such as soil parameters. This allowed us to move forward with our modeling and to make preliminary recommendations. In order to have an accurate understanding of the watershed, data to fill in the gaps will have to be collected. These gaps are addressed in the final step of our approach where we suggest a comprehensive monitoring program for our partners (see Section 6.1).

In order to gain an understanding of the water supply and sanitation problems that some citizens of San Cristóbal face every day, we conducted informal interviews (see Appendix 8.2) with citizens living in recent settlements. For the most part, these settlements are inhabited by people who moved to the area after 1994, due to religious and political turmoil. While the information we collected does not constitute a complete data set, the information indicated many of the human needs that need to be addressed with in a management plan for the area.

Management options were then compiled that addressed concerns within the watershed. To do this, we began by making a list of Best Management Practices (BMP) that could be applicable to the situation in San Cristóbal (Section 6.2). For each BMP, information on its purpose, construction, immediate and long-term costs, and local feasibility was collected (see Table 6.7

for a summary of this information). In addition to researching BMPs, we also explored a variety of wastewater treatment options to deal with the large amount of wastewater that requires treatment.

Figure 1.1. Project approach.



2.0 Partnerships and Collaboration

Building lasting partnerships and engaging in collaborative research is integral to the success of any watershed management plan. In 2004, several organizations recognized a common concern for sustainable water resource management in the city of San Cristóbal and its rural periphery. The organizations formed a partnership, the San Cristóbal Hydro-Resources Partnership (SHRP) with the collective goal of investigating the water cycle in San Cristóbal and developing a plan for sustainable use and urban growth within the basin. By combining the resources and capacities of the member institutions, the SHRP is well positioned to rigorously study the system, define the needs of the population, and affect policy change that is rooted upon a scientific understanding of the system and focused on the ideal of sustainability.

The participating entities include El Colegio de la Frontera Sur (ECOSUR), Skolta'el Yu'un Jlumaltic, A.C. (SYJAC), and a government-chartered citizen advisory board for the municipal water utility, Servicio de Agua Potable y Alcantarillado Municipal (SAPAM). ECOSUR is a publicly-chartered research institution providing research and post-graduate education focused primarily on the development and linkage of Mexico's southern-most states. ECOSUR maintains five campuses, including one in San Cristóbal. SYJAC is a nonprofit organization based in San Cristóbal, whose objective is to support community building and improved quality of life in the indigenous communities around the city. SYJAC regularly participates in sustainable works projects in indigenous communities, including potable water supply and sanitation improvements. The SAPAM advisory board is a citizen-staffed, citizen-elected board in charge of administrating the actions of SAPAM and ensuring public participation and consensus with the activities of the organization.

Our work has focused primarily on collecting information on the local water resources and characterizing the challenges that face the citizens of San Cristóbal. This effort was made possible through strong partnerships with various researchers at ECOSUR, including Jesús Carmona, Juan Morales, Duncan Goliche, Antonino García García, Edith Kauffer Michel, Alejandro Flamenco Sandoval, Emmanuel Valencia, and Diego Martín Díaz Bonifaz.

Jesus Carmona has served as a vital partner for our project because of his positions as a researcher at ECOSUR and as the vice-president of SHRP. He has provided us with local water resource information and with data on SAPAM's operations. He also brought together a group of researchers from various departments at ECOSUR that have provided us with additional information. Antonino García García's doctorate thesis provided us with information on the history of water resource management in San Cristóbal. The Laboratorio de Análisis de Información Geográfica y Estadística (LAIGE) provided us with maps of the watershed detailing elevation, land use, and land cover along with many other useful layers of GIS data. 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/.

SYJAC, specifically Sabás Cruz García and Hilda Guadalupe Macias Samano**,** have been integral in providing information on the socio-economic context of San Cristóbal. Through this organization we were able to set up informal interviews in the settlements surrounding the city, meet with doctors serving the local community, and learn about the social and political climate in

San Cristóbal. Jesus Miguel Peate Martineaz assisted the project by collecting water quality samples. For more information on the work of SYJAC, visit http://www.syjac.org.

In addition to our partners in Mexico, Jordan Clark, a hydrogeologist from the Geology Department at the University of California, Santa Barbara, has committed to doing research in San Cristóbal. Clark specializes in the use of artificial and naturally occurring tracers to quantify the dynamics of superficial and subterranean aqueous transport and will be able to use these and other techniques to help the researchers at ECOSUR understand the hydrogeologic dynamics of the watershed. During a trip to San Cristóbal in January 2006, Clark conducted preliminary research that will help him to determine the age of the water, its residence time, and the storage capacity of the system.

Finally, this project would not have come to fruition without the vision and impetus of Brice Loose. Loose first suggested the idea of a water project after spending time working in San Cristóbal and has been integral in fostering the relationship between our group and our partners in Mexico. He is also a co-founder of Waterscience Research Community (WRC), a nonprofit organization that aims to foster sharing of information and collaboration in water-related disciplines. There is a possibility that some of the research done for this project may be submitted to their database in the future. For more information on WRC, visit http://www.watersci.org/home.php.

The potential for future collaboration between partners is great. Undoubtedly, there will continue to be an exchange of information between the Donald Bren School of Environmental Science and Management and ECOSUR. The results of this project will act to set up a water quality monitoring program to be implemented by researchers at ECOSUR. We hope to train researchers from ECOSUR on the use of a watershed model and its applications for watershed management. In addition to information exchange and training, there is also a possibility for publishing a paper using San Cristóbal as a case study for watershed management.

3.0 Physical Description of the Watershed

3.1 Physical Features and Geographic Landforms

The state of Chiapas is located in the southernmost region of Mexico. The city of San Cristóbal de Las Casas is located in the central portion of Chiapas, approximately 50 kilometers east of the of the state's capital, Tuxtla Gutiérrez (Figure 3.1).

Figure 3.1. San Cristóbal de Las Casas is located in southern Mexico, approximately 50 kilometers from Tuxtla Gutiérrez, the state capital of Chiapas (Source data: ESRI 2004, see Appendix 8.4).

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 valley walls rise steeply from the valley floor, quickly reaching elevations of 2,500 meters to the south and west. The valley walls rise slightly more gradually to the northwest and east, but reach approximately the same elevation. The elevation in the far northern extent of the watershed reaches the highest elevation within the watershed, at approximately 2,800 meters (Figure 3.2).

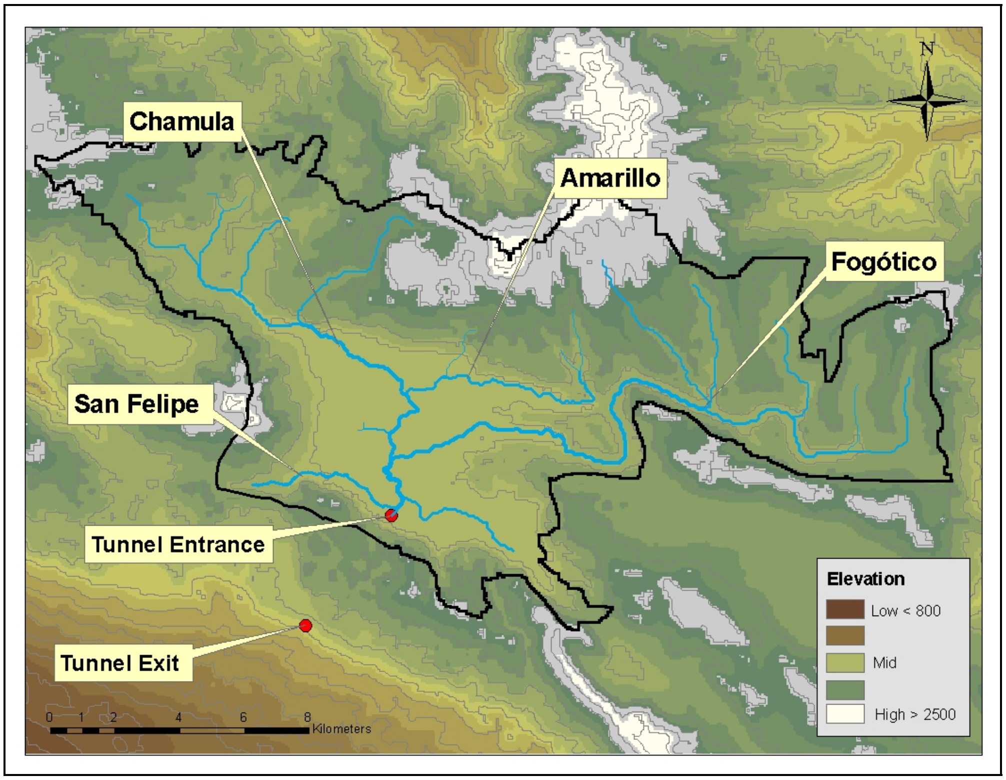


Figure 3.2. The elevation of the watershed ranges from its lowest point at 2,180 meters to its highest point at approximately 2,800 meters (Data source: ECOSUR, see Appendix 8.4).

The watershed includes portions of four different municipalities (Figure 3.3), but is primarily located in two. The southern portion of the basin is in the municipality of San Cristóbal de Las Casas, while the northern part is located in Chamula. A small section in the eastern extent of the watershed is located in Huixtan, and an even smaller section to the northwest is located in Tenejapa.

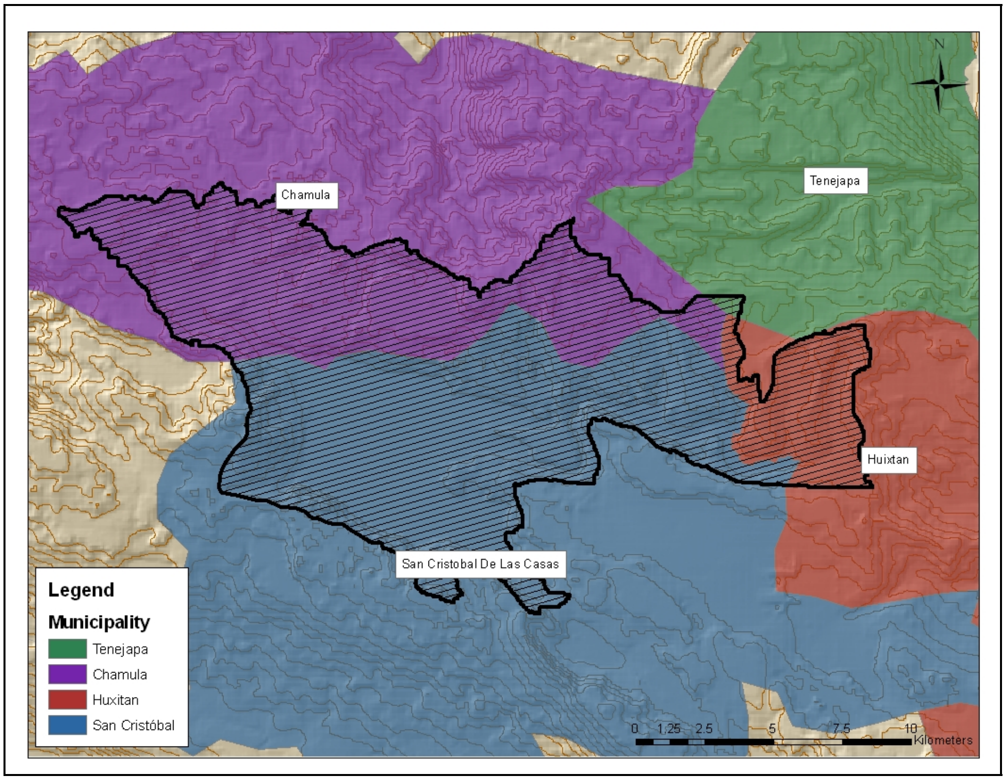


Figure 3.3. The portions of the San Cristóbal watershed that lie within the municipalities of San Cristóbal de Las Casas, Chamula, Tenejapa, and Huixtan (Source data: ESRI 2004 and ECOSUR, see Appendix 8.4).

Soils

Topsoil in the central region varies significantly by location within the watershed. The central low-lying areas are dominated by gleysols and feozems which, compared to the surrounding areas have a higher hydraulic conductivity. The northwestern portion is predominately a luvisol and the northeastern portion is predominately a fine grained acrisol with lower hydraulic conductivity (Figure 3.4). The depth of topsoils within the watershed is highly variable, dependent on location and slope. The central flat region has thicker soil, with the soil depth decreasing as slope increases to the extent that on many hills in the valley, the underlying rock formations are exposed. Soil depth is easily observed at a number of locations throughout the watershed where roadways were cut into the valley hillside.

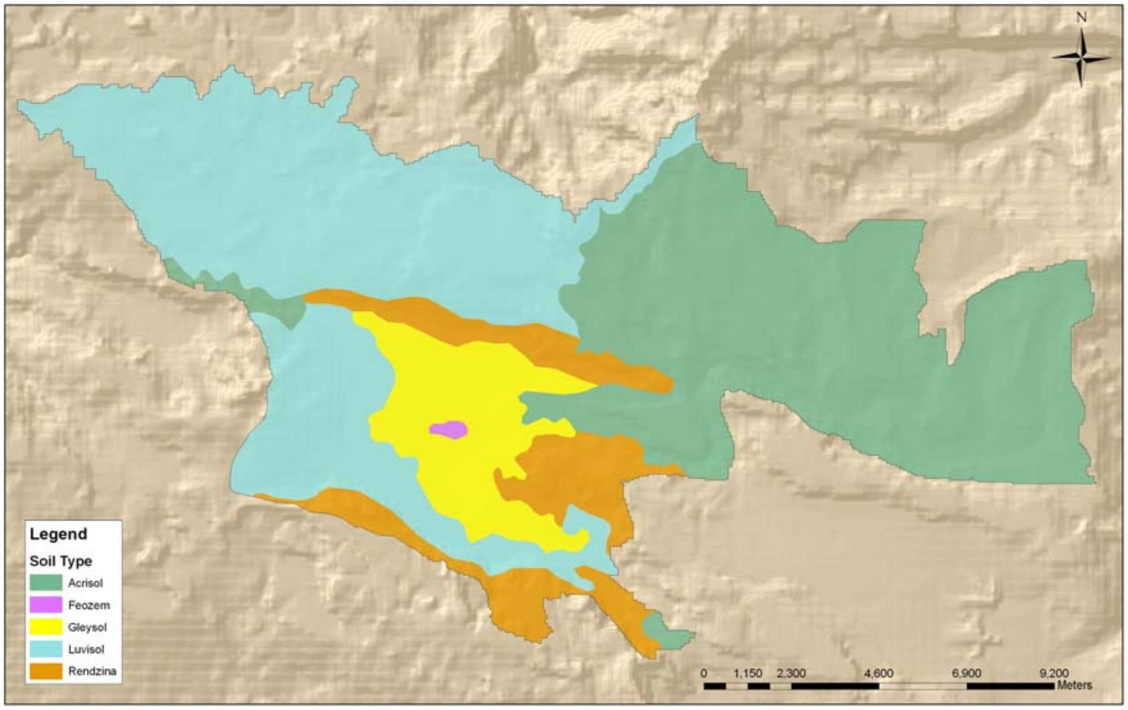


Figure 3.4. Predominant soil types of the San Cristóbal basin (Source data: ECOSUR, see Appendix 8.4).

Regional Geology

The state of Chiapas is located on the Mayan block on the southern portion of the North American Plate, near the triple intersection of the North American, Cocos, and Caribbean plates. The Cocos plate is currently moving in an easterly direction with respect to the other two plates, and is being subducted beneath the North American and Caribbean plates. The North American plate is currently moving in a northwesterly direction with respect to the Caribbean plate, establishing a fault system. Most large volcanic events in southern Mexico are associated with the subduction of the Cocos plate underneath the North American plate (Sedlock, *et al.* 1993), (Nencetti, *et al.* 2005).

During the Cretaceous Period, from 144 to 65 million years ago, most of Chiapas was covered by an ocean. Marine sedimentation from this period is present throughout much of the state. The shallow sea withdrew from the region (in an easterly direction) during the late cretaceous or early tertiary period, approximately at the same time that uplift in the area began (Ferrusquia-Villafranca 1993). The marine sedimentation led to the formation of the Sierra Madres de Chiapas Limestone platform (Morán Zenteno 1994). The region's geology is further complicated by the extensive folding of Mesozoic and Tertiary sedimentary rock layers into a "Northern folded Ranges and Plateaus" region (Ferrusquia-Villafranca 1993); (Nencetti, *et al.* 2005). The folds and plateaus of the region, including the mesetas de San Cristóbal, trend in a northeast-southeast direction (Ferrusquia-Villafranca 1993). The direction of the folds can be traced to three sinistral faults; the Mortagua, the Polochic and the Jocotan-Chamelecon at the boundary of the Caribbean and North American plates (Sedlock, *et al.* 1993).

San Cristóbal de Las Casas
San Cristóbal is situated in an alluvial valley, on the Chicoasen-Cristóbal anticline, northeast of the Sierra Madres de Chiapas and southwest of the gulf coastal plain of Tabasco (Chubb 1959). The karst topography present in the tertiary limestone of the Chiapas highlands is present in the area surrounding San Cristóbal, and can be seen in the natural tunnel that originally drained the watershed (Chubb 1959). Karst topography is primarily comprised of calcium carbonate and characterized by fractures that create a positive feedback, allowing more water to circulate and intensifying the karstification.

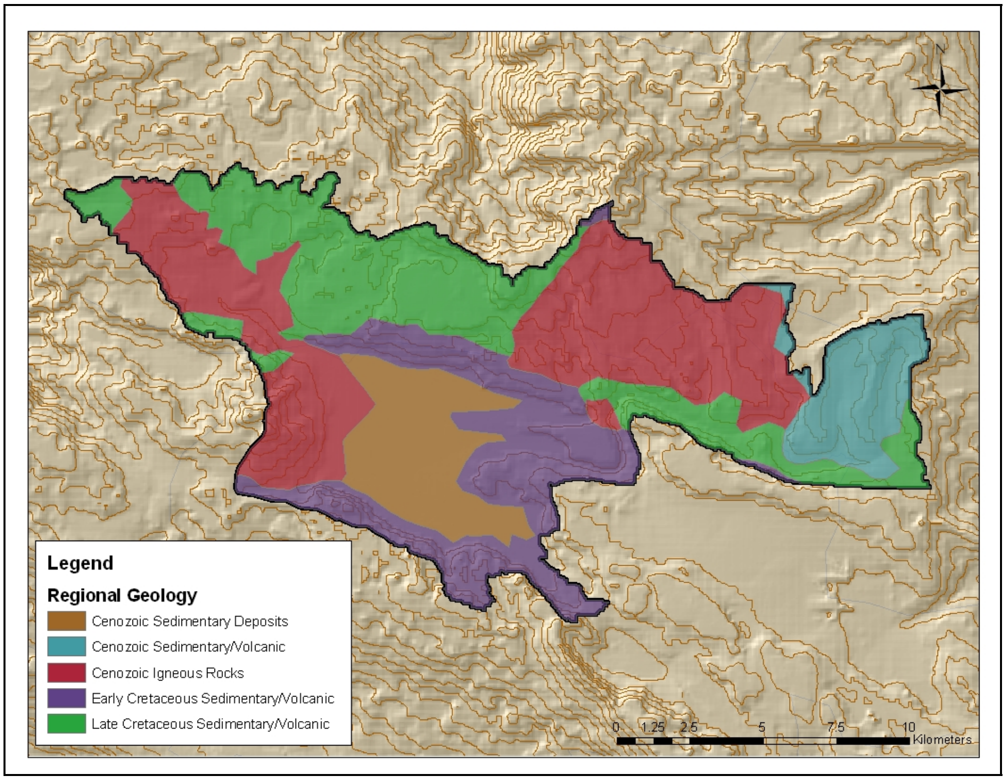


Figure 3.5. Major geologic features of the watershed (Data source: ECOSUR, see Appendix 8.4).

The subsurface stratification of the area can be broadly divided into four distinct units (Fuentes, *et al.* 2003). The depth and thickness of each of the units is highly variable based on location within the watershed (Table 3.1).

Table 3.1. Geologic layers in San Cristóbal (adopted from (Fuentes, *et al.* 2003).

Unit	Depth found (m)	Description
1	0-3	Topsoil. Primarily sand and gravel. Thickness varies from 2-3 meters.
2	3-20	Muddy Clay deposits. Thickness varies from 12-20 meters
3	20-60	Sedimentary limestone deposits, with potential origin in the Sierra Madre de Chiapas group. Thickness varies from 15-40 meters.
4	60+	Volcanic deposits, especially prevalent in the northern portion of the valley.

3.2 Basin Hydrology

In 1998, the Mexican National Water Commission, Comisión Nacional de Agua (CNA), split the country into 13 administrative water regions (I – XIII). These regions were drawn based on hydrologic boundaries, rather than the traditional means of using state borders, thus promoting a more natural means of managing the country's water resources (Comisión Nacional del Agua 2003). San Cristóbal is located within region XI, or the Frontera Sur. The Frontera Sur region consists of the states of Chiapas and Tabasco, as well as portions of the states of Oaxaca and Campeche. Hydrologic data reported for the Frontera Sur region is used in our analysis where specific data is not available for San Cristóbal itself.

3.2.1 Climate

Mexico's National Meteorological Service, Servicio Meteorológico Nacional (SMN), has set up a series of monitoring stations throughout the country to gauge daily temperature, precipitation, wind speed, and other climatologic factors. Average climatic conditions for a 20 year period from 1981 to 2000 were determined using data from the stations located in San Cristóbal.

Temperature

San Cristóbal's climate is characteristic of a mountainous subtropical rainforest, with an annual mean maximum temperature of 23 ºC (73 ºF). Throughout the year, the average monthly maximum fluctuates between 20 and 25 ºC (71 and 77 ºF) and average monthly minimum temperatures range between 3 and 11 ºC (37 and 52 ºF) (Figure 3.6).

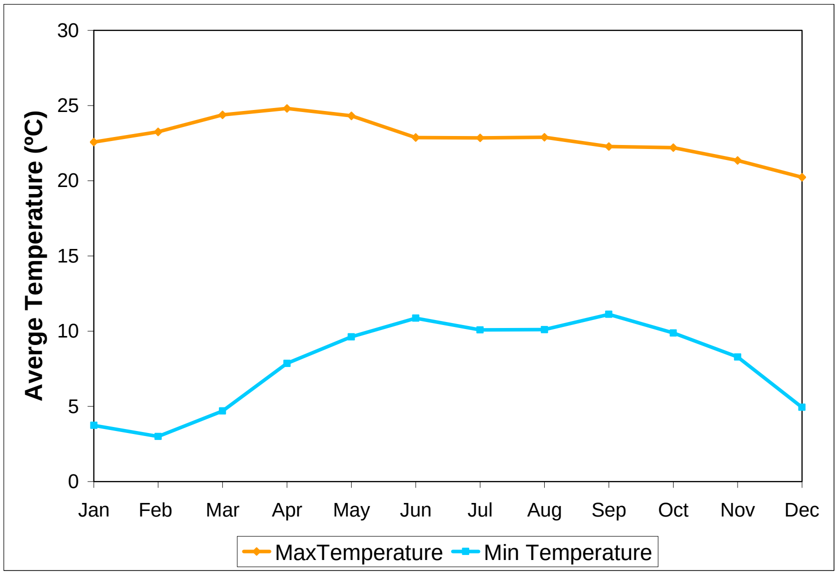


Figure 3.6. Mean monthly maximum and minimum temperatures in San Cristóbal from 1981 to 2000 (Servicio Meteorológico Nacional de México 2003).

Precipitation

While the Frontera Sur hydrologic region is by far the wettest in Mexico, receiving 2,260 millimeters of precipitation per year, San Cristóbal, located in the drier central highlands, only received an average yearly total of 1,109 millimeters from 1981 to 2000 (Figure 3.7). The annual distribution of precipitation is quite variable, with the majority of precipitation falling between the months of June and October (Figure 3.8).

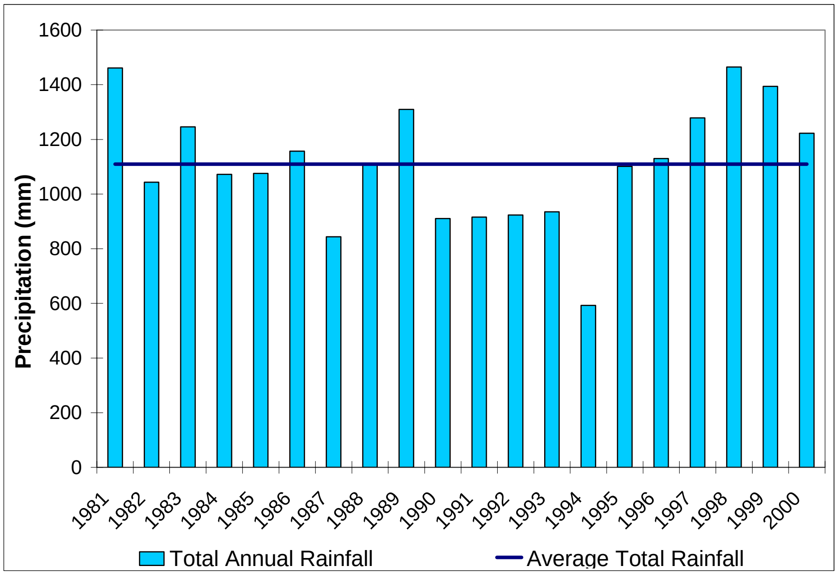


Figure 3.7. Total and average annual precipitation in San Cristóbal from 1981 to 2000 (Servicio Meteorológico Nacional de México 2003).

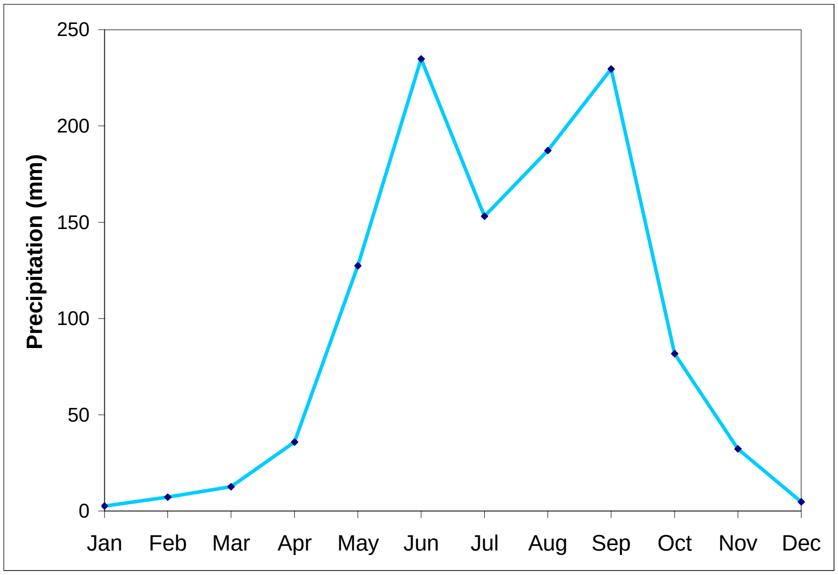


Figure 3.8. Mean monthly precipitation in San Cristóbal from 1981 to 2000 (Servicio Meteorológico Nacional de México 2003).

3.2.2 Watershed Sub-Basins

The watershed can be split into four main sub-basins based on drainage patterns, each of which we named after the surface water system that drains it. The four sub-basins are: the Chamula (5,955 hectares), the Amarillo (2,866 hectares), the Fogótico (1,690 hectares), and the Sumidero (4,167 hectares). The Chamula, Amarillo, and Fogótico are all headwater basins, with the area of each basin draining into its respective river before they all come together in the Sumidero Basin, which is the lowest point and outlet of the watershed (Figure 3.9).

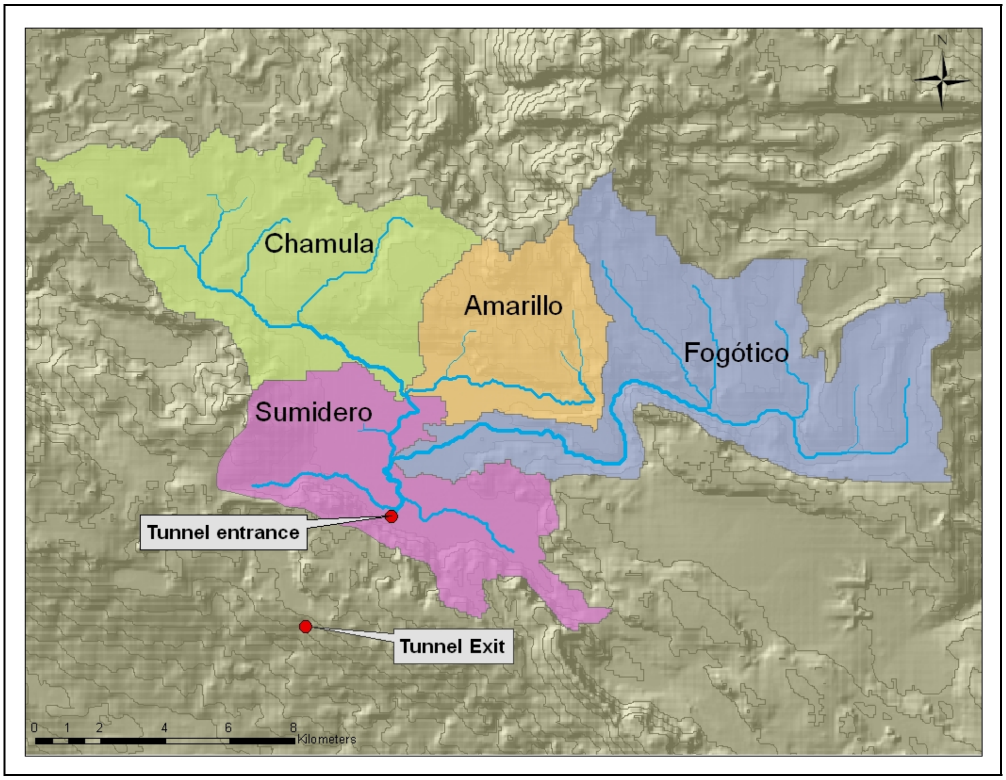


Figure 3.9. The four sub-basins of the San Cristóbal watershed (Data source: ECOSUR, see Appendix 8.4).

The two largest surface water systems in the watershed are the Río Fogótico and the Río Amarillo. The Río Fogótico is the largest, originating in the northeastern section of the watershed. It travels approximately 22 kilometers until it reaches its confluence with the Río Amarillo. The Río Amarillo originates in the northern portion of the watershed and is about 12 kilometers in length.

Though it is much smaller, the Arroyo Chamula is of notable importance because it is suspected to contribute a large amount of pollutants to the river system due to upstream agricultural practices. Historically, these streams were used for small hydroelectric generation projects via the construction of small dams or channels (Velázquez-Velázquez and Schmitter-Soto 2004), (García García 2005). These three systems, as well as a number of other smaller tributaries and streams, converge in the lowest section of the watershed where they flow south and out of the watershed through an outlet tunnel.

Historically, water flowed out of the watershed through a series of natural geologic features at the base of the southern mountains. Frequent flooding caused by slow drainage of the original outlet during the rainy season became a nuisance as the urban population grew. Finally in 1973 a large storm blocked the natural outlet and flooded the city. To address this problem the city built a tunnel, 6 kilometers in length, through the southern mountains of the watershed, allowing rapid drainage of the landscape. This tunnel, known locally as the 'sumidero' is now the watershed outlet. Pictures of the natural and constructed outlets are displayed in Picture 3.1.

Picture 3.1. The image on the left is the natural outlet of the watershed as it looks today. This outlet has been blocked off and the river diverted from its natural path to the constructed tunnel about 25 meters away. Water now drains directly to the tunnel, shown in the image on the right.

3.2.3 Hydrogeology

During the dry season, little to no rain falls within the watershed, and stream flow is driven by groundwater input. The amount of input is a function of the subsurface storage capacity of the watershed. Schlumberger electrical resistance field tests conducted by Alta Tecnologia en Pozos (ATP) described three hydro-geologic units in San Cristóbal. The units are differentiated by lithologic characteristics, structure, porosity, and permeability that affect capacity for water infiltration, storage, and transmission to the subterranean water. The first unit is comprised of permeable clastic deposits of sand and pebbles, with a variable thickness of 15 to 175 meters located below the valley floor of the watershed. The second unit, in the hills and mountains of the southern valley, is made up of fractured calcium and limestone. The third unit is made up of volcanic materials at depths of 30 to 70 meters and is located in the northern portion of the valley (Fuentes, *et al.* 2003).

3.3 Land Use and Land Use Change

3.3.1 Land Cover Types

Urban landscape, forested areas, agriculture, and pasture lands comprise the dominate land cover types in the San Cristóbal watershed. The land within the watershed has supported a variety of functions for many years. Typical land uses range from traditional small-scale agricultural practices, to cattle ranching, urban landscape, and industrial uses. It is critical to understand the impacts that different land uses have on the dynamics of the water resources within the watershed. Specifically, evaluating the impacts of these land cover types helps to explain various effects such as surface water quality, increased stormwater runoff, nutrient loading, and groundwater contamination.

Overall, the combination of croplands, pastures, and cleared non-vegetated fields comprises roughly 30% of the land area in the watershed. When the 11% of urban landscape is accounted for, over 40% of the land in the watershed functions for direct human use. The total area of each land use type and percentage of total land within the watershed are quantified in Table 3.2.

Table 3.2. Land use classification of the San Cristóbal watershed (Data source: ECOSUR, see Appendix 8.4).

Land Use	Area (hectares)	Percent of total area
Urban	2,241	11%
Cropland	3,132	16%
Pasture/Grasslands	2,704	13.5%
Cleared or Non-vegetated fields	242	1%
Pine and Oak Forest	2,299	12%
Primary Forest	3,621	18%
Scrubland	965	5%
Secondary Forest	4,485	22%
Water/Wetlands	22	<1%
Other	297	2%
Total Area	20,007	100%

The land use classifications of the San Cristóbal watershed presented in Table 3.2 are graphically depicted in Figure 3.10. The central southern portion of the watershed is dominated by the urban and sub-urban landscapes. Though wetlands are still present near the urban area, they have been significantly reduced and now represent only a small percentage of the landscape. Surrounding much of the urban area, scrublands persist on lands that have been used intermittently for livestock production and agriculture or have been abandoned. Throughout the watershed, beyond the urban limits, a large percentage of cropland is present. Primary forests and pine and oak forest classifications comprise nearly 30% of the land use as shown in Table 3.2.

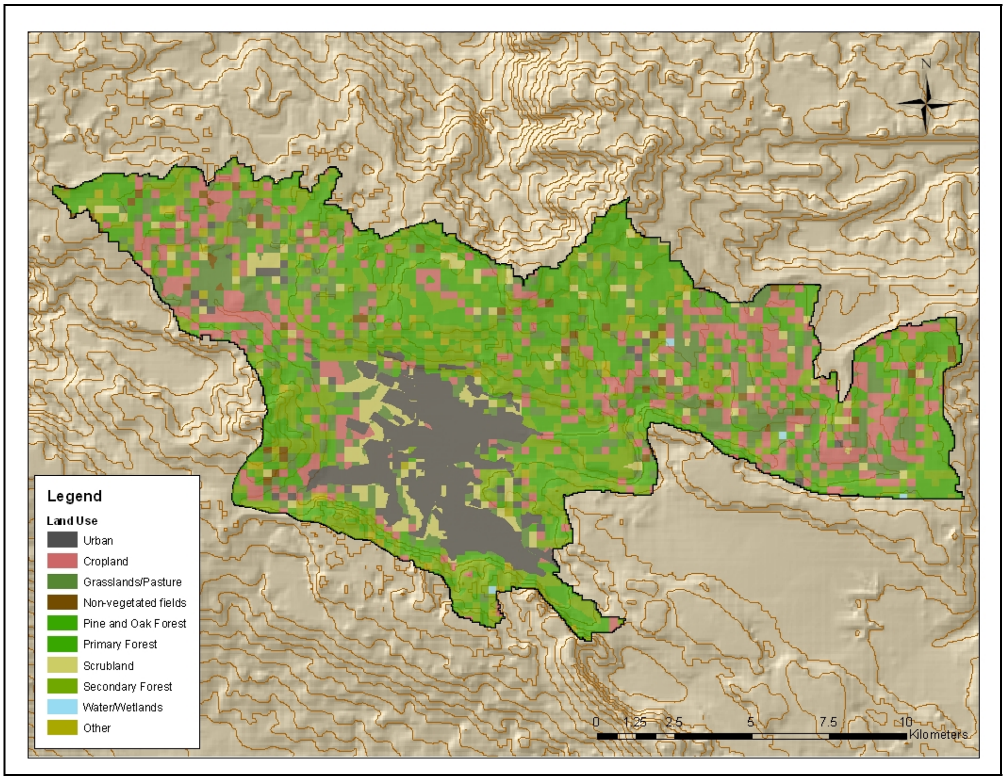


Figure 3.10. Land use classification within the San Cristóbal watershed (Data source: ECOSUR and Zermologio 2005, see Appendix 8.4).

3.3.2 Urban Growth

In an area confined by mountains, the watershed has predominately been consumed by urban sprawl. Prior to the 1950s, seasonal flooding augmented a small intermittent lake in the lowlands of the San Cristóbal valley. Lake María Eugenia (Picture 3.2) covered an area of approximately 5 to 6 hectares. In order to open new fields for agriculture, cattle ranching, and residential growth, the lake was drained in the mid-1950s (Velázquez-Velázquez and Schmitter-Soto 2004).

Picture 3.2. Lake María Eugenia, circa 1950 (Velázquez-Velázquez and Schmitter-Soto 2004).

This mix of ranching and agriculture persisted until population growth and demand for space on the flat valley floor limited these practices to the outskirts of the urban periphery. However, flood risks persisted (Picture 3.3) until construction of the tunnel occurred in 1975. The completion of the outlet tunnel further facilitated the urban expansion of San Cristóbal as it decreased the risk of seasonal flooding and allowed for an additional 600 hectares of land on the valley floor to be used for residential development (García García 2005).

Picture 3.3. Flooding in San Cristóbal, circa 1932 (García García 2005).

Though urban growth in the San Cristóbal valley is ultimately limited by the surrounding mountains, smaller communities have sprung up along hillsides and other marginalized land areas outside of the main urban zone. Figure 3.11 details the historic growth of the urban center of San Cristóbal. A large portion of the urban growth has taken place over the last 15 years due to the volatile socio-political situation throughout Chiapas (see Section 4 for a discussion of these factors).

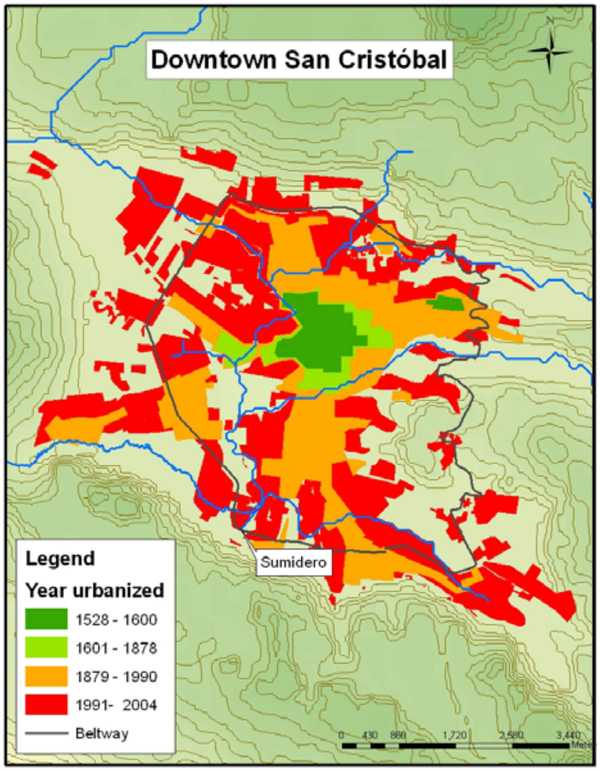


Figure 3.11. Urban expansion of San Cristóbal de Las Casas, 1528-2004 (Data source: ECOSUR, see Appendix 8.4).

3.3.3 Wetlands

Historically, wetlands covered much of the low-lying areas in the southern area of the San Cristóbal watershed. The wetlands served as a natural filtering system for surface runoff. Before draining into the groundwater via the cavernous karst features, much of the water was filtered through these wetlands. Today, urban expansion has consumed much of the wetlands. Scattered wetlands still exist near the natural outlet tunnel, though communities are rapidly encroaching on their boundaries (Picture 3.4). The remaining wetland area is insufficient to treat the large pollutant loads from the growing San Cristóbal population.

Picture 3.4. Wetlands (area outlined in blue) around confluence of the Río Fogótico and the Río Amarillo (Data source: ECOSUR, see Appendix 8.4).

3.3.4 Agricultural and Grazing Land

Though urban sprawl has replaced croplands and pastures on the valley floor over the last 10 to 15 years, small-scale agriculture still persists throughout the watershed. Additionally, forest clearing for agriculture and wood resources takes place outside the urban periphery.

Subsistence farming has long been an important way of life within the watershed. The majority of cropland consists of mixed cornfields, legume, and coffee productions. Additionally, pasture lands comprise a significant percentage of the landscape. Though cattle grazing declined between 1980 and 2000, the total amount of land dedicated to the grazing of cattle, sheep, and pigs has risen (Ochoa-Ganoa 2001).

3.3.5 Forest Cover

Forest cover, ranging from primary and secondary forests to mixed pine and oak forests comprises about 52% of the landscape (see Table 3.2). However, it is important to note that as a result of agriculture and wood harvesting, much of these forests suffer from fragmentation. Fragmented forests, as well as secondary forests, have reduced capacity for providing ecosystem services. The percentage of existing forests, both in San Cristóbal and Chiapas as a whole, has been in a steady decline since the 1950s. Forest reductions directly correlate with increases in land used for agricultural or pastoral production. Once fields are abandoned, grasslands are dominant as secondary forests slowly begin to regenerate (Howard and Homer-Dixon 1996). In addition, logging for firewood and other wood resources has contributed to deforestation and forest fragmentation.

3.3.6 Effects of Land Use Change

There has been little attention paid to land use change indicators such as soil erosion, deforestation, and water contamination from both the urban and rural populations (Reyes-Ramos, *et al.* 1998). The movement of peasants around Chiapas, clearing land and planting as they move, increases the rate of land degradation. Though land use effects are a result of various factors, population growth has been the underlying driver of change.

As a result of urban growth, the fraction of remaining wetland areas comprises only 0.1% of the land in the watershed (see Table 3.2). Increased pollutant levels from urban expansion and population growth in combination with a reduction in the size of wetlands, has severely compromised the ability of these wetlands to act as a filter for both urban and rural water runoff.

The spread of populations onto marginalized land and an increase in the intensity of subsistence agriculture has contributed to soil erosion and stormwater management problems. Increased livestock production and forest clearing in recent decades is indicative of immigration into and around the San Cristóbal watershed region. More generally, although agriculture in Chiapas still supports a large population, it is characterized as seasonal and lacking in technical resources. The region has suffered from reduced agriculture production as a direct result of the mismanagement of natural resources (Reyes-Ramos, *et al.* 1998). The scarcity of cropland has resulted from an increased demand, combined with a decrease in available land resources. More land has been exploited to meet the needs of both the growing urban and rural populations, thus pushing people onto increasingly physically marginal areas.

Soil erosion and stormwater runoff have been further augmented by the increase in livestock grazing on steep slopes characterized by thinner, more fragile soils. The combined effects of agriculture and livestock production increase nitrogen and phosphorus loading and sedimentation in surface water runoff, decreases the water infiltration capacity, and generally increases rates of water lost to surface runoff.

Expanding populations have contributed to deforestation and forest fragmentation throughout the watershed. The effectiveness of forests in terms of providing ecosystem services such as water infiltration, soil stability, pollutant filtering, and providing habitat, has been severely compromised by the conversion of these areas to secondary forests and croplands. Widespread forest alteration in the watershed has contributed to increased stormwater runoff and decreased potential for aquifer recharge. Although there is evidence of forest regeneration in areas where agricultural fields or pastures have been abandoned, there is a strong trend toward more fragmented and secondary forests (De Jong, *et al.* 1999).

3.4 Fish and Wildlife Resources

Chiapas sits at the northern edge of Conservation International’s Mesoamerican Hotspot, one of 34 world Biodiversity Hotspots chosen because of high species richness, endemism, and threat status. The state of Chiapas has protected 980 hectares, or 13.31% of its total area, in 14 protected areas (Conservation International 2006). San Cristóbal also lies within two World Wildlife Fund Ecoregions, the Central American pine-oak forests and the Chiapas montane forest. Between them, these two ecoregions provide habitat for 925 terrestrial vertebrate species, and 368 of these live in San Cristóbal (Municipio de San Cristóbal 2004). San Cristóbal is home to five species of birds which are found only in Mesoamerica (Municipio de San Cristóbal 2004), and at least two endangered species found only in the watershed: the San Cristóbal Shrew, *Sorex stizodon* (World Wildlife Fund 2006) and the San Cristóbal pupfish, *Profundulus hildebrandi* (Velázquez-Velázquez and Schmitter-Soto 2004).

According to Velázquez-Velázquez and Schmitter-Soto (2004), the San Cristóbal pupfish is severely threatened by degradation and destruction of its habitat, as well as by the introduction of another species, the largemouth bass (*Micropterus salmoides*). The pollution of 60% of the pupfish's habitat with raw sewage is cited as a particular concern to the species' survival. The pupfish's habitat is also important because the species can only survive in alpine wetlands which are rare and understudied in Mexico. This ecosystem is threatened by urban growth and its impacts. In order to conserve the pupfish, an improvement in the water quality in San Cristóbal and the conservation of the alpine wetland habitat, which includes the structure and biota of rivers and catchments, is necessary (Velázquez-Velázquez and Schmitter-Soto 2004).

4.0 Social Context

Along with the physical aspects of the watershed, it is important to understand the social context in which this project is embedded. San Cristóbal has lower socio-economic indicators than the national average, but higher indicators than the rest of the state of Chiapas (Table 4.1). These numbers provide a general idea of the level and effects of poverty in San Cristóbal.

Table 4.1. Socio-economic indicators in San Cristóbal compared to state and national averages (CONAPO 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 dollars	5,073	3,302	7,495
Index of infant survival[1]	0.848	0.790	0.839
Index of human development[2]	0.752	0.693	0.791

In this section, a brief history of San Cristóbal as it relates to water management is provided, along with a discussion on the recent population growth and its implications, the economic situation in the city, and how the current water management is affecting the city's health and economy.

4.1 Political and Social Climate

4.1.1 Historical Context

The city of San Cristóbal de Las Casas was founded by the Spanish in 1528. Since this time, the city has had long tradition as the cultural and economic center for a large indigenous population (Van den Berghe 1994). Under Spanish rule, Chiapas was part of the colonial kingdom of Guatemala and the city enjoyed relative prosperity during the colonial period (Van den Berghe 1994). Since the nineteenth century, however, the central highlands of Chiapas trailed behind the rest of Mexico in development and most economic and quality of life indicators (CONAPO 2000; Van den Berghe 1994).

In the second half of the twentieth century, Mexico experienced cycles of prosperity and crisis as the nation encouraged private business investment. These cycles were unevenly felt: Chiapas felt the prosperity less and the crisis more. President Carlos Salinas, who served between 1989 and 1993, attempted to change this trend by moving US$500 million dollars into Chiapas through the national antipoverty program, "Solidarity" (Womack Jr. 1999).

San Cristóbal has a history of the indigenous population revolting against exploitation by the ruling elite. The city's namesake, the Bishop Bartolomé de Las Casas, began the struggle against exploitation of the indigenous population in 1545 (Womack Jr. 1999). Since this time, Chiapas has experienced dozens of revolts "which were incited principally due to poverty and excessive exploitation" (Gossen 1996).

[1] Based on the probability of survival during the first year of life.
[2] Based on life expectancy, education, and GDP per capita.

While Mexico was debating joining NAFTA, and the end to price supports for corn and beans that it would bring, San Cristóbal held a celebration in 1992 to mark the 500th anniversary of Columbus' "discovery" of the Americas. Nine thousand indigenous people from the surrounding region protested against NAFTA and "500 years of robbery, death, and destruction of the Indian people" by staging a day-long demonstration in the city (Womack Jr. 1999). Unjust treatment of Indians is also cited as a causal factor in the Zapatista Rebellion, which began on January 1, 1994, the same day that NAFTA came into effect (Womack Jr. 1999). The social conflict associated with the rebellion of 1994 continues into the present time and has caused many people to immigrate from the rural areas into the urban area of San Cristóbal. These trends are discussed in more detail in Section 4.1.3.

4.1.2 Water Management and Institutions

Water management in San Cristóbal also has a history of conflict. Conflicts exist between domestic, agricultural, and industrial users of water. As the groundwater which supplies the artesian wells became scarce, many citizens believe that the volume of water extracted by The Coca-Cola Company is responsible (García García 2005). However, these wells are responsible for around 2% of the groundwater extracted by drinking water pumps in the city (see Section 5.1.1).

In addition, there is conflict between citizens and the government over appropriate governance of water resources. Citizen protests in 1994, 1995 and 2003 followed the 1992 revision of the national water laws, which allowed more private investment in the water sector and facilitated the process of suppliers charging users for water consumption. In 2003, the citizens were protesting the proposed privatization of the municipal water utility, SAPAM (García García 2005).

Water management in Mexico is the responsibility of the federal government. Management of water resources is carried out by the National Water Commission, Comisión Nacional de Agua (CNA), and several smaller organizations:

- National Water Commission (CNA): CNA is an agency of the Ministry of the Environment and Natural Resources, created in 1989 by Article 4 of the National Waters Law. The mission of the CNA is "To manage and preserve national waters with the participation of society, in order to achieve the sustainable use of this resource." CNA divides Mexico into Hydrological-Administrative Regions, and these are broken into hydrologic regions according to watershed boundaries (San Cristóbal is in the Grijalva-Usumacinta Region within the Southern Border Administrative Region) (Comisión Nacional del Agua 2004).
- River Basin Councils: These councils were formed to coordinate the efforts of federal, state, and municipal entities involved in "water management, developing hydraulic infrastructure and related services, and preserving the river basin's resources." The Grijalva-Usumacinta River Basin Council was formed in 2000 (Comisión Nacional del Agua 2004).

In addition, auxiliary organizations such as River Basin Committees and Technical Groundwater Committees can by formed within the River Basin Councils, but none have been created in the San Cristóbal region (Comisión Nacional del Agua 2004).

In order to utilize national water resources, users must obtain a concession or allotment from CNA and in order to discharge wastewater, users must obtain a permit. Permits, concessions, and allotments are recorded in the Public Registry of Water Rights (REPDA). All water quality monitoring is conducted by the National Water Quality Monitoring Network (Comisión Nacional del Agua 2004).

CNA's funding comes from the collection of fees and fines, contributions for improvements, and usufruct (77%); complementary fiscal resources (21%); and foreign loans (2%). The budget is spent on drinking water and sanitation (40%), hydro-agricultural infrastructure (32%), and water management and regulation (28%). Nationwide, investments in drinking water, sewerage, and sanitation declined significantly from 1991 to 2002 (Figure 4.1) (Comisión Nacional del Agua 2004). The most significant decrease occurred in the mid-nineties, with fairly constant investments since then.

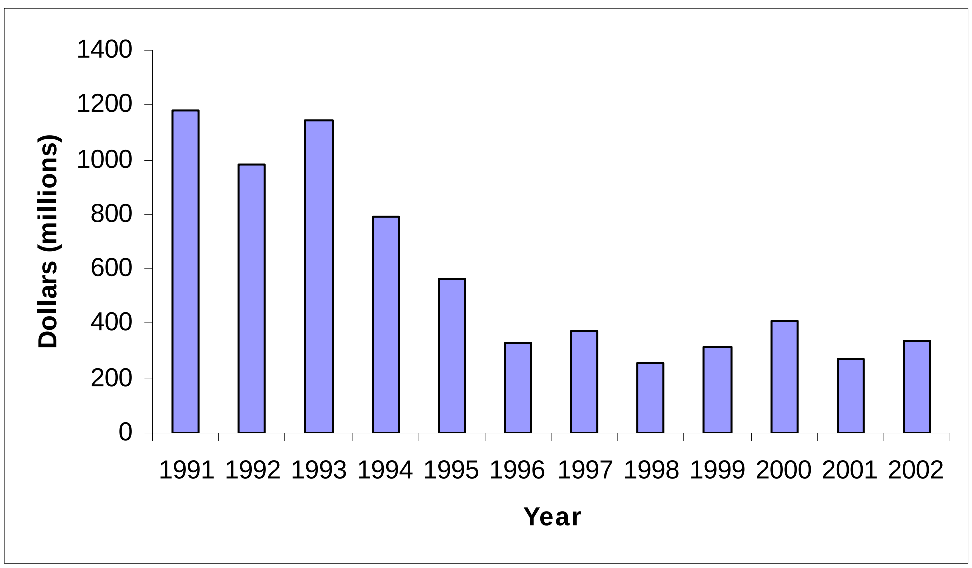


Figure 4.1. Investments in drinking water, sewerage and sanitation 1991 – 2002, in millions of dollars at 2003 constant price[3] (Comisión Nacional del Agua 2004).

The budget for CNA between 1995 and 2003 is not increasing at a sufficient rate to keep up with the increases in population over the same time period (Figure 4.2).

[3] Figures 4.1 and 4.2 use the conversion of 1 peso = 0.0897 dollars (April 8, 2006).

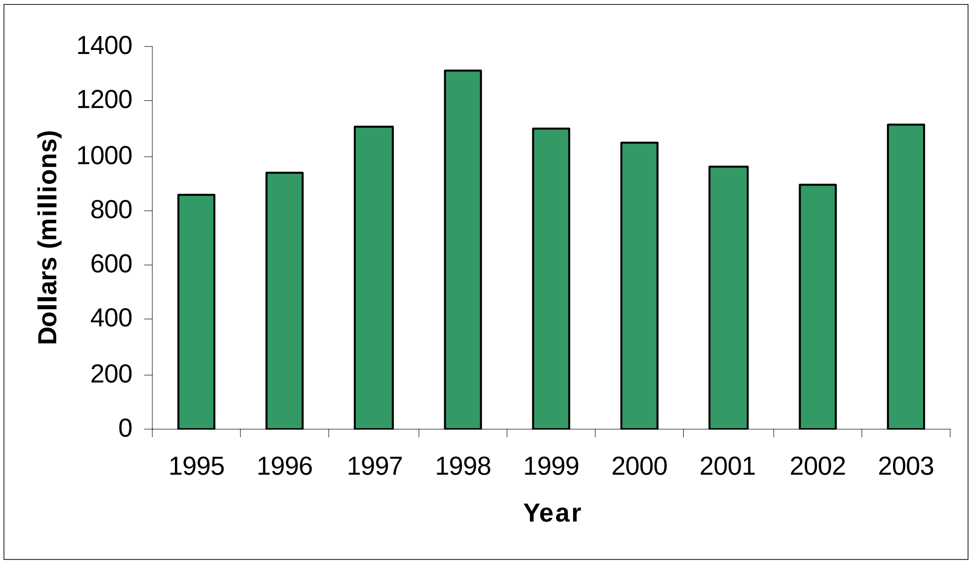


Figure 4.2. National Water Commission budget 1995 – 2003, in millions of dollars at 2003 constant prices (Comisión Nacional del Agua 2004).

4.1.3 Water Management, 1993-2005

Even with the investments discussed above, and with annual rainfall well above the national average, many people in the watershed surrounding the urban area of San Cristóbal lack access to basic water and sanitation services. The problem is exacerbated in San Cristóbal by recent rapid population growth occurring in the city (García García 2005).

The Municipal Potable Water and Sewerage Service, Servicio de Agua Potable y Alcantarillado Municipal (SAPAM), has struggled since its creation in 1991 to meet the water supply needs of the citizens. In 1993, before the Zapatista rebellion, 93% of families supplied by SAPAM paid for their water services. Between 1994 and 1995, however, the collection of fees for water fell by 70%. In the next decade, SAPAM patched leaks in pipes and maintained pumping equipment, but did not build any new infrastructure. This static period ended in 2004 when SAPAM, with money from the federal government, drilled a deep well to serve the northern part of the city (García García 2005).

During the period from 1995-2000, when the population of the city was growing rapidly and SAPAM was not building new infrastructure, CNA (funded by the Inter-American Development Bank) built thirteen water supply systems for rural communities. These projects allowed their users to be autonomous both from the municipality and from SAPAM (García García 2005).

4.1.4 Recent Population Growth

These problems of water management are exacerbated by rapid population growth in the city. During the colonial period and through the first half of the twentieth century, San Cristóbal grew slowly. Starting in the 1970s, however, the city experienced rapid population growth (Figure 4.3). This growth was driven primarily by local immigration of indigenous people from the rural countryside surrounding San Cristóbal (Van den Berghe 1994).

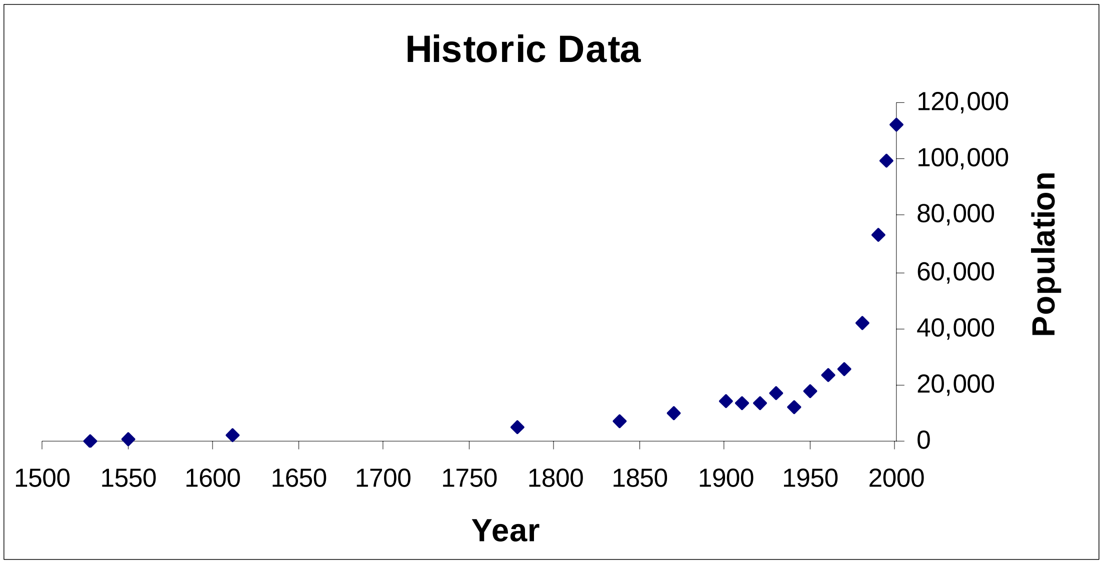


Figure 4.3. Historic population data from the city's founding in 1528 until 2000.

San Cristóbal's 2005 estimated population is 138,000 in the urban center, with the population of the rural communities estimated at 32,000[4]. Approximately 81% of the 170,000 people in the watershed live within the urban area of San Cristóbal.

Several factors contributed to the dramatic influx of people into San Cristóbal. First, villagers are frequently expelled from their villages after converting to a religion different from the rest of the community. Many villages are centered on one church, so conversion to another religion is often met with fierce opposition and persecution by the community. This widespread problem has led to many people moving into the outskirts of San Cristóbal (Kovic 2005).

Second, between 1974 and 1976, the government constructed a cement tunnel to replace the natural water outlet for the city, as discussed in Section 3. With the construction of a cement tunnel to replace the natural tunnel, the city no longer experienced frequent floods. As a consequence, six hundred hectares of land became developable and was built upon soon thereafter (García García 2005).

Third, land scarcity drove many people from rural communities into the city. Most of the rural population in the watershed was once able to support itself with subsistence farming, but increasing population density led to insufficient availability of grazing and agricultural land. Some farmers turned to cash crops, and others left the land for the cities (Van den Berghe 1994), (Womack Jr. 1999). Many of these migrants chose to settle in San Cristóbal because the city has functioned for centuries as a center for economical, commercial, administrative, cultural, health-related, and educational activities (Municipio de San Cristóbal 2004). The city's profitable tourism industry may also draw migrants to the urban area for economic reasons.

[4] This number was generated using a constant growth rate equation to interpolate between the 2000 census (from INEGI) and the 2017 projection estimate from ECOSUR. We used the same methods to estimate the population of the rural communities in the municipality. This method assumes that the city center and the rural areas of the municipality are growing at the same rate. While this will give us a rough estimate of the rural population, it is probable that the rural population is growing at a slower rate, and that our estimate is high.

4.2 Economic Base

Chiapas is one of the poorest states in Mexico despite its apparent wealth in industrial and agricultural resources, particularly oil, hydropower, and coffee. San Cristóbal, however, is not as poor as other areas of the state. The two primary reasons for San Cristóbal's relative wealth are that city functions as a trade and transportation hub of the central highlands and the development of a successful tourism industry in the city (Van den Berghe 1994). The following section describes the city's economy in more detail.

San Cristóbal has functioned as a regional trade center for its entire history. The produce market, for example, is a daily meeting place for vendors and customers from surrounding towns. The market has increased in size along with the city's population; as of 1994, the produce market covered 8-10 hectares, and presumably it has grown since this time (Van den Berghe 1994).

Picture 4.1. The colonial buildings of downtown San Cristóbal are one reason that tourists visit the city.

Few jobs are created by San Cristóbal's small industry sector; instead, the city depends largely on the tourist industry for jobs. The city has actively encouraged its tourism industry with policies such as building codes and preserving the traditional colonial architecture (Van den Berghe 1994). Between 1996 and 2001, approximately 313,000 tourists visited the city each year, with an average stay of one week (García García 2005). The tourism industry creates both formal and informal employment in hotels, restaurants, shops, travel agencies, the "street economy," and rural jobs. The street economy involves hundreds of people, most of whom are from Chamula, a town located in the western portion of the watershed, and provides a source of income via activities such as hawking, shoe-shining, and begging. The rural segment of the industry involves thousands of women, who produce textiles and pottery for sale in the San Cristóbal tourist market. In 1994, an estimated minimum of 1,500 people made their living from tourism activities (Van den Berghe 1994), and the number has probably increased in the past 12 years.

Picture 4.2. Many women sell textiles and other crafts on the streets of San Cristóbal.

4.3 Effects of Inadequate Water Supply and Sanitation

Inadequate water supply and sanitation influences a population by causing health problems (with their associated costs) and via socio-economic effects.

4.3.1 Health Impacts of Inadequate Water and Sanitation

Poor water quality and inadequate supply create a suite of problems which debilitate individuals and families with illness, consume scant economic resources, and trap people in poverty. Worldwide, 4.0% of all deaths and 5.7% of the total disease burden is caused by water-related illnesses (Prüss, *et al.* 2002).

There are four categories of water-related diseases: fecal-oral diseases, water-washed diseases, water-based diseases and water-related insect vector (UN-HABITAT 2003). Interviews with community members and health care professionals have not indicated major problems with diseases in the water-based category (including guinea worm, schistosomiasis) or water-related insect vector category (including malaria). The following section, therefore, considers only fecal-oral diseases and water-washed diseases. Incidence and causes of hepatitis were not considered.

Fecal-oral disease: These illnesses, primarily diarrhea, occur when fecal matter enters the mouth. This can occur when water sources are contaminated with fecal matter or when improper hygiene brings fecal matter into direct contact with the mouth or with food. These are the most common types of water-related illnesses and are among the most widespread of all illnesses in affected communities worldwide. These diseases also account for most of the water-related infant and child deaths worldwide (UN-HABITAT 2003).

Water-washed disease: These diseases, including skin and eye infections, occur when people do not have adequate water for washing (UN-HABITAT 2003). Lack of water for hygiene purposes can also cause respiratory infections (WHO and UNICEF 2005).

4.3.2 Costs of Illness

In addition to causing discomfort and unhappiness, these illnesses are a significant economic burden on families and on society. Some of the costs that can accrue during an illness include lost productive days, fees from healthcare practitioners, transportation costs to visit a healthcare facility, and the costs of medications (WHO and UNICEF 2005).

Flores, *et al* studied the effects of inadequately prescribing of drugs in San Cristóbal and Tuxtla Gutierrez. They found that costs associated with an episode of diarrheal illness can cost approximately US$86[5], or the equivalent to 28 days of work at minimum wage. Medications (prescribed by doctors, drug vendors, and other health care workers, or self-prescribed) can account for up to 50% of the health-care expenditures for poor households. In San Cristóbal and Tuxtla Gutierrez, a survey found that 73% of people purchasing medications do so without a prescription. The cost of common medications ranges from US$2.53 to $6.65 (Flores, *et al.* 2003).

Inadequate treatment of diarrhea is a problem in San Cristóbal and Tuxtla Gutierrez. Standard treatment norms in Mexico for diarrhea recommend oral rehydration therapy (ORT) for all cases of diarrhea, and recommend antibiotics only in cases when blood is present in the stool. Although less than 10% of cases of diarrhea have blood in the stool, ORT is only recommended by doctors and drug vendors in 0-2% of cases, while antibiotics are recommended in 31-53% of cases and antiparasitics are recommended in 31-38% of cases. Inadequate treatment most frequently comes from traditional healers and pharmacy drug sellers (Flores, *et al.* 2003).

Cost Benefit Analysis of Improving Water and Sanitation Services

Estimating the costs and benefits of providing water and sanitation services is a complex task. While many factors which determine the costs and benefits are location-specific, it is possible to make some regional generalizations. Hutton and Haller performed a comprehensive evaluation of these costs and benefits, which has been published by the World Health Organization (Hutton and Haller 2004). Using their per capita estimates for the epidemiological sub-region which includes Mexico, we analyzed the potential costs and benefits of providing water and sanitation in San Cristóbal (Table 4.2).

In the scenario presented in Table 4.2, we assumed that 40,000 people do not have access to adequate water and sanitation in the San Cristóbal watershed. This number is based on SAPAM's estimate that 123,00 people are connected to their water supply infrastructure (SAPAM 2002). For this scenario, we calculated the benefits if all 40,000 people were provided with access to improved water supply and improved sanitation. We then calculated the costs of providing regulated piped water supply and sewage connection to all citizens, including basic treatment of sewage. Detailed definitions for improved services are in Appendix 8.3.

[5] This figure is based on direct costs, such as consultation fees, hospital fees, drugs, supplies, tests and transportation, as well as the time costs. This case is an example and should not be extrapolated to the entire population.

Table 4.2. Costs and benefits of providing water and sanitation services to citizens without the described services in the San Cristóbal watershed. Estimates are based on Hutton and Haller (2004).

	San Cristobal	**Economic Costs**	**Economic Benefits**
Total population	170,000		
Annual number of diarrhea cases averted	17,000		
Total cost of interventions		$3,774,000	
Annual health sector treatment costs saved			$326,400
Annual patient treatment costs saved			$ 8,964
Value of productive days gained			$32,976
Value of school days and baby days gained			$666,874
Value of averted deaths (predicted future earnings)			$33,616
Annual value of time savings			$5,077,269
Total economic costs and benefits		$3,774,000	$6,146,252
Benefit/Cost	1.63		
Net Benefit			$2,372,252

This scenario results in a positive benefit cost ratio: it would yield about $1.63 for every dollar invested. The costs of providing potable water and adequate sanitation are balanced by the savings to the health sector and the time savings of individuals. This analysis is a conservative estimate of the benefits of providing water and sanitation in San Cristóbal; it assumes the highest costs and the lowest benefits.

An analysis for other scenarios, such as providing improved services to only half of the population, or providing potable water piped into every house, is presented in Appendix 8.3.

4.3.3 Socio-economic Effects of Inadequate Water and Sanitation

Along with the health impacts of inadequate supply of water and sanitation, these problems also reinforce inequality and poverty (UN-HABITAT 2003). In San Cristóbal, the inconsistency of water supply to many communities is a significant inconvenience. Many other problems related to inadequate water and sanitation have been identified as common throughout the globe (UN-HABITAT 2003), but no data on these problems specific to San Cristóbal exist. The following problems should be considered in future studies:

- Time spent fetching and carrying water. This chore could take significant time and effort, especially in rural areas of the watershed.
- Indignity caused by people having to defecate in the open.
- Sexual harassment of women and girls who have to defecate in the open.
- Reluctance of children and women to visit public toilets after dark due to safety concerns.
- Stress caused by conflict among community members over scarce water resources.
- Disproportionate burden of inadequate provision of water and sanitation on women and girls, because they are generally responsible for providing water and disposing of waste.

4.4 Future Population Growth

Many of the problems of inadequate water and sanitation are caused or aggravated by the rapid population growth of the past 35 years. San Cristóbal will face increasing challenges as its population continues to grow.

Future projections of population growth until 2030 are based on estimates by the Development Plan of the city of San Cristóbal (Municipio de San Cristóbal 2004)and ECOSUR[6] (García García 2005). Given these two estimates, it is likely that the population of the city of San Cristóbal will be between 230,000 and 375,000 in the year 2030 (Figure 4.4). Using the same methods, we estimate the total population in the entire watershed by 2030 to be between 284,000 and 463,000 people.

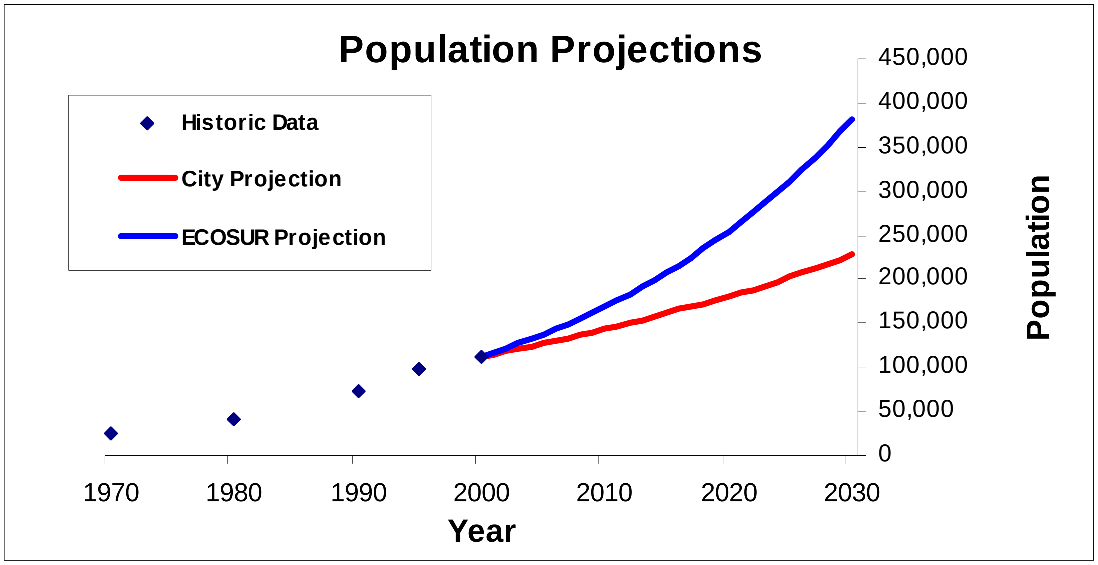


Figure 4.4. Recent population data and two estimated projections for San Cristóbal.

5.0 Problem Identification

In order to develop a framework to solve the problems that have been discussed in the preceding sections, the problems themselves must be further defined. In this section we outline the current water supply and sanitation conditions, stakeholders and their concerns in the development of a management plan, a preliminary water quality assessment, and identify target management areas of special concern.

[6] To obtain the ECOSUR-based and City-based estimates, we fit a curve to ECOSUR's 2017 and the City of San Cristóbal's 2018 population estimates.

5.1 Water Supply and Sanitation

5.1.1 Water Supply

CNA reports that the total amount of surface and groundwater available in the environment in the Frontera Sur region is 158.26 km^3, the equivalent of 24,549 m^3/capita-year (Comisión Nacional del Agua 2005a). Despite this abundance however, only 77.8% of the population of Chiapas has some form of connection to a potable water source, making it one of only five Mexican states below an 80% coverage level (Instituto Nacional de Estadística Geografia e Informática 2006). The amount of water actually extracted in the Frontera Sur region, based on sales reported by municipal water suppliers, is approximately 2 km^3 or 305 m^3/capita-year. This number accounts for sales to all sectors, including domestic (22%), agriculture (75%), and industry (3%) (Comisión Nacional del Agua 2005a). To put this number into perspective, this is less than half of the 791 m^3/capita-year rate reported for all of Mexico (World Resources Institute 2006). While data on individual municipalities has not been compiled by CNA or the Frontera Sur region, our analysis suggests that San Cristóbal falls into an even lower percentile for potable water coverage relative to the state of Chiapas.

Local Water Supply

The primary source of water for the city is 25 artesian wells distributed along the north and eastern slopes of the watershed. However, within the last decade, 7 of these 25 artesian wells have dried up completely, while another 12 function intermittently throughout the year. This leaves six wells to supply the potable water for the city (Consejo Consultivo de SAPAM 2003). The municipality runs five main pumping stations that use these wells to supply water to the city. Due to a combination of diminishing spring water and population growth, the municipality plans regular disruptions in water supply service so that neighborhoods receive water on a rotating basis (Carmona 2006).

Water extraction

To estimate average water usage in San Cristóbal we obtained monthly pumping rates for December 2004 through October 2005 for five of SAPAM's pumping stations. The monthly volume of water pumped at each station is summarized in Figure 5.1.

In addition to municipally run stations, there exists at least one other major pumping system in the watershed, which is operated by a FEMSA bottling plant for the Coca-Cola Company, located on the western outskirts of the city. FEMSA operates at least two private wells on its properties. FEMSA's pumping rates were estimated by García García (2005) and are included in Figure 5.1.

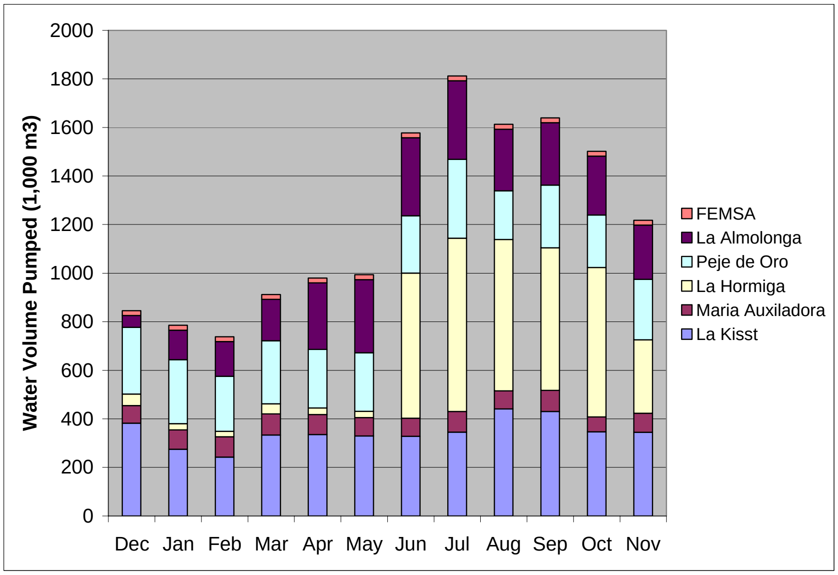


Figure 5.1. Total water pumped by month from five SAPAM pumping stations and the FEMSA plant between December 2004 and November 2005[7] (SAPAM 2005) and FEMSA (García García 2005).

Assuming that these were the only pumps used in this time period, the total amount of water extracted from the watershed in this time period was approximately 14.6 million cubic meters.

Human Consumption Rates

Using SAPAM's pumping data we approximated water consumption rates for the urbanized region of the watershed. Assuming that approximately 50% of the water pumped is lost in the system due to leaks (Arreguín, *et al.* 1997) and that water is distributed to the entire urbanized population of approximately 138,000 in San Cristóbal, we estimate a per capita water supply of approximately 143 L/cap-day, or 52 m^3/cap-year. As SAPAM has both domestic and commercial customers, this amount would account for purchases by both sectors.

5.1.2 Water Quality and Sanitation

In 2003, only 59.6% of households in the state of Chiapas were connected to a sewage system, compared to the national average of 77.2% (Instituto Nacional de Estadística Geografia e Informática 2006). In addition, there are only five municipal wastewater treatment plants operating in the state, which has a population of roughly three million people (Comisión Nacional del Agua 2005a). Currently, in San Cristóbal there is no form of wastewater treatment, but there is a sewerage collection system in the urban center of the city. As no treatment infrastructure exists, the wastewater which is collected and conveyed from the central downtown region is not treated before it is discharged into the watershed's surface water system. It is unknown how many discharge locations there are on each river or stream. While it is likely that many of sewage outfalls are located downstream of the urban center we did observe direct inputs of waste at locations near central parts of town (Picture 5.1).

[7] In order to calculate yearly water use, we estimated pumping for November 2005 because no data was available for this month. We estimated that November pumping was equal to the average rate of the other 11 months of the year.

Picture 5.1. A sewage outfall into the Río Amarillo at a location on the northern end of the urban center of the watershed.

At the time of this study, no detailed water quality information was available for the surface or the groundwater in San Cristóbal. However, it has been estimated that approximately 60% of the surface water in San Cristóbal is heavily polluted with sewage (Velázquez-Velázquez and Schmitter-Soto 2004). In addition to the sewage input from the approximately 138,000 urban residents, there are nearly 32,000 people that live in the outskirts of the watershed upstream from the main urban area. Here, there is little to no infrastructure to collect wastewater and prevent other waste from washing into the local surface waters. Another major contamination source is the carcasses of dead domestic animals which are often discarded directly into the rivers (Consejo Consultivo de SAPAM 2003).

5.2 Stakeholders and Concerns

This section describes the organizations, both governmental and non-governmental, and groups of individuals that have an interest in the development of a watershed management plan in San Cristóbal. In addition to identifying the groups that may be affected, their major reasons for being concerned with the process are also identified. The information for this section was derived from a series of personal conversations with our partner organizations (ECOSUR and SYJAC) and through informal interviews with individuals living in and around the city (see Appendix 8.2). A summary of stakeholders and their associated concerns can be found at the end of this section.

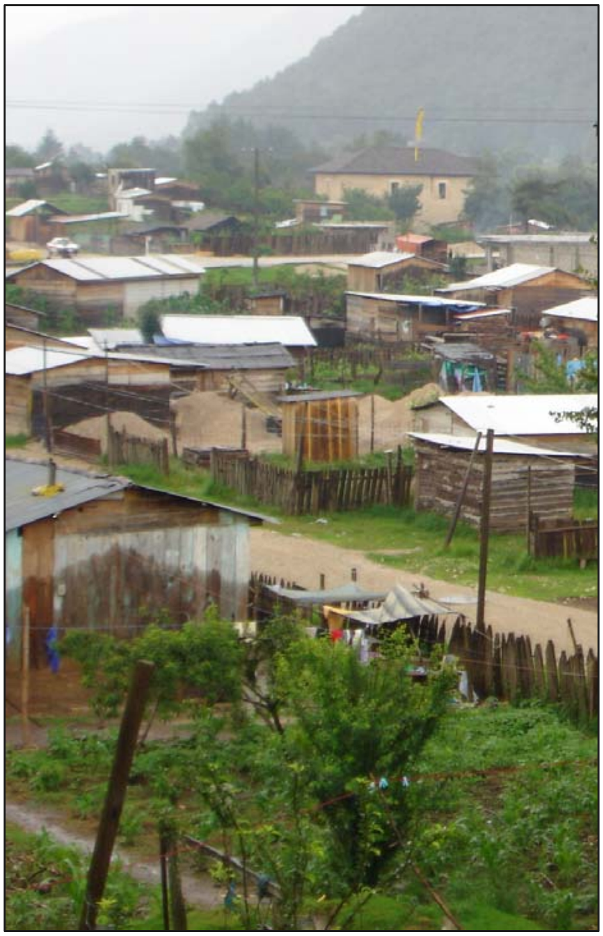
5.2.1 Stakeholders

There are 12 stakeholder groups that have been identified as having a concern in the development of a watershed management plan. As the development and implementation phases of the management plan move forward, other groups of citizens may come forward with an interest in the process. The stakeholders that have been identified at this time fall into four distinct categories: private citizens, government agencies, private industry, and organizations involved with research and/or community development.

Within the category of private citizens, there are five further distinctions. The first group of citizens are those living in the city center who have consistent access to water in their homes via SAPAM (Picture 5.2). This group tends to have a higher average income than those that live on the periphery of the downtown area. Because of this higher socio-economic position, this group uses the municipal water for general household needs, such as cleaning and bathing, but purchases drinking water from businesses that deliver 19 liter jugs of water. Water that they receive from SAPAM is stored in cisterns on top of their houses and passes through two filters before being used.

Picture 5.2. Downtown San Cristóbal.

Citizens living in recent settlements on the periphery of the downtown area who have a fairly consistent supply of water from SAPAM make up the second group (Picture 5.3). These citizens live in areas of San Cristóbal that have generally been settled since 1994 and have subsequently been added to SAPAM's water supply system. These citizens have taps in their homes, but water is generally only available five to six days per week. The water is stored for use in the same types of cisterns used in the city center. Unlike those in the city center, these citizens must use the water for cooking and drinking, in addition to cleaning and bathing. When the water is used for consumption it is often treated with chlorine drops. Some families in these communities are able to buy one or two jugs of water per week to use for cooking and drinking depending on their income. During the dry season or other periods with limited water supply, these citizens will occasionally use nearby river water for washing clothes or cleaning their homes.



Picture 5.3. A typical community surrounding the urban area.

The third group is also composed of citizens living in the surrounding new settlements, but whose neighborhoods are not supplied with water by SAPAM (Picture 5.4). Most of these citizens have come to San Cristóbal since 1994, but are currently living illegally on private or publicly owned land and therefore have no formal property rights. Without property rights to the land they are on, SAPAM is not required to supply these communities with water. Some of these areas have been able to install water spigots in a few locations in the neighborhood where water is available two or three times per week. Given this severe lack of piped water, these citizens are forced to use natural water supplies, specifically, shallow wells and surface water, for more household uses. The majority of these families do not have a cistern in which to store and filter water and are not financially able to buy jugs of water for consumption.

Picture 5.4. A community spigot that is left open at all time with buckets ready in case the water is turned on.

Further away from the city center, in the outskirts of the watershed, are smaller communities that have little to no access to water infrastructure nor to a SAPAM-provided supply (Picture 5.5). These communities are generally reliant on independent water supply systems or local springs.

Picture 5.5. The small community of Piedrecitas is not connected to the municipality water supply network.

The final group of citizens that has been identified with a stake in this process are those that are involved in small-scale agriculture (Picture 5.6). This group contains citizens involved in subsistence agriculture and those with small-scale agricultural businesses outside the watershed, but who receive water after it has passed through San Cristóbal. In both instances, water is usually diverted directly from the surface flow to irrigate their fields.

Picture 5.6. A farmer outside of the San Cristóbal watershed who uses the water that flows from the city to grow his crops.

The two government agencies that have been identified as stakeholders in the development of a watershed management plan are SAPAM and CNA. SAPAM's three principal objectives are "1) to provide the required services of potable water and piping to the municipality, neighborhoods, communities and private citizens, 2) to execute studies, projects, to construct, increase and better the systems of potable water and piping networks, and 3) to formulate and execute the plans and programs necessary for the operation, administration and conservation of the systems of potable water and piping in this municipality" (Consejo Consultivo de SAPAM 2003). As the federal water agency, CNA is responsible for setting and enforcing water quality standards. On a general level, their mission is to administer and to preserve the national waters, with the participation of society for the success of the sustainable use of the resource (Comisión Nacional del Agua 2006a).

The private industries in San Cristóbal that are potentially interested in the management of the watershed are the tourism industry, water suppliers and bottlers, and a FEMSA bottling plant. Here, the tourism industry includes the hotels, restaurants, travel agents, and vendors. Most of these businesses are located in the city center and are dependent on tourists, both domestic and international, for business. The water suppliers and bottlers extract water from the local sources, treat the water, bottle it in 1 and 19 liter jugs, and sell it to private citizens in San Cristóbal. The Coca-Cola Company/FEMSA bottling plant is located on the periphery of town with two of its own wells used to extract water for the bottling process. This plant services a large portion of both southern Mexico and Central America.

The final two stakeholders in this process are ECOSUR and SYJAC. Our contacts at ECOSUR are involved both with water management and the generation of spatial information. The information coming from ECOSUR is being used to guide the actions of SAPAM and to help make recommendations as to how the resources should be managed in San Cristóbal. SYJAC is principally concerned with improving the lives of people throughout Chiapas and specifically in San Cristóbal. SYJAC works toward this aim through a wide variety of actions that includes improving human health, defending human rights, and stewardship of the environment (SYJAC 2006). One way that SYJAC is actively helping marginalized people in San Cristóbal is by working to get them property rights to the land on which they are living. There may be other organizations in the San Cristóbal area who are also concerned with local water issues and who may become involved in the planning process as it proceeds. We focused on SYJAC as a stakeholder because of Sabás Cruz García's involvement with the San Cristóbal Hydro-Resources Partnership (SHRP).

5.2.2 Concerns

After identifying stakeholders, we attempted to identify and prioritize concerns for each stakeholder group. The concerns listed here are not an exhaustive list of all potential concerns related to water and the environment in San Cristóbal. In order to narrow down and prioritize the problems to be addressed with this project, we focused on the concerns that are of highest importance to the greatest number of people. Additionally, we focused on the concerns that our partners would like to see addressed.

Description of each concern

<u>Water for human consumption</u>

Quantity – This implies a sufficient amount of water for drinking, cooking, and basic household needs, such as bathing and cleaning. This is a concern mainly for the citizens living in the settlements surrounding the city center and those that live far away from the city who do not always receive the water necessary for daily life in their homes and who are forced to use surface water for household uses, including consumption. There are a few settlements, such as "Cinco de Marzo", where the people have no access to water in their houses and must rely on community taps that are located in central parts of the neighborhood.

Quality – Water quality refers to uncontaminated water, specifically to a specific level of pathogens, that is of sufficient quality for human consumption. This is primarily a concern for citizens who must use surface water for household needs and those who drink water that is supplied by SAPAM. Furthermore, quality is a seasonal issue for all citizens because of the increased levels of sediment present in the water during the wet season and an increase in pollutant concentration during the dry season. Most water that people receive from SAPAM is treated by the users with chlorine drops before it is consumed to disinfect it.

Consistency – A consistent water supply is one that is available without interruption. Often people living in the settlements have varying degrees of consistency; some receive water five to seven days a week, while others may only receive water two to three times a week.

Cost – The price of water is a concern for many citizens as many are not able to buy bottled water for consumption and household uses. Most citizens are able to cover the cost of the water that is supplied by SAPAM, but many are unable to augment their drinking supply with bottled water due to its high price.

Sanitation
Wastewater treatment – Most homes in San Cristóbal have a conventional toilet with a drain that leads to a wastewater collection system. Some of the recent settlements have not been able to set up this infrastructure and use basic pit toilets. While wastewater is collected from most homes in the city center, this water eventually ends up back in the surface water after the rivers pass through downtown and ultimately leaves the city untreated. SAPAM is especially concerned with developing the proper infrastructure to deal with wastewater as they are being fined every year by CNA for the river contamination.

Stormwater management – A proper system for stormwater management that collects water during extreme weather events. During the wet season, San Cristóbal experiences large amounts of rainfall that cause the streets in the city center to flood, the sewerage system to back up in some parts of town, and for some homes in low lying areas to become flooded.

Local business concerns
Quality – A consistent level of quality would be helpful to businesses in the area who use the surface and ground water so they can avoid excessive costs to treat the water before it is used.

Quantity – Local industries are concerned with having a sufficient quantity of water for both current and future uses.

Other concerns
Environmental health – Some organizations, mainly the municipality's Environmental Division, are concerned with the improvement or maintenance of environmental quality (water, land, air, etc.) in San Cristóbal. This idea is also important in terms of maintaining the aesthetics of the region in order to continue attracting the more than 300,000 tourists (García García 2005) that visit San Cristóbal every year.

Cost of solutions – The costs of any solution to water quality and quantity concerns will be an important factor in the decision making process. Because SAPAM and other stakeholders have limited funds to deal with the management of water, the cost effectiveness of all options for management need to be considered before any action is recommended.

Education – Providing education to the public on issues surrounding water use and sanitation for protection of human health and improved environmental quality is a concern for organizations involved in the process because it is a cheap way to modify people's behavior and understanding of the local water resources.

Inter-stakeholder trust – Building trust and lasting relationships between the various stakeholder groups in order to create and implement a substantive agreement for sustainable watershed management is essential to the implementation and success of the project.

Table 5.1. This table indicates the main concerns of each stakeholder group. An 'X' indicates a main concern for the stakeholder. It does not indicate that concerns without an 'X' are not something that a person, business, or organization may care about or take into consideration when involved in the planning process.

	Citizens – city center, consistent water supply	Citizens – periphery, consistent water supply	Citizens – periphery, limited water supply	Citizens – subsistence and small business agriculture	SAPAM	CNA	Tourism industry	Water suppliers and bottlers	Coca-Cola	ECOSUR	SYJAC
Human consumption											
Quantity	X	X	X	X	X	X				X	X
Quality	X	X	X	X	X	X				X	X
Consistency	X	X	X	X	X	X				X	X
Cost	X	X	X	X	X	X				X	X
Sanitation											
Wastewater treatment	X	X	X		X	X				X	X
Stormwater management	X	X	X		X	X				X	X
Industry needs											
Quantity					X	X	X	X	X		
Quality					X	X	X	X	X		
Other concerns											
Environmental health	X				X	X	X			X	X
Cost of solutions					X	X				X	X
Education					X	X				X	X
Inter-stakeholder trust					X	X				X	X

5.2.3 Deriving Priorities

The situation in San Cristóbal is a complicated one that not only has an environmental management component, but also a compelling social need to provide the basics of water supply and sanitation to its growing population. Through our visits to the area and conversations with both citizens and other stakeholders, it is clear that a complete wastewater conveyance network and the proper treatment of this wastewater would act to address many of the concerns of the various stakeholder groups. Eliminating the flow of wastewater directly into surface waters has the potential for improving human health, as many people become ill from washing and bathing with this water. Additionally, this will improve the environmental quality throughout the watershed by removing a portion of the human derived sources of nutrients, such as pathogens and organic loads. A by-product of improving human and environmental health is the improvement of the aesthetics of the region which can have a positive economic effect on the tourism industry which is reliant on visitors spending time in San Cristóbal. This action would also benefit the local water bottlers and suppliers by improving the quality of the water that they extract from the surface waters in the area. It could potentially reduce their costs by requiring less treatment of the water before it is sold to consumers. In turn, this could benefit the citizens that cannot currently afford to buy jugs of water if the reduced costs are passed on to the consumer. Ultimately, removing the wastewater from the surface water would benefit those on the other side of the tunnel who use the water that flows from San Cristóbal through the tunnel.

Conceptualizing the concerns of the stakeholders in this way aided us in determining the priorities for our project. On one hand, there is a need for the researchers and water managers to have a better understanding of the local resources and how they will be affected by infrastructure and/or management changes. At the same time, many people living in San Cristóbal just need basic water supply and sanitation. By providing the decision-makers with knowledge and tools of watershed management, they will be able to make the best decisions to benefit the citizens of San Cristóbal, now and in the future.

5.3 Water Quality Assessment

Currently, there is no data available on the state of surface water quality in San Cristóbal. To gain a preliminary understanding of the water quality in several locations throughout the watershed, we undertook a simple monitoring plan.

Initially, we wanted to test the hypothesis that surface water upstream of the city center would have lower nutrient levels and pathogens than the water leaving the city. To do so we chose one sampling point far upstream of the urban center of the watershed, two locations near the edge of the urban area, one point downstream of the urban area, one point that gave access to groundwater, and a water cistern containing supplemental potable water supplies for SYJAC. The name and location of the sampling locations are listed below and can be seen in Pictures 5.7 through 5.11:

- Sampling point 1: Río Fogótico just outside the urban center of the watershed.
- Sampling point 2: at the Río Amarillo just inside the urban center of the watershed
- Sampling point 3: at the Arroyo Chamula just inside the urban area of the watershed
- Sampling point 4: at the confluence of the Rios Amarillo and Fogótico
- Sampling point 5: of the water outside the SYJAC cistern
- Sampling point 6: water inside the water cistern at SYJAC, to represent water delivered by the municipality

In order to carry out sampling throughout the year, our project partner, SYJAC, provided a volunteer, Jesús Miguel Peate Martineaz, to help with sample collection and analysis. During the first trip to San Cristóbal in June 2005, project members traveled to all of the sample sites and trained this volunteer on the desired sampling procedures. It was hoped that we would be able to obtain 1-2 data sets per month; however, Martineaz was limited by time and transportation costs and was only able to take samples when time permitted.

Using Hach Water Quality Test Strips we tested for ammonia, nitrates, nitrites, phosphorus, pH, alkalinity, hardness, free chlorine, and total chlorine. Using Hach Pathogen Reagents we tested for the presence or absence of bacteria. Finally, we made qualitative observations about the amount of sediments in the water, odor, and color at the sampling point. A summary of the results of this preliminary sampling program can be found in Tables 5.2 through 5.8 at the end of this section. Each table represents the test results at one sampling site for all dates it was sampled.

These results only provide a very general idea about the surface water quality. All locations had positive pathogen tests and many had poor odors and colors. We learned that the set of test strips being used to measure ammonia (NH_4), nitrates (NO_3), and nitrites (NO_2) may be inaccurate, so we cannot rely on upon these results to give us a clear understanding of the level of nutrients in the surface water. While the test strips do not provide precise results, they do provide an idea of the range under which the value would fall. A more detailed water quality monitoring plan will be designed and provided to our partners so that a better understanding of the water quality in San Cristóbal can be obtained.

Picture 5.7. Sampling point 1 on the Rio Fogótico just outside the urban center of the watershed.


Picture 5.8. Sampling point 2 at the Río Amarillo just inside the urban center of the watershed.


Picture 5.9. Sampling point 3 at the Arroyo Chamula just inside the urban area of the watershed.

Picture 5.10. Sampling point 4 at the confluence of the Ríos Amarillo and Fogótico.

Picture 5.11. Sampling point 5 of the water outside the SYJAC cistern.

Table 5.2. Water quality results for the upper Río Fogótico (sampling point #1).

Date	Bacteria	NH_4 (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	P (mg/L)	pH	Alk	Hardness	Sediments	Odor	Color
6/17/05	positive	0-0.25	0	0	5 - 15	7.2	40-80	120	high	no	clear Brown
6/23/05	positive	0	0-1	0	5	6.8	80	120	very low	no	almost transparent
7/7/05	negative	0	0 - 1	0	5 - 15	7.0	120	120	no	no	almost transparent
12/6/05		0	0	0	5	7.4	240				
12/24/05		0	0	0	15	8.4	120	120	no	no	almost transparent
1/5/06		0 – 0.25	0 - 1	0	5 - 15	7.8	120-180	120	no	no	transparent
1/20/06		0	0	0	5	8.4	180	120	no	no	transparent
2/6/06		0	0	0	5 - 15	8.4	120-180	120	no	no	transparent

Table 5.3. Water quality results for the Río Amarillo (sampling point #2).

Date	Bacteria	NH_4 (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	P (mg/L)	pH	Alk	Hardness	Sediments	Odor	Color
6/21/05	positive	3	2	0.15	5 - 15	8.4	180	120	high	high	Clear
6/23/05	positive	0 - 0.25	1	0	5 - 15	7.2-7.8	120-180	120	no	no	almost transparent
7/7/05	positive	0 - 0.25	0 - 1	0	15	7.2 - 7.8	120 - 180	120	low	no	almost transparent
12/3/05		0.25	0	0	15	7	240				
12/24/05		0.25	0	0	15	8.4	180	120	no	low	almost transparent
1/5/06		0.25	0	0	15 - 30	8.4	120	120	no	low	almost transparent
1/20/06		0.25	0	0	5 - 15	8.4	240	120	no	no	almost transparent
2/6/06		0.25 - 0.5	0	0	5 - 15	8.4	180	120	no	low	almost transparent

Table 5.4. Water quality results for the Arroyo Chamula (sampling point #3).

Date	Bacteria	NH_4 (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	P (mg/L)	pH	Alk	Hardness	Sediments	Odor	Color
6/23/05	positive	0-0.25	1 - 2	0-0.15	5 - 15	7.8 - 8.4	120 - 180	120 - 250	very low	no	transparent
7/7/05	positive	0 - 0.25	1 - 2	0	5 - 15	7.8 - 8.4	120 - 180	120	low	no	transparent
12/4/05		0.1	2	0	15	7.8	240				
12/24/05		0 – 0.25	1 - 2	0	15	8.4	120 - 180	250	no	low	almost transparent
1/5/06		0 – 0.25	1 - 2	0	15 - 30	7.8 – 8.4	120 - 180	120	low	no	almost transparent
1/20/06		0 - 0.25	1 - 2	0 - 0.15	15	8.4	240	120 - 250	no	low	almost transparent
2/6/06		0	1 - 2	0	5 - 15	8.4	180	250	no	no	almost transparent

Table 5.5. Water quality results for the Fogótico-Amarillo confluence (sampling point #4).

Date	Bacteria	NH_4 (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	P (mg/L)	pH	Alk	Hardness	Sediments	Odor	Color
6/21/05	positive	0.5	0 - 1	0	5	7.8	180	120	medium	no	clear brown
6/23/05	positive	0.25 - 0.5	0 - 1	0 - 0.15	15-30	7.8-8.4	180	120	very low	no	almost transparent
7/7/05	positive	0.25 - 0.5	0 - 1	0	5 - 15	7.0	120	120 - 250	low	low	almost transparent
12/24/05		0.25 – 0.5	1 - 2	0	15 - 30	8.4	180 - 240	250	low	high	almost transparent
1/5/06		0.25 – 0.5	1 - 2	0	30	7.8 – 8.4	180 - 240	120 - 250	low	high	almost transparent
1/20/06		0.25 - 0.5	0 - 1	0	15 - 30	8.4	240	250	low	high	almost transparent
2/6/06		0.25 - 0.5	1 - 2	0	15 - 30	8.4	240	250	low	high	almost transparent

Table 5.6. Water quality results for the water outside the SYJAC water cistern (sampling point #5).

Date	Bacteria	NH_4 (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	P (mg/L)	pH	Alk	Hardness	Sediments	Odor	Color
6/23/05	positive	0	5	0	5 - 15	8.4	180-240	425	no	no	transparent
7/7/05	negative	0 - 0.25	5 - 10	0	0 - 5	7.8	240	250	no	no	transparent
12/5/05		0	0.5	0	5	7.6	240				
12/24/05		0 – 0.25	0 - 1	0	5 - 15	7.8 - 8.4	120 - 180	250	no	no	almost transparent
1/20/06		0	0	0	5 - 15	8.4	240	250	no	no	transparent

Table 5.7. Water quality results for the water inside the SYJAC water cistern (sampling point #6).

Date	Bacteria	NH_4 (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	P (mg/L)	pH	Alk	Hardness	Sediments	Odor	Color
6/23/05	positive	0	1	0	5 - 15	7.8-8.4	180-240	425	no	no	
7/7/05	negative	0	1 - 2	0	5 - 15	7.2 - 7.8	180	250	no	no	transparent
12/24/05		0	1	0	5 - 15	8.4	240	120 - 250	no	no	almost transparent
1/20/06		0	1	0	5	8.4	240	250	no	no	transparent

Table 5.8. Water quality results for other points that were only monitored on one occasion.

Date	Location	Bacteria	NH_4 (mg/L)	NO_3 (mg/L)	NO_2 (mg/L)	P (mg/L)	pH	Alk	Hardness	Sediments	Odor	Color
6/17/05	Rio Amarillo (electrical plant)	positive	0	0	0	0 - 5	7.8	120	120	white, high	no	clear
6/18/05	Duraznal	positive	0.25	0 - 1	0	5 - 15	8.0	180	250	low	low	clear brown
6/18/05	Duraznal	positive	3	1 - 2	0	10 - 15	7.8	180	200	medium	high	brown
6/18/05	Tunnel exit	positive	6	1 - 2	0	10 - 15	7.8	180	250	medium	high	brown
6/18/05	Cinco de Marzo well	positive	1 - 3	20	0.3	10 - 15	7.8	180	250	very low	low	clear
6/21/05	Stormwater	positive	0	0 - 1	0	5 - 15	6.8	40	50	medium	no	clear brown
6/21/05	Canal that drains into the Rio Amarillo	positive	0.5 - 1	2	0.15	15	7.2 - 7.8	180	120	low	low	brown
12/7/05	Río Amarillo at EJE 1	positive	3	0	0	15	7.4	240				
12/8/05	Coca-Cola	positive	4.5	0	0	15	8.4	240				

5.4 Critical Areas Study

The city of San Cristóbal is known to have elevated contamination levels in its surface waters after they pass through the city. This contamination is reducing the amount of potable water available and is causing adverse health effect on the local community. The lack of a centralized wastewater treatment system leads to the discharge of the sewage into the river system which results in unsafe conditions for human use. Additionally, pollutants are released from non-point sources located outside of the urban area. The change in the land use in the region from natural forest to cultivated land is suspected to impact and influence the water quality. Runoff from agricultural fields and pastures release contaminants like pesticides, herbicides, fertilizers, and manure, affecting the quality of the water before it enters the city.

The goal of this analysis is to identify the areas inside the San Cristóbal watershed that may contribute to a significant amount of pollutant loading in the rivers and streams of the region. The analysis focuses on areas outside of the urban region that are known to discharge non-point sources of pollution. This study used Geographical Information System (GIS) software to model the potential transport of pollutants and to provide a spatial description of critical areas that have a significant impact on the water quality within the watershed.

In order to locate these potential areas of concern, a model of the pollutant load was developed to identify the regions in the watershed, outside of the urban area, that may significantly contribute to pollutant levels in the water. With this information we were able to assess the potential pollutant levels in particular regions throughout the 20,000 hectare watershed. These areas, referred to as critical areas, became the focus of the preliminary management plan, specifically, where educational and structural BMPs could be applied in order to maximize the efficiency of pollution control.

The analysis unit for this project was a 50 by 50 meter grid cell based on the DEM layer of the state of Chiapas. The calculation of the critical areas for non-point sources of pollution is described in the Figure 5.2. The physical characteristics of the watershed are represented by the input data of: land use, soil type, river systems, vegetation and topographic maps (DEM). The flow chart summarizes the method use in the multi-criteria analysis to identify the critical areas.

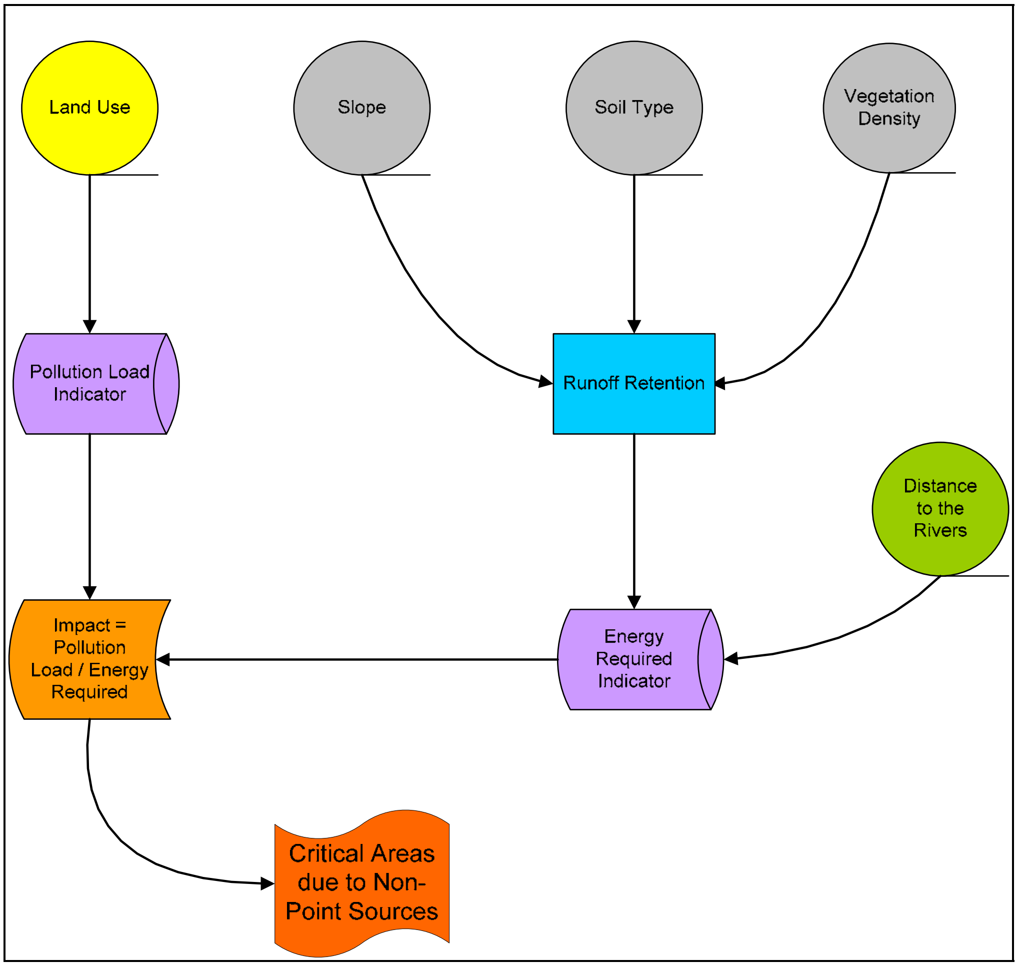


Figure 5.2. Flowchart of the model for the critical areas analysis.

Objectives and Criteria of Analysis

Two objectives were considered in this analysis in order to identify critical areas (areas that could impact water quality) within the San Cristóbal watershed:

1. Pollutant Load – Potential amount of pollutants produced by each region (grid cell) based on land use. High coefficients of this index were associated with high pollutant generation.
2. Runoff Retention – A calculation of the potential water flow as runoff from each grid cell to the nearest stream. The runoff retention was calculated as a function of soil conductivity, slope, land use, and distance to the rivers. High coefficients indicated that the pollutants were less likely to reach the stream.

The runoff was measured as an indicator of transport from its source (where pollutants are generated) to its destination (sections of the rivers). The runoff retention takes into account surface characteristics and the geographic location of each site in reference to the nearest stream. This index can also be understood as the amount of "energy" necessary for the water to flow from a particular grid cell to the closest stream. Note that this "energy" is not an absolute value, but a relative value in comparison to the range of values found in the watershed.

1. Criteria for the Pollutant Load

The pollutant load was based on the land use of the region. Land use is an important factor in identifying areas that contribute to the amount of contaminants in the water. Human activities significantly affect the amount of contaminants in the soil. Agricultural activities enrich the soil with nutrients from fertilizers; grazing inputs bacteria, nitrogen, and phosphorus from livestock wastes; and wildlife contributes bacteria and nitrogen loads through animal waste.

The land use layer employed in the analysis was extracted for the Chiapas land use layer. The layer was clipped for the watershed and then reclassified in values that ranged from 1 through 10. Low values were assigned to areas where the activities would produce low pollutant loads (forests), while high values were assigned to areas that would produce large amounts of pollution (agricultural areas and pastures). Since the analysis was focused on the non-point sources of pollution located outside of the city limits, low value indices were applied to urban areas.

Table 5.9. Land use indices used in the analysis.

Land Use	Index
Primary Forest	1
Secondary Forest	1
Pine and Oak Forest	1
Cleared, Tilled, or Non-Vegetated	4
Scrubland	4
Grassland/Pasture	10
Cropland	10
Urban Areas	1
Water and Wetlands	1

2. Criteria for Runoff Retention

As mentioned above, the runoff retention index is a function of the topography, vegetation cover, soil properties, and distance to the rivers. For the first part of the calculation, a data set was calculated based on slope, vegetation density, and soil conductivity. The data layer generated was used as the input to the cost distance tool in ArcGIS. This tool uses the surface runoff retention layer of each grid cell and its geographic location with respect to the closest river to calculate the likelihood of runoff. The cost distance tool of GIS made it possible to determine the "energy" required for the water to travel from each site (source) to the river (destination). Since pollutants are carried by runoff and water leaching into the soil, the energy required for water to travel could be associated with the likely movement of the pollutant over the terrain surface. The indices of flow resistance were classified based on the assumption that high flow resistance is equal to low water runoff. Therefore, all characteristics that would reduce the water runoff were assigned high indices and vice versa.

<u>Topography</u>

The slope of the terrain is an important factor influencing the amount of runoff at the surface. "The slopes in a watershed have a major effect on the peak discharge at downstream points. Slopes have greater effect on how much of the rainfall will runoff. As watershed slope increases, velocity increases, the time for runoff to begin decreases, and peak discharge increases" (Franklin; Hampden; and Hampshire Conservation Districts 1997).

The slope used in this analysis was derived from a 50 by 50 meter DEM. The slope was then converted to raster data based on its percent and then grouped into classes. Since steep slopes increase runoff, they were assigned low values, while low percentage slopes were assigned high values. Therefore, the energy required for water to travel in a path of gentle slope would be higher than it would be to travel the same path with a steep slope.

Table 5.10. Slope indices used in the analysis.

Slope (%)	Slope Index
0 - 4.8	10
4.8 - 11.1	9
11.1 - 17.9	8
17.9 - 25.1	7
25.1 - 33.3	6
33.3 - 42.5	5
42.5 - 53.6	4
53.6 - 67.1	3
67.1 - 85.5	2
85.5 - 100	1

Vegetation Density

Vegetation density is another characteristic of the land surface that affects the amount of runoff. In locations with high vegetation density, the foliage and its litter maintain the soil's infiltration potential by reducing the impact of raindrops on the soil surface. “Vegetation, including its ground litter, forms numerous barriers along the path of the water flowing over the surface of the land. This increased surface roughness causes water to flow more slowly, lengthening the time of concentration and reducing the peak discharge (Franklin; Hampden; and Hampshire Conservation Districts 1997). Vegetation also influences the rate of evapotranspiration and water uptake from the soil. Therefore, dense forest areas would absorb a higher volume of water from soils than areas with little to no vegetation.

The vegetation density was derived from the land use layer. The vegetation layer was clipped to watershed boundaries and reclassified according to type of plant cover that characterized its density. The types of vegetation density were compared and classified with values ranging from 1 – 10, where lower values represent areas with low vegetation density and higher values indicate areas with high vegetation density. Areas without vegetation, mainly the urban areas, were classified with the lowest value for land cover. Additionally, these areas are considered to be mostly impervious surfaces. The indices were positively related to the cost raster values, as the assumption that high vegetation density creates a physical barrier to the water runoff, increasing the energy required for the water to travel over the area.

Table 5.11. Vegetation indices used in the analysis.

Land Use	Index
Primary Forest	10
Secondary Forest	10
Pine and Oak Forest	10
Cleared, Tilled, or Non-Vegetated Fields	1
Scrubland	5
Grassland/Pasture	2
Cropland	5
Urban Areas	1
Water and Wetlands	1

Type of soil

The last criterion used in the analysis of the flow resistance was the soil conductivity. Using the soil type layer, it was possible to estimate the percent of silt, sand, and clay contained in each soil type. From this, the size of the pores within the soil layer was estimated allowing for the calculation of the soil conductivity for each type. "Soil texture is the relative proportion of sand, silt, and clay. The texture of the soil influences many of its characteristics, such as permeability, erodibility, and infiltration capacity" (Rawls, *et al.* 1998).

Increased soil texture implies high porosity, which in turn increases the soil conductivity and permeability. We decided to use this property as a criterion for runoff retention, assuming that high soil conductivity increases the amount of water infiltration, reducing the amount of runoff, and increasing runoff retention.

Since the soil type was extracted from the Chiapas soil data, the resolution of the layer was poor. The layer allowed for the identification of four ranges of soil conductivity, resulting in a simplified estimate of soil conductivity in the watershed.

Table 5.12. Soil conductivity indices used in the analysis.

Soil Conductivity	Index for Soil
3,600	1
3,601-6,000	4
6,001-8,400	7
8,401-12,480	10

Because the results of the soil layers would later be aggregated with the other indices (vegetation and slope), the same index range (1-10) was used. The indices of the soil layer were positively related with the conductivity since an increase in conductivity reduced the runoff potential. The indices chosen in this reclassification were equally dispersed based on soil permeability. Because of the roughness of the layer and the poor range of the soil permeability, the data is limited and only provides a general idea of the soil properties at the surface. Further improvement of this data layer is advised in order to improve the accuracy of the analysis.

Aggregation of Data
After all the layers were reclassified, they functioned as inputs for the weighted overlay tool in ArcGIS. With the combination of the three layers, it was possible to assess the surface resistance of the entire watershed. The same weight was assigned to the topography and vegetation criteria. However, because of lower precision of the soil layer, it was decided that this layer should be weighted less than the other two criteria. This allowed the analysis to take into account the soil properties without giving too much weight to a generic data set. The weights assigned in the weight overlay were the following:

- 40 % to the Slope Layer
- 40 % to the Vegetation Density Layer
- 20 % to the Soil Conductivity Layer

Therefore, the equation for flow resistance was based on the following equation:
Runoff retention = 0.4 Slope index + 0.4 Vegetation index + 0.2 Soil Conductivity index.

Once the runoff retention layer was aggregated, it was used with the river system as input to calculate the energy required. The ArcGIS tool analyzed the runoff retention and calculated the energy necessary for the water to travel from each grid cell, over the land surface, and finally, to a stream. Hence, shorter distances values related with high probability of the pollutant load reaching the nearest river system and vice versa.

With the data sets of flow resistance and pollution load, it was possible to calculate the impact of each site on the river system. The impact can be understood as having a depreciative effect on the water quality conditions of the river. The impact of each site related to non-point sources of pollution can be calculated with the following equation:
Impact = Pollution load / Runoff retention.

For each grid cell of the watershed, the impact index was calculated based on the amount of potential pollution created by a non-point source, divided by the cost distance. After the layers were reclassified and analyzed in GIS, the impact values were normalized in order to acquire a 0 to 1 scale. It is important to note that the impact of each region on the water quality of the river system increases with an increase in the total amount of pollution produced. However, the impact is inversely related to the runoff retention index: the higher the runoff retention of the land surface, the lower the impact of that cell on the river system.

Results
The results of the analysis are shown in Figure 5.3.

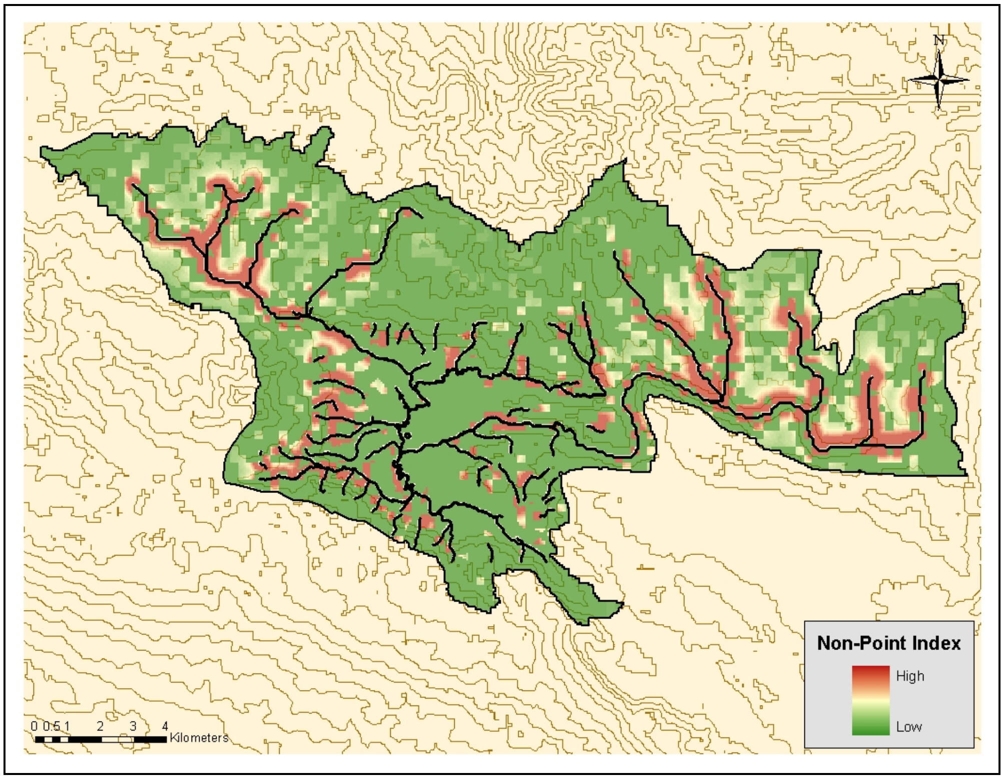


Figure 5.3. Critical areas due to non-point sources of pollution.

Since pollution from the urban area was not taken into account in this analysis, the city perimeter had no impact on the water quality, resulting in a zero impact index in those areas. The results indicate that the northern and the southern parts of the watershed have no significant impact on the water quality. This can be attributed to the slopes of these areas. Even though these regions have steep slopes, which increase runoff, the slopes also act to prevent activities such as intensive agriculture and grazing that would generate a non-point source of pollution.

Most of the critical areas were heavily influenced by their proximity to the river system. Critical sites were between 30 and 200 meters of the rivers. Most of the impacted areas are located in northwest and northeast portions of the watershed. According to the model, the Río Fogótico to the east and the Arroyo Chamula to the west, along with their tributaries, are the rivers that are most likely impacted by non-point sources of pollution. In these areas, the presence of pastures and agricultural fields near rivers increases the chance of pollutant and nutrient flows into the water.

Assumption and Uncertainty
The model developed in this analysis outlines the basic steps for assessing areas of highest concern for non-point sources of pollution. This model uses simple sets of data and ArcGIS tools to generate a spatial assessment of the watershed. As with any other model, assumptions about the physical environment and characteristics are generalized over a large area which results in uncertainty in the results.

Because the original soil data layer was extracted from Mexican soil layer, it lost some resolution at the local level and misses details that are specific to the San Cristóbal region. In order to overcome this lack of precision in the data, the soil layer data was assigned lower values in the weighted overlay tool. This ensured that the surface resistance would not be greatly affected by this generalized data layer of the soil types. A sensitivity analysis of the soil parameter was performed to analyze how it would affect the final results. The results of this analysis indicate that changing the weight from 20% to 30% (thus giving all criteria the same weight) produced little change in the identification of the critical areas. Therefore, the sensitivity analysis showed that changes in the soil weight parameters did not significantly affected the results of the analysis.

Limitations and Future Research

A limitation was encountered during the building of the model in the calculation of the runoff resistance. It seems that the cost distance tool in ArcGIS is highly influenced by the distance to the river system. It would be interesting to see how the results would change if the ArcGIS tool was weighted more for the surface resistance data.

Conclusion

The analysis of the critical areas in the San Cristóbal watershed provided a visual description of the geographic locations that significantly impact the water quality in the region. The information provided in Figure 5.3 helped to identify sampling sites for the water quality monitoring program suggested in Section 6.1. Monitoring at these points will provide information about the water quality of the river before and after the critical areas to provide a better understanding of the impact of the non point-sources of pollution on those areas. The information also identified places where BMPs and educational campaigns could be implemented in order to maximize their effectiveness.

6.0 Tools for Developing a Sustainable Watershed Management Plan

6.1 Water Quality Monitoring Program

In order to develop a sustainable watershed management plan, first it is necessary to assess the water quality conditions in the region. Currently, there is insufficient information to evaluate the conditions in San Cristóbal. Due to the lack of data, this study suggests an extensive long-term monitoring program for surface water and drinking water supply. With information on the pollutants of concern and areas which affect water quality, pollution prevention and water management programs can be implemented more successfully and effectively.

6.1.1 Surface Water Quality Monitoring Program

Currently, there is not sufficient information to quantitatively classify the surface water quality in San Cristóbal. There are no previous studies on the water conditions of watershed. It is known, however, that the water quality, especially in the city itself, is inadequate for human use. The proposed water monitoring program aims to provide local stakeholders with the necessary data about the present condition of the water so they can make informed decisions as to how best to manage the water resources.

This proposed monitoring program provides a comprehensive, long-term monitoring plan that will assess the water quality conditions upstream from the city, as it runs through the urban area, and finally as it exits the watershed through the tunnel. The objective of the monitoring program is to collect data in order to characterize the surface water profile for local authorities and stakeholders. Specifically, data collection will allow one to:

- evaluate the current status of the water quality in the San Cristóbal watershed,
- determine if the surface water meets the water quality objectives set by the Official Mexican Norm (Norma Oficial Mexicana),
- set reference conditions of current water quality and its seasonal variations,
- understand the impacts of point and non-point sources of pollution on surface water, and
- evaluate the effectiveness of best management practices (BMPs) as they are implemented.

The first part of the program is focused on establishing the current water quality conditions. Measurements of different water quality parameters of surface water will determine which pollutants are of highest concern in the region. Also, these conditions can be used in the future as a baseline to evaluate management actions.

The second part of the monitoring program will focus on identifying sources of pollutant load and subsequently quantifying the effectiveness of specific BMPs in reducing the level of contamination in the water. By establishing the current conditions first, we will be able to compare the present levels of impairment to the conditions after the implementation of different management options. The difference between these conditions will help to evaluate the effectiveness of the plan and inform the adaptive management phase of the process.

Water Quality Standards

Once the results of the monitoring events have been determined, they should be compared with ambient water quality standards. The ambient water quality standards describe the maximum pollutant levels allowable for human use and for maintaining the integrity of riparian environment. Most of the ambient water quality standards are region specific. As a starting point, the results of the monitoring plan can be compared with standards of other regions or with the standards for residual water of Mexico's National Water Commission, Comisión Nacional de Agua (CNA).

The EPA describes a series of ambient water quality standards, such as the Ambient Water Quality Criteria Recommendations, which could be an initial reference for the monitoring plan. The EPA also has the National Recommended Water Quality Criteria, which is a set of criteria in compliance with the Clean Water Act. The document contains a table that summarizes the concentration of chemicals and nutrients recommended for surface water, human health, and aquatic life (U.S. EPA 2004).

CNA also has the Official Mexican Norm that sets the standards for residual water for all of Mexico. These standards are summarized in Table 6.1.

Table 6.1. Maximum permissible limits for basic contaminants (NOM 1996).

	Use in Agricultural Rivers		**Use in Urban Rivers**		**Use for Protection of Aquatic Life**	
Parameters	Monthly Average	Daily Average	Monthly Average	Daily Average	Monthly Average	Daily Average
Temperature (degrees Celsius)	N.A.	N.A	40	40	40	40
Oils (Simple Weighted Average)	15	25	15	25	15	25
Suspended Solids (ml/L)	1	2	1	2	1	2
Total Suspended Solids (mg/L)	150	200	75	125	40	60
BOD (mg/L)	150	200	75	150	30	60
Total Nitrogen (mg/L)	40	60	40	60	15	25
Total Phosphorus (mg/L)	20	30	20	30	5	10

As another reference for ambient water quality standards, the California Department of Health Services (DHS) states that public beaches and public water contact shall not exceed:

- 1,000 total coliform bacteria per 100 ml, if the ratio of fecal/total coliform bacteria exceeds 0.1; or
- 10,000 total coliform per 100 ml; or
- 400 fecal coliform bacteria per 100 ml; or
- 104 enterococcus bacteria per 100 ml.

Water Quality Indicators

The monitoring program allows for a characterization of surface water quality by measuring physical, chemical, and biological indicators of water quality. A brief description of each of these indicators follows below.

Physical Indicators:

- Water color – Indicator of suspended solids and possible indicator of pollution.

- Temperature – Parameter that influences quality of aquatic habitat, metabolic rates of organisms, and the amount of dissolved oxygen in water.
- Turbidity – Measurement of cloudiness of water caused by materials such as dissolved sediments and organic residues. Parameter associated with soil erosion, waste discharge, urban runoff, and algal growth.
- Width and depth – Parameters used to estimate river flow.

Chemical Indicators:

- pH – Parameter that indicates the acidity or alkalinity of the water. These levels determine many biogeochemical reactions. At either extreme, pH levels could be toxic to aquatic life.
- Alkalinity – Measurement of the acid neutralizing capacity of the aquatic system; it acts as a buffer capacity, minimizing variation in water pH.
- Hardness – Measurement of magnesium and calcium carbonate dissolved in water, which can be correlated with total dissolved solids (TDS).
- Phosphate – Nutrient that is positively correlated with the eutrophication of a water system.
- Nitrate and Nitrite – Indicators of water quality associated with eutrophication.
- Ammonium – Extremely toxic nutrient that can pose a threat to aquatic organisms even at low levels.
- Total Nitrogen – Parameter that measures the total amount of nitrogen in water (dissolved inorganic and organic nitrogen, particulate organic and inorganic nitrogen, not including nitrogen gas).

Biological Indicators:

- Fecal coliform bacteria – Indicates the contamination of the water with waste from warm-blooded animals. The presence of high levels of coliforms is also correlated with the presence of other pathogens and bacteria that live in the same environment.

Further investigation of pesticides and industrial contamination could be addressed in accordance with the level of stakeholder interest. Sampling and analysis for the detection and identification of pesticides is more costly and requires more sophisticated equipment such as gas chromatography and mass spectrometry.

Monitoring Points

The monitoring program consists of 24 sampling points that would provide researchers with an accurate understanding of the water quality throughout the watershed. Nine points focus on measuring the water quality of surface water within San Cristóbal, while the other 15 will focus on assessing the quality of the water that is extracted from the wells. The monitoring points were placed on the main rivers (Fogótico, Amarillo, San Felipe and Chamula) in order to get an overview of the conditions throughout the watershed.

Contamination of the water in the watershed is caused by both point and non-point sources of pollution. The primary pollutant load in the urban center of the watershed derives from discharges of untreated wastewater into the surface waters. Non-point sources such as agricultural fields, pastures, and stormwater, contribute to the loading of nutrients from animal waste, fertilizers, and sediments. Additional non-point sources in San Cristóbal include urban and semi-urban residential areas that do not have an adequate sewage system.

Since the main concern of our partners (SAPAM and ECOSUR) is understanding the quality of the water inside the city, the nine monitoring points selected are located in the urban area. The monitoring of key locations in the urban region will provide an understanding of which section of the city and which type of land use is having the greatest impact on the health of the surface water.

At the present time, the specific point sources of wastewater discharge from the urban area are not available. These points can be considered to be major impact sites that intensely reduce water quality. Knowledge of their locations would be essential to a complete monitoring plan. Measurements of the nutrients upstream and downstream from those sewage discharge points would allow for an assessment of the impact of that particular point source on the water quality. After treatment of municipal sewage begins, additional monitoring of downtown points will be necessary to assess the effectiveness of this treatment. Additional monitoring within urban areas may also be warranted if high concentrations of non-organic human waste (i.e. oils and metals) are discovered downstream of the city.

Sampling sites were carefully chosen to maximize our understanding of the pollutant load and the flux of those nutrients in the surface waters. The sampling sites presented in this report were selected according to the following criteria:

1. Control sites – Points upstream of the urban areas that would determine the quality of the water before it enters the city.
2. Impact sites due to urban or agricultural contamination – The impact sites are the sampling points along the river where there is a high chance of water contamination due to urban or agricultural contamination.
3. Impact sites due to tributary impact – The impact sites are points downstream from the incorporation of a tributary with the main surface waters.
4. Recovery sites – The recovery sites are the points just downstream of where a BMP is implemented with the purpose of improving the water quality.
5. Outlet Site – The point in the river system where the water leaves the watershed.

The location of the monitoring sites could be modified to some extent without compromising the purpose of the program. Other criteria for site location that need to be taken into account are site accessibility, site safety, and permission to cross onto private property.

It is understood that cost and time can be limiting factors in implementing the monitoring program. Therefore the site selection process attempted to minimize distance between each of the monitoring points.

Sampling Strategy

This section provides standard procedures that should be followed while collecting the samples in order to improve precision and ensure accuracy. These considerations are as follows:

1. Make sure that the samples are taken in waters that are well mixed.

2. Avoid collecting samples at pools and riffle areas; collect somewhere in between these areas.
3. Never take samples in stagnant waters.
4. If possible, collect water at different sections within the cross section of the river and integrate them into a single sample, taking care to mix the sample well.
5. Make sure not to touch the inside of the bottle and the lid in order to avoid contamination.
6. Samples should be collected only if conditions in the stream are not dangerous.
7. Safety materials, such as gloves, should be provided to those taking samples.
8. At each point, water samples should be collected and immediately analyzed at the location whenever possible.
9. Whenever possible, the sampling time at each location should remain consistent throughout the monitoring program.
10. In addition to the field measurements, a sample vial (500ml or 1L) should also be collected and taken for analysis in laboratory.
11. The vials should be identified with the sampling location, date, time, and a code number.
12. Observations should be recorded on the datasheet, indicating abnormal conditions (rain event, amount of trash, color of the water, animals on the margins, etc.).
13. Samples and equipment should be returned to ECOSUR at the end of the sampling activities.
14. Water samples should be kept refrigerated for further analysis. Ice chests should be used to keep water samples below stream temperature during transportation.
15. Debriefing of the day's activities should occur between the sampling team and project coordinator.
16. The project coordinator should make sure that all the datasheets are filled out completely and that all the samples are labeled and stored correctly.

Measuring River Flow

Flow is the measurement of the volume of water passing a point on the stream at a specific time. The amount of water in the river or stream has a direct impact on the water quality, diluting or concentrating the nutrients and bacteria depending on the amount of water present. Flow measurements are also required to calculate the total pollutant flux at any given sampling location. Although most water quality standards are set by concentration, it is also important to determine the mass flux in order to better understand nutrient loading through time.

Flow measurements are normally taken at gauging stations set up near the river's margin. Gauging stations are sited in the stream to take systematic observations of the water level. Gauging stations make use of a scale anchored in the water or stamped to a fixed structure in the stream margin, which facilitates the observations of the water level of the watercourse (see Picture 6.1 for examples). From records of the water levels and other characteristics, like river width and water velocity, the river flow can be calculated.

The site location for this procedure is extremely important since it is necessary to enter the stream and measure the water depth. Easy accessibility and site security are the major requirements for selecting sites for river discharge measurements. The best places are sites with fixed structures in the river, like a bridge or cemented cross section. It is recommended that gauging stations be used to facilitate the observation of the water depth over time.

When choosing a cross section, places that lack eddies and obstacles are recommended. Look for a place that:

- has a relatively smooth cross section profile,
- has easy accessibility, and
- does not exceed the range of measuring devices being used.

Picture 6.1. Gauging stations used to measure water flow on Carpinteria Creek in Santa Barbara (left) and in San Cristóbal (right).

Once the gauging station is set on the river margin it is necessary to calibrate it. The best way to calibrate the gauging station is by taking flow measurements of the river and recording the water level on the scale bar. After a series of observations are collected, they then can be used to build a rating curve of that river section.

In order to produce the rating curve, the flow measurement has to be calculated. The stream flow should be determined at each site during each sampling round, using the protocol described below. Flow should not be directly measured if stream conditions are dangerous and entering the stream is hazardous in any way.

Since stream flow is the volume of water passing a certain point in the stream at a specific time, flow can be estimated using the cross sectional area of the stream multiplied by the water's average velocity: Stream Flow (m^3/s) = Cross Section Area (m^2)* Average Velocity (m/s).

To calculate the cross sectional area of the river (Figure 6.1), the river width and depth need to be measured prior to collecting water quality data. At every cross section, it is recommended that 10 equally spaced points be used across the width of the stream to determine the bed profile.

Once the data is collected, a cross sectional area can be calculated by multiplying the average depth by the width of the cross section.

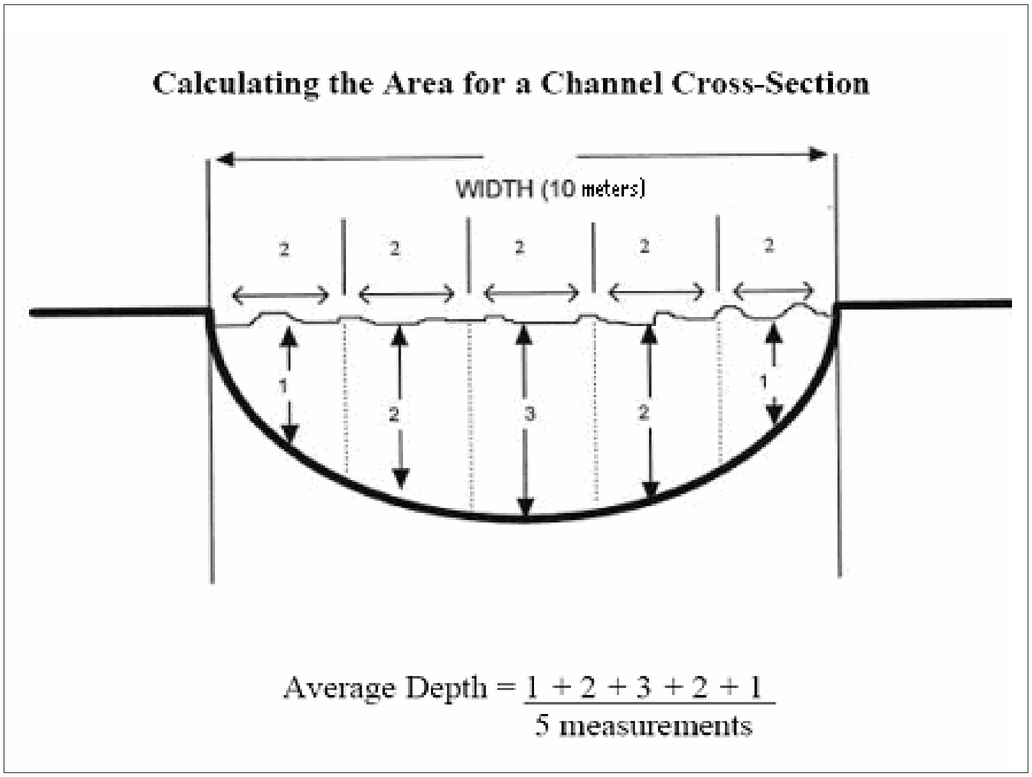


Figure 6.1. Calculation of the cross section (Nader, *et al.* 2006).

Picture 6.2. Measurements of the width and depths of a river cross section.

Once the area is measured, the next step is to measure water velocity. Measuring the time it takes a floating object (flotation device, wood stick, orange peel, etc.) to travel a known distance will yield an estimate of water velocity (Figure 6.2). We suggest using a minimum of 5 measurements (at different distances from the bank) to calculate the average velocity of the river.

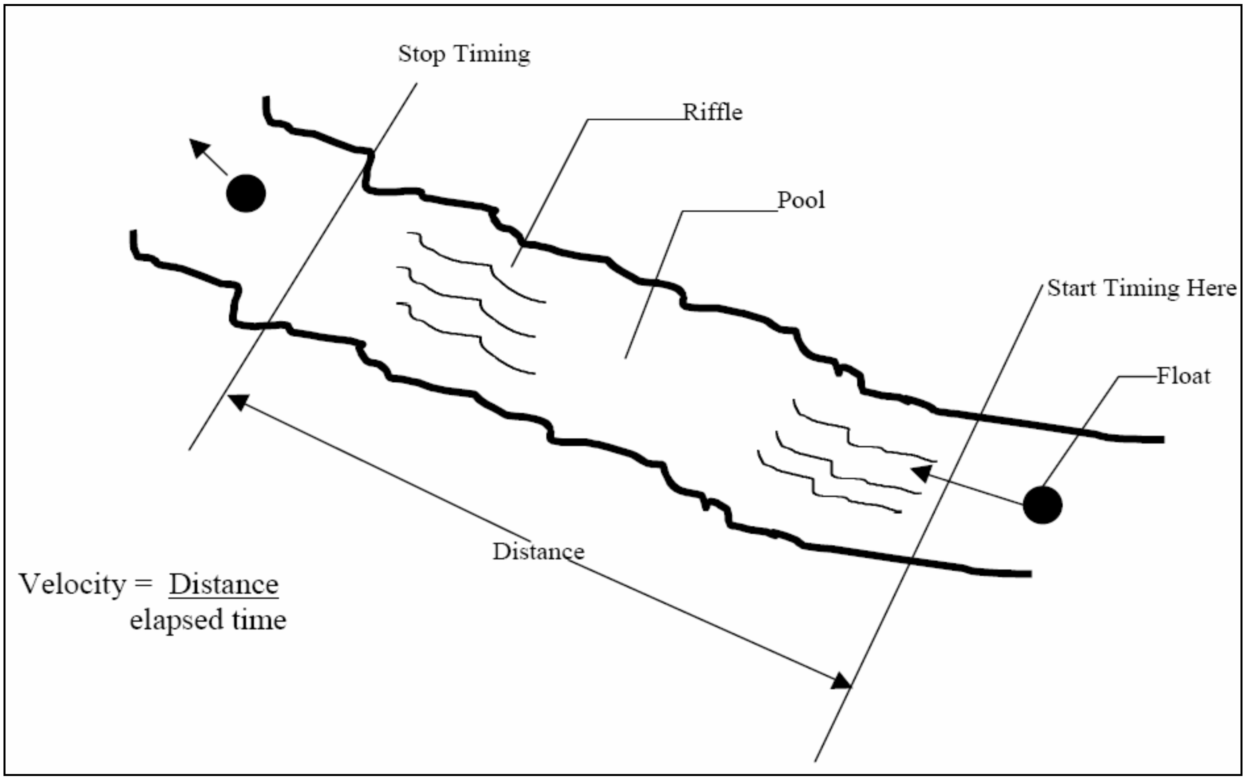
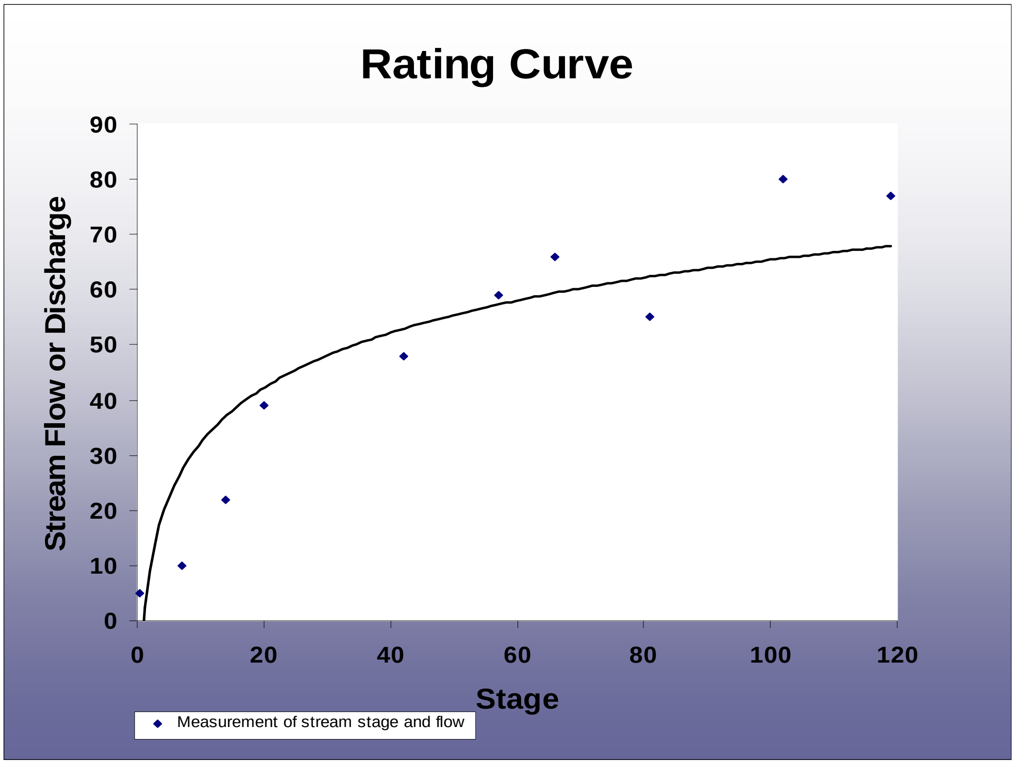


Figure 6.2. Calculation of the water velocity (Nader*, et al.* 2006).

After the average velocity and the area is measured, the calculation of the river discharge can be calculated using the following equation: Q=AV, where: Q = river discharge, A = total area, and V = average velocity.

Since the velocity of the water varies at different depths in the water column due to the drag of the water in contact with the river bottom the velocity measurement has to be adjusted with a correction factor. The most widely accepted correction factor for natural bottom rivers is 0.8 (Dunne and Leopold 1978). Rough river bottoms, with large rocks have a lower correction factor of 0.75 (Hewlett 1982) and channelized rivers with concrete bottoms have a larger correction factor of 0.85 (Chow*, et al.* 1994).

Once the river discharge has been calculated and the level of the stage gate has been observed at multiple times at different flows, it is possible to create a rating curve for that segment of the river. The rating curve is the best fit line to the measurements of stream flow (y-axis) with the observations of the water level at the stage (x-axis) (Figure 6.3). Once the rating curve is calculated, the river flow can be easily assessed by observing the water level of the stream and matching it with the stream flow value on the rating curve. It is recommended that the flow measurements be taken at all sites and that gauging stations be set up wherever feasible.



F**igure 6.3.** Example of a rating curve.

Sampling Protocol
In order to minimize bias and contamination and to improve accuracy and precision of the results, a series of protocols are suggested below. Some of those protocols are parameter and equipment specific, therefore, changes in the indicators sampled or equipment used would result in a change of the sampling protocol. However, these protocols provide valuable guidance for general methods.

The Water Quality Monitoring Report (Nader, *et al.* 2006) describes the 'screw-cap bottle' protocol for water samples as follows:

> *A. Remove the cap from the bottle just prior to sampling. Avoid touching the inside of the bottle or the cap. If you accidentally touch the inside of the bottle, use another one.*
>
> *B. Hold the bottle near its base and plunge it (opening downward) below the water surface. If you are using an extension pole, remove the cap, turn the bottle upside down, and plunge it into the water facing upstream. Collect a water sample 8 to 12 inches beneath the surface or mid-way between the surface and the bottom if the water is shallow.*
>
> *C. Turn the bottle underwater into the current and away from you. In slow-moving river reaches, push the bottle underneath the surface and away from you in an upstream direction.*

D. Leave a 1-inch air space (Except for DO and BOD samples). Do not fill the bottle completely (so that the sample can be shaken just before analysis). Recap the bottle carefully, remembering not to touch the inside.

pH - Use a field pH meter for this analysis. It is also necessary to have buffer solutions and distilled water to calibrate the instruments before the readings are taken. It is necessary to calibrate the pH meter and record the calibration reading before analyzing any sample. Record the temperature at which the instrument is calibrated and at which the samples are taken. At the sampling points, place the probe in the water column and wait until the meter reading stabilizes before recording the pH. Rinse the probe with distilled water after taking the measurements and after turning off the equipment.

Figure 6.4. Types of pH meter[8].

Temperature - Temperature can be measured with the same instrument used to measure pH. After taking the pH reading, measure the temperature reading in the water column and record it on the datasheet.

Dissolved Oxygen - The dissolved oxygen (DO) in the water can be measured with a DO meter. Like the pH meter, the DO meter needs to be calibrated before it is used in the field. Calibrate it according to the manufacturer's instructions. Record the calibration used for that day. At the site, place the meter in the water and stir the probe. Let the reading stabilize before recording it. Turn off the instrument and rinse with distilled water. It is recommended that a second sample be collected as a duplicate and analyzed immediately after collection. Compare the DO readings collected in the field and the results of the duplicate sample.

[8] More detailed information of pH meter could be found at the following manufacture's websites: http://www.hach.com and http://www.radiometeranalytical.com.

Figure 6.5. Types of DO meters[9].

Total Dissolved Solids - A conductivity meter is necessary to measure the total dissolved solids (TDS). After the conductivity meter has been carefully calibrated, turn it to the “TDS Mode”. Take the readings, stirring the probe in the water. Record the readings on the datasheet. It is also recommended to collect a second sample as a duplicate as described above.

Multiparameter equipment - Many of the instruments available today, are capable of measuring multiple parameters at the same time, including pH, temperature, conductivity, salinity, and DO.

Figure 6.6. Multi-probe meters[10].

Nutrient Sampling - It is recommended that the nutrient samples be analyzed with a colorimeter. The colorimeter DR/850 Portable Colorimeter from Hach was provided by UCSB to ECOSUR as resource to initiate the monitoring of the water conditions. The colorimeter allows for the absorbance of a solution at a particular frequency of visible spectrum. Using the absorbance or transmission, the colorimeter is able to measure the concentration of nutrients dissolved in solution. This equipment can measure over 50 water quality parameters using specific reagents.

[9] More detailed information of DO meter could be found at the following manufacture’s websites: http://contractor-books.com, http://www.hach.com, and http://www.forestry-suppliers.com

[10] More detailed information of Multi-probes meters could be found at the following manufacture’s websites: http://www.globalspec.com and http://www.hach.com.

Figure 6.7. DR/850 Portable Colorimeter used to measure a series of water quality parameters (Hach Manufacturer).

Fecal Coliform Bacteria Parameter - Before taking samples in the field, notify the laboratory where the samples will be analyzed so they can take the necessary preparatory actions. Pre-label the sterile bottles with the site code, date, time, and name of the person taking the sample.

Due to the high probability of contamination of this parameter, make sure to sometimes collect duplicates and triplicates of samples to compare results. Use sterile water bottles to collect the samples. It is recommended to take the sample in the middle of the stream. Be sure not to touch the inside of the cap or the bottle to avoid any contamination. Turn the bottle upside down (open end facing the water column) and submerge the bottle in the water, and then turn over bottle right-side up while it is still submerged. Avoid collecting any water from the surface. Allow some air inside the bottle and close it. Place the sample in a cooler with ice as soon as possible. Fecal coliform samples need to be analyzed the same day. Measurements of the fecal coliform bacteria are expressed as the number of organisms per 100 ml.

A list of the different equipment used to monitor the water quality parameters mentioned above was compiled in order to compare the prices of different manufactures and estimate costs (Table 6.2).

Table 6.2. Cost of some equipment used to measure water quality parameters in the field.

Item	Cost (US$)	Use	Retailer
Cooler (medium sized)	$45	Store water samples	Longs Drug Store
500 ml bottles (HDPE)	$3	Water samples to be sent to lab	Coleparmer
Oakton pH 110 Advanced Portable Meter	$446	pH meter	Fisher Scientific
Acorn pH 5 Meter Kit	$181	pH meter	Fisher Scientific
Oakton pH testr-3 w/buffer solutions	$126	pH meter	Coleparmer
WD-35640-00 Portable DO Meter 100	$489	DO meter	Pulse Instruments
Fisherbrand Traceable Portable DO Meter	$459	DO meter	Fisher Scientific
Accumet AP65 Portable Conductivity Meter	$778	Conductivity meter	Fisher Scientific
YSI 55	$699	DO meter and Temperature	Fisher Scientific
YSI 30	$695	Temperature, Salinity and Conductivity	Fisher Scientific
YSI* Model 556 Multi-Probe System	$1,750	pH, DO, Conductivity, Temperature, Salinity and ORP	Fisher Scientific
sensION156 Portable	$1,050	pH, DO, Conductivity, TDS, Salinity and Temperature	Hach
sensION378 Laboratory	$1,575	pH, DO, Conductivity, TDS, Salinity and Temperature	Hach
La Motte 2020	$800	Turbidity	Fisher Scientific
LaMotte* Portable Turbidity Meter	$829	Turbidity	Fisher Scientific
Surface Water Test Kit	$230	Ammonia, chlorine, pH, nitrate, dissolved oxygen, phosphorus, and temperature	Hach
CEL/890 Advanced Portable Laboratory	$2,413	pH, Temperature, Conductivity, TDS and 26 popular parameters	Hach
MEL/MPN	$1,670	Total Coliform and E. coli	Hach
DR/820 Portable Colorimeter	$649	Multiparameter (20 parameters)	Hach
DR/890 Portable Colorimeter	$961	Multiparameter (90 parameters)	Hach

After the costs for the equipment were found for different retailers, a series of devices and supplies necessary for the monitoring plan were chosen according to their necessity and cost

(Table 6.3). According with the estimates, it would be required less than US$3,000 dollars as an initial investment to acquire all supplies needed for the monitoring program. Some of the supplies, like La Motte and Flowmeter, can measure an indefinite amount of samples and can last for years if proper handled and maintained. Other supplies, like Nitrite Reagents and Pathoscreen, would last for 5 to 6 months.

Table 6.3. Cost of the supplies necessary to measure the water quality parameters.

Item	**Cost (US$)**	**Use**	**Retailer**
Cooler (medium sized)	$45	Store water samples	Longs Drug Store
500 ml bottles (HDPE)	$49	12 Water sample bottles	Coleparmer
La Motte 2020	$800	Turbidity	Fisher Scientific
sensION156 Portable	$1,050	pH, DO, Conductivity, TDS, Salinity and Temperature	Hach
Ammonia Reagent (DR/850 Colorimeter)	$61	Ammonia, Nitrogen	Hach
Total Nitrogen Reagent (DR/850 Colorimeter)	$66	Nitrogen, Total Inorganic (TIN)	Hach
Nitrate Reagent (DR/850 Colorimeter)	$28	Nitrate, Nitrogen	Hach
Nitrite Reagent (DR/850 Colorimeter)	$21	Nitrite, Nitrogen	Hach
Total Phosphorus Reagent (DR/850 Colorimeter)	$41	Phosphorus, Total and Acid Hydrolysable	Hach
Flow Probe Hand-held Flowmeter	$695	Water flow meter	Forestry Suppliers Inc.
PathoScreen Field Test Kit (100 tests)	$35	Measure presence of absence of pathogen bacteria	Hach
Total Equipment Cost	**$2,891**		

Frequency
This monitoring program is designed such that samples will be taken once a month at a minimum. The systematic collection of water samples throughout the year is extremely important to account for seasonal variations in the water quality.

River discharge in the San Cristóbal watershed varies significantly between the dry and wet season (Picture 6.3). Due to the drastic change in the water volume, it is expected that the pollutant concentration will also change between the dry and wet season. Observations recorded during our study in the region indicated that during the wet season, total suspended solids are higher, while during the dry season there is a higher algae concentration.

Picture 6.3. Río Fogótico during the dry season (left) and the wet season (right).

It is also important to monitor the streams during major storm events. During precipitation, nutrients that have accumulated on the soil surface are carried with the water runoff to the streams and rivers. The flux of nutrients tends to increase, provoking a nutrient peak a few hours after the storm. The nutrient concentration is likely to decline slowly after this peak due to the delay in the water arrival, which travels underground, percolating into the soil. The monitoring of storm events would provide information on the peak of nutrient flux as well as some information about the velocity of runoff in the system.

Resources
The monitoring program is expected to be organized and implemented by ECOSUR. Samples can be collected by students or volunteers interested in water quality issues and sampling methods. Training sessions for the potential volunteers should be held to explain the goals and importance of the project, methods that will be used, sampling protocols, and site locations. Samples should also be analyzed and stored at the laboratories of ECOSUR. It will be at the discretion of ECOSUR to decide which laboratories and equipment are used for this project.

It is already expected that improvements in the water quality generated by BMP implementation will have a time lag before changes are reflected in the water quality indicators. Depending on the type of BMPs implemented, the changes in water quality indicators could take months to years to be realized. Structural BMPs normally result in a more rapid response in water quality parameters, as compared to non-structural BMPs.

6.1.2 Drinking Water Quality Monitoring Program
Along with the monitoring program developed for surface water, a drinking water monitoring program was also compiled for San Cristóbal. The program reflects an interest of the local stakeholders to monitor not only the ambient water but also the drinking water supply. Currently, the water is generally distributed without analysis of its quality parameters. Therefore, it is not known if the water supplied to the people in San Cristóbal meets the standards set by the government authorities.

The objectives of the drinking water monitoring program are to

- evaluate the current condition of the water pumped from major artesian wells and four independent wells in the city of San Cristóbal,
- determine if the drinking water meets the water quality objectives set by the Official Mexican Norm (Norma Oficial Mexicana), and to
- determine what type of treatment or purification, if any, is necessary to improve the water quality.

Water Quality Standards

The results of the water analysis from the wells should be compared with the Official Mexican Norm that sets the national standards for drinking water in Mexico. This document compiles the maximum permissible levels of contaminants that assure safe human use and consumption (Table 6.4).

Table 6.4. Maximum concentration limits of chemical constituents in the (NOM 1994). (Limits expressed in mg/L, except when indicated other unit)

Characteristics	Acceptable Limits
Aluminum	0.20
Arsenic	0.05
Barrio	0.70
Cadmium	0.01
Cianuros (like CN-)	0.07
Free Residual Chlorine	0.2 - 1.50
Chlorides (like Cl-)	250.00
Copper	2.00
Total Chromium	0.05
Total Hardness like (CaCo3)	500.00
Phenols	0.00
Iron	0.30
Florines (like F-)	1.50
Manganese	0.15
Nitrates	10.00
Nitrites	0.05
Nitrogen Ammonia	0.50
pH (in units of pH)	6.5 - 8.5
Insecticides in micrograms/L (Aldrin and Dieldrin - separated or combined)	0.03
Chlordane (Total Isotopes)	0.30
DDT (Total Isotopes)	1.00
Gamma-HCH (Lindane)	2.00
Hexachlorobenzine	0.01
Heptachlorine and Epoxy of Heptachorine	0.03
Metoxiclhorine	20.00
2,4 – D	50.00
Lead	0.025
Sodium	200.00
Total Dissolved Solids	1000.00
Sulfates (i.e. SO_4)	400.00
Substances Activated by the Methylene Blue (MBAS)	0.50
Total of Trihalometanes	0.20
Zinc	5.00

CNA uses the most probable number (MPN) standard for assessing bacteria level in water and setting standards for national drinking water quality. According to the CNA standards, the total coliform should not exceed 2 MPN/100mL and fecal coliform should not be detected (0 MPN/100mL).

Another standard that could be used as a reference is the Drinking Water Standards from the World Health Organization (WHO) (Table 6.5). The full version of the standards for the WHO can be found in the Guidelines for Drinking-Water Quality, third edition.

Table 6.5. Summary of WHO drinking water standards (World Health Organization 2004).

Parameter	WHO Guideline
Color (TCU)	<15 [F]
pH	6.5 to 8.0
Turbidity (NTU)	<5 [F]
Total Coliform Count	Must not be detectable in any 100ml sample
Sodium (mg/L)	200 [T]
Chloride (mg/L)	250 [T]
Sulphate (mg/L)	250 [T]
Nitrate as NO_3 (mg/L)	50 [A]
Total Dissolved Solids (mg/L)	1000 [T]
Nitrite as NO_2 (mg/L)	3 [A] / 0.2 [BP]
Ammonium (mg/L)	[N] / 35 [T]
Iron (mg/L)	0.3 [T]
Manganese (mg/L)	0.1 [T] / 0.5 [C]
Fluoride (mg/L)	1.5
Arsenic (mg/L)*	0.01 [P]
Copper (mg/L)	2 / 5 [T]
Chromium (mg/L)	0.05 [P]
Lead (mg/L)	0.01
Nickel (mg/L)	0.02 [P]
Boron (mg/L)	0.5 [T]
Chlorine Free (mg/L)	0.5 to 5 [C]

A Short term exposure
B Long term exposure
C concentrations of the substance at or below the health-based guideline value may affect the appearance, taste or odour of the water, resulting in consumer complaints.
F Aesthetic guideline
N Occurs in drinking-water at concentrations well below those at which toxic effects may occur
P provisional guideline value, as there is evidence of a hazard, but the available information on health effects is limited
T provisional guideline value because calculated guideline value is below the level that can be achieved through practical treatment methods, source protection, etc.
X Taste threshold

Monitoring Points

Most of the water for the city is being pumped from nine major artesian wells. As requested by the stakeholders, the drinking water monitoring plan will focus on measuring the nine major wells that are managed by SAPAM, as well as the other four independent wells in the region (Table 6.6).

Table 6.6. Monitoring points for drinking water.

SAPAM wells	
1	Almolonga
2	La Kisst
3	La Hormiga
4	Navajuelos
5	San Juan de los Lagos
6	Salsipuedes
7	Campanario
8	Peje de Oro
9	Ojo de Agua
Independent Wells	
10	Huitepec
11	Alcanfores
12	La frontera
13	La Garita

The nine major wells administrated by SAPAM were identified in the map below.

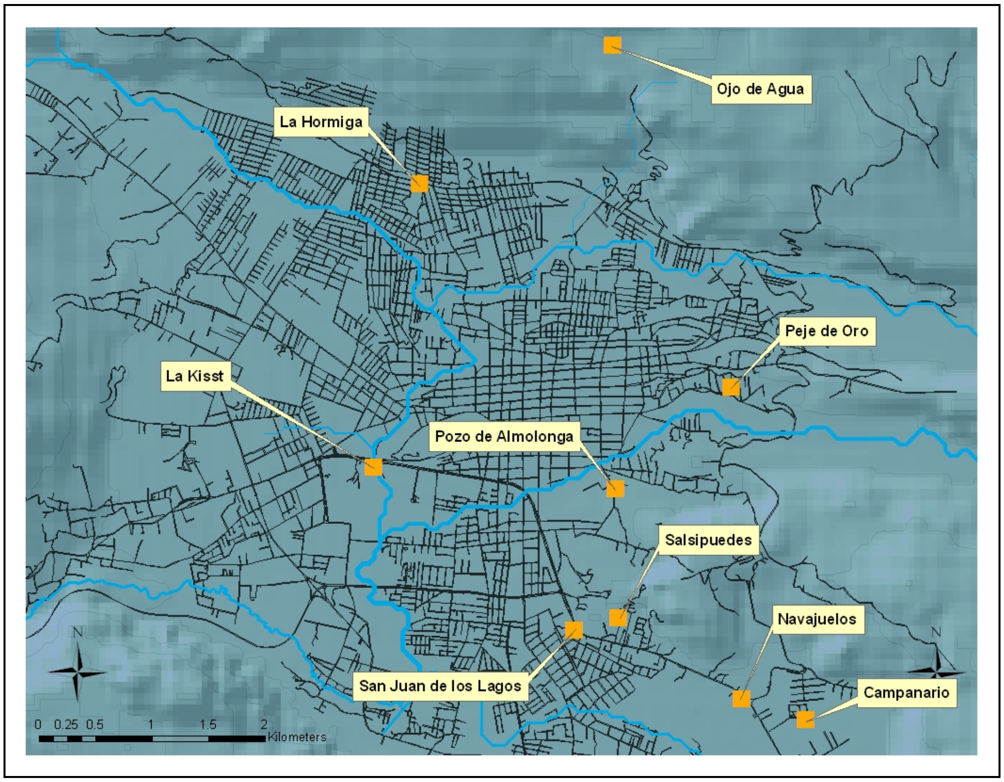


Figure 6.8. Location of the major wells in San Cristóbal.

The plan should follow sampling procedures, protocols, frequency and resources described in the surface water quality monitoring program described above. It is important to stress that sampling should be conducted every month. If, due to a lack of resources, the monitoring of all samples becomes unviable, the independent wells should be considered the lowest priority due to the small amount of water that they extract. Then, a possible solution would be to monitor these small wells once every two or three months.

It is important to note that both of these suggested monitoring programs should not be seen as a rigid project. As the program matures, the monitoring plan should be flexible and adapt to the current needs. Indicators and monitoring sites should be added or removed from the monitoring plan according to priorities, time, and the available resources. If, from the analysis results, indicators are determined to not be a concern for the region, their analysis could be discontinued without compromising the objectives of the plan.

On the other hand, consistency in the sampling procedures, frequency, and analysis will establish the strength and precision of the results. The longer the monitoring program is performed, the more accurately the results will characterize the water quality conditions of the watershed.

6.2 Best Management Practices

A critical component of the decision making framework that we are presenting to our partners is information on the best management practices (BMP) that are most likely to address the concerns within the watershed. The following analysis covers a broad range of BMPs, from composting latrines to oxidation ponds. The criteria used in this preliminary selection were cost, physical requirements, concerns addressed, and potential barriers to local implementation.

The primary concerns identified from the preliminary water quality assessment (see Section 5.3) and from discussions with our partners include nitrogen and phosphorus loading (from agriculture run-off, soaps and detergents, and human and animal wastes), sedimentation (from soil erosion), high levels of pathogens (from human wastes), large stormwater events, and decreased aquifer storage (less infiltration and groundwater recharge). For the upstream communities, additional problems may include soil erosion, access to a consistent supply of potable water, water storage, and flooding. There are various methods that can be implemented to address the aforementioned water quality concerns. The following table focuses on the BMPs best suited to meet water quality and quantity concerns in San Cristóbal.

Table 6.7. Best management practices for addressing water quality and quantity in San Cristóbal.

BMP	Problems Addressed	Potential Load Reduction	Cost Estimates	Potential Obstacles	Feasibility
Detention Basins	Stormwater runoff, some N and P loading	60% suspended solids, 20% P, 30% N, 25-50% metals	Size dependent, low to high	Maintenance, mosquito breeding potential, cannot remove soluble pollutants	Some Feasibility
Retention Basins	Stormwater runoff, N and P loading	65-70% suspended solids, 45-50% P, 30-35% N, 25-70% metals, 60-65% Bacteria	Size dependent, low to high	Maintenance, potential wetland alteration or loss	Feasible
Bioswales	Stormwater runoff, pollutant filtering, groundwater recharge	Soil and site specific	Land value	Some labor intensive maintenance	Feasible
Bioretention cells	Stormwater runoff, pollutant filtering, groundwater recharge	Soil and site specific	Land value	Some labor intensive maintenance	Feasible
Media Filters	Pollutant loads form stormwater runoff	60%-95% of suspended solids, 40-85% total phosphorus, 40%-50% total nitrogen, 25-90% of metals, up to 55% of bacteria	$2.50 to $7.50 per cubic foot treated ($85 to $260/cubic meter, average $175)	High Costs, maintenance to unclog filters, limited capacity	Limited Feasibility
Porous Pavement	Stormwater runoff, pollutant filtering, groundwater recharge	70% reduction in surface runoff	Costs estimates are $21-$32/ square meter.	High costs, maintenance	Very Limited Feasibility
Wetlands	Stormwater runoff, Secondary sewage treatment	Site specific for secondary sewage. Removal rates for Suspended solids- 65%, P- 50%, N- 30%, Bacteria- 75%	Protection for existing wetlands. For wetland construction- $65,000-$140,000/hectare	Land area encroachment	Limited Feasibility
Contour Water Retention Trenches	Sedimentation, N and P loading, erosion control, groundwater recharge, stormwater	70% Reduction	Labor Costs, land dedication	Maintenance required	Feasible
Percolation Trenches and Dry Wells	Sedimentation, N and P loading, erosion control, groundwater recharge, stormwater	70-75% Reduction	Porous Material, drilling & labor cots	Maintenance required	Limited Feasibility

BMP	Problems Addressed	Potential Load Reduction	Cost Estimates	Potential Obstacles	Feasibility
Conservation Agriculture	N and P loading, sedimentation and erosion control	P~ 25%, N~ 25%	Low	Education, monitoring, and enforcement	Feasible
Animal Waste Management	BOD, N and P, parasites/illness	Unknown	Low to medium	Education, monitoring, and enforcement	Feasible
Composting Latrines	Human waste disposal, sanitation, water contamination	70-80% Pathogen die off	Low to medium	Maintenance required	Feasible
Septic Tanks	Human waste disposal, sanitation, water contamination	50% of solids decompose, 50% must be removed as sludge	Low to medium	Maintenance, leaks, sludge disposal. Required land space	Some Feasibility
Pit Latrines	Human waste disposal, sanitation	Fecal coliform contamination reduction	Low	Groundwater contamination	Limited Feasibility
Pour-Flush Latrines	Human waste disposal, sanitation	Fecal coliform contamination reduction	Low	Groundwater contamination	Some Feasibility
Oxidation Ponds	Secondary sewage treatment	N & P~ 75% Reduction, 99.9% coliform reduction	Medium	Lack of sunlight, available land	Some Feasibility
Grey Water Separation/ Filtering	Supply, N loading	Average 20% re-use for irrigation. N load reductions	Low	Education, proper use, maintenance	Feasible
Rain Water Harvesting	Water availability	Increased Availability & Access	Low	Maintenance	Feasible
Small-Scale Water Tanks	Water storage and availability	Increased Availability & Access	Low to medium	Infrastructure	Some Feasibility
Soil Aquifer Treatment	Wastewater	70% Pathogen reduction	Relatively inexpensive/ pumping costs	Groundwater contamination	Very Limited Feasibility
Artificial aquifer recharge, Vadose-Zone Wells	Aquifer recharge	Increase water availability	High	Groundwater contamination	Limited Feasibility
Sanitation Campaigns	Poor sanitation, wastewater, human waste contamination	Significant	Educational costs	Lack of adoption, educational costs, behavior changes	Feasible

6.2.1 Best Management Practice Descriptions

The following is a more detailed description of each BMP listed in Table 6.7 above.

Detention Basins (Dry)

Purpose - Dry detention basins are basins designed to collect runoff during storms and provide temporary storage of water. Due to the limited residence times, the basins do not offer significant water quality improvements.

Function and method of construction - The structures are simple basins, with berm and discharge moderation structures to limit outflow. Outlet structures may be modified to achieve specific water quality criteria, allowing for manipulation of storage time and discharge volume.

Potential load reductions - Detention ponds can be effective in sediment collection, as well as in the reduction of nitrogen and phosphorus loads. Reduction estimates are 60% of total suspended solids, 20% of total phosphorus, 30% of total nitrogen, and 25-54% of metals (U.S. EPA 2002a). Detention basin performance is closely linked to site design, and local hydrological and environmental conditions (Iowa Association of Municipal Utilities 2000). Detention basins are not effective for the removal of soluble pollutants.

Costs - Costs are site specific and depend on labor inputs and available land. Cost estimates for the U.S. are: $C=12.4V\wedge^{0.760}$, where: C=construction, design, and permitting cost, and V=volume needed to control the 10-year storm (ft^3). Typical U.S. costs are: $41,600 for a 1 acre-foot pond, $239,000 for a 10 acre-foot pond, $1,380,000 for a 100 acre-foot pond (U.S. EPA 2002a).

Potential obstacles - Some maintenance is required for the seasonal clearing of vegetation. Basins may also become grounds for mosquito breeding, which can pose a risk to human health and decrease property values (U.S. EPA 2002a).

Feasibility - Detention basins could be effective in both upstream and downstream areas of San Cristóbal. The use of detention basins may be most applicable in areas directly upstream from the urban settlement for stormwater attenuation and nutrient load reduction.

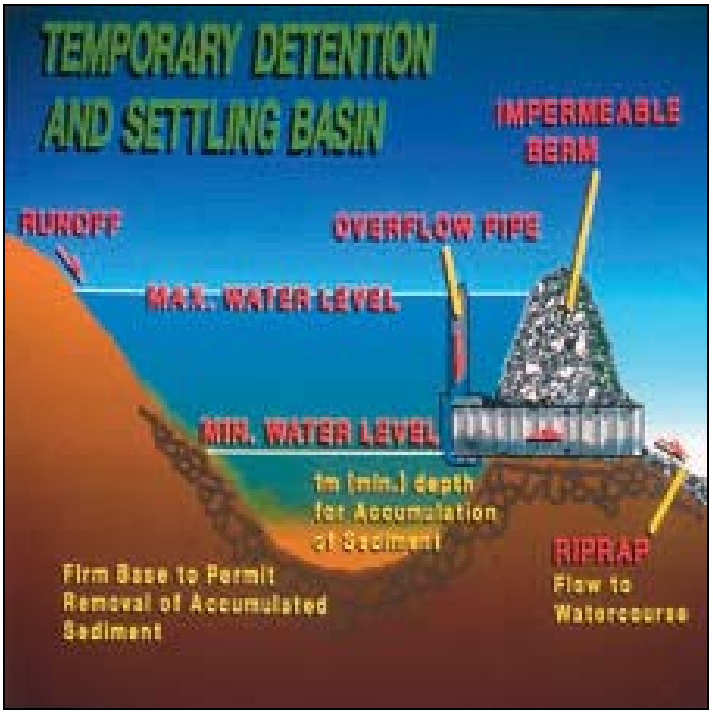


Figure 6.9. Detention basin schematic (Department of Fisheries and Oceans 2001).

<u>Retention Ponds</u>

Purpose - Like detention basins, retention ponds are designed to mitigate pollutant loads from surface runoff during storm events. However, retention ponds are more effective at removing pollutants and trapping sediment than detention basins due to the increased residence time of water in the system.

Function and method of construction - Like detention basins, the retention ponds are dug out of low areas or below the confluence of two or more streams. Unlike detention basins that dry out between events, retention basins maintain some amount of water at all times. The permanent pool of water is replaced in part, or in total, by stormwater during a rain event. The design is such that any available capture volume is released over time. The residence time in the retention ponds for low intensity storm events is generally longer than in detention ponds (U.S. EPA 2002d). Two stage outlets allow for more rapid discharge during larger events (Caltrans 2002). To maintain the required water levels, a liner and/or a high groundwater table are required. Retention ponds can also incorporate vegetation to facilitate pollutant filtration and uptake.

Potential load reductions - Estimates of potential load reduction are 65-70% of total suspended solids, 45-50% of total phosphorus, 30-35% of total nitrogen, between 25-70% of metals, and up to 65% of bacteria (U.S. EPA 2002d).

Costs - Costs are site-specific and depend on labor inputs and available land. Some maintenance is needed. Costs for the U.S. are: $C=24.5V\wedge^{0.705}$, where: C=construction, design, and permitting cost, and V=volume needed to control the 10-year storm (ft^3). Typical U.S. 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 (U.S. EPA 2002d).

Potential obstacles - Intermittent increase of mosquito breeding habitat is a concern. Retention ponds may cause the loss of wetlands if constructed in the wrong location. Generally, retention ponds are not appropriate for dense urban areas, may cause stream warming, and pose safety hazards (U.S. EPA 2002d).

Feasibility - Ponds may be constructed upstream or downstream from San Cristóbal. The use of retention basins may be most applicable in areas directly upstream from the urban settlement to reduce stormwater runoff and pollutant loads. A liner for the retention pond may be especially important given the depth of the shallow groundwater table and San Cristóbal's karst geology.

Bioswales and Buffer Strips

Purpose - Bioswales and buffer strips are used to slow stormwater runoff and facilitate infiltration. They are designed to be used in and around urban areas in order to reduce the load on stormwater conveyance systems during rain events. By reducing the volume and velocity of surface runoff, bioswales serve as an alternative to traditional stormwater systems and sewers. They contribute to on-site water infiltration by reducing the amount of impervious material. Likewise, bioswales and buffer strips may reduce the volume of water to be treated by downstream wastewater treatment sites (Caltrans 2002).

Function and method of construction - Swales are generally constructed next to impervious surfaces to allow for the slow conveyance of surface runoff. Low-lying areas are dug out in the form of a wide trench and vegetated with native plants. Depending on site specifics and the desired infiltration rate, a mixture of porous materials (sand, rock, gravel, etc.) may be added to the ground below the swale. Bioswales can filter both large rain events and the small, more frequent episodes. Discharge may be designed to enter the groundwater, stormwater drains, or back into the surface water (Iowa Association of Municipal Utilities 2000). Buffer strips serve some of the same functions, though to a lesser degree. Vegetated strips are mixed in urban or agricultural zones with high percentages of impervious surfaces. The strips allow for some stormwater mitigation during events, facilitate on-site infiltration, and provide limited habitat to native flora and fauna.

Picture 6.4. Example of a bioswale (Pimpama Coomera Waterfuture Project 2006).

Picture 6.5. Example of buffer strips (Georgia Stream Buffer Institute 2005).

Potential load reductions - The effectiveness of a bioswale is site-specific. The size, location, and design will determine potential pollutant load reductions

Costs - Costs will depend on land value.

Potential obstacles - Bioswales and buffer strips require a sufficient amount of land and ongoing maintenance in order to be effective. Maintenance may be labor intensive, though not technologically demanding. Improperly designed swales that do not drain rapidly after storm events may contribute to mosquito breeding zones. It may be necessary to mix porous medium into the substrate in order to increase the infiltration rate.

Feasibility - The implementation of bioswales and buffer strips is most feasible in the urban periphery, new development sites, and in open space corridors. Due to limited space in the city center, bioswales may not be appropriate. Space permitting, small scale buffer strips may be applicable around the urban center.

Bioretention

Purpose - Bioretention cells serve similar functions as bioswales. They are designed to collect large volumes of water during rain events and store the water for longer periods of time. The bioretention cells absorb large volumes of water from impervious surfaces and reduce the pollutant loads from direct surface runoff (U.S. EPA 1999a).

Function and method of construction - Similar to swales, bioretention cells are depression areas, which are dug slightly deeper to absorb more runoff. A selection of porous material may be mixed in the subsoil to allow for increased infiltration. The bioretention areas are typically replanted with native vegetation. They are most effectively used in areas where a high percentage of impervious surfaces produce a significant pollutant load runoff (Iowa Association of Municipal Utilities 2000).

Potential load reductions - The effectiveness of bioretention cells is site-specific. The size, location, and design will determine potential pollutant load reductions.

Costs - Costs depend on land value.

Potential obstacles - Bioretention cells require a sufficient amount of land, the possible addition of porous materials, and ongoing maintenance in order to be effective. Bioretention technology is generally not appropriate where the water table is within 1.8 meters of surface (U.S. EPA 1999a). Maintenance may be labor intensive, though not technologically demanding. Improperly designed bioretention cells that do not drain rapidly after storm events may become mosquito breeding zones.

Feasibility - The implementation of bioretention cells would be most feasible in the urban periphery, new development sites, and in open space corridors. Due to limited space in the city center, bioretention cells may not be appropriate.

Media Filters (Sand and Organic)

Purpose - A portion of the pollutants found in stormwater can be removed by media filter facilities. Media filters can reduce the stress on downstream wastewater treatment plants by treating some of the stormwater before it is discharged into the stream network. Effectiveness of media filters will depend on the strategic location of facilities and the number and diversity of filters used to process incoming water. Potential application could include locating facilities near areas of high concentrations of pollutants, and filtering water before the runoff enters the stream network.

Function and method of construction - The facilities use some form of granular or membrane filter, with or without a pre-settling basin, to remove stormwater pollutants. The most typical filter is sand, but other materials are commonly used, including peat mixed with sand, compost with sand, geo-textiles, and absorption pads and beds (U.S. EPA 2002b). Slow sand filters can remove particles that are smaller than the spaces between sand grains. Slow sand filters contain very fine sand and usually function without chemical pre-treatment, such as chlorination or flocculation. The low filtration rate causes long detention times of the water above the sand and within the sand bed. This allows substantial biological activity. Slow sand filtration removes particles mainly at the surface of the sand bed.

Potential load reductions - Potential load reductions depend on the number and diversity of media filters used. Removal estimates range between 60-95% of suspended solids, 40-85% of total phosphorus, 40-50% of total nitrogen, 25-90% of metals, and up to 55% of bacteria (U.S. EPA 2002b). The ranges of pollutants filtered will depend to the type of medium used to filter, as well as subsequent re-filtering in different tanks.

Costs - The average U.S. cost of treatment using media filter facilities ranges from $2.50 to $7.50 per cubic foot ($85 to $260 per cubic meter treated, average $175/cubic meter) (U.S. EPA 2002b).

Potential obstacles - Limited space and potential costs may limit the use of media filters.

Feasibility - Though media filters are able to remove substantial amounts of pollutants, the cost of treatment is high. Therefore, the feasibility of media filters to capture non-point source runoff for filtration is limited.

<u>Porous Pavement</u>

Purpose - Porous pavement is designed to allow for stormwater infiltration. A portion of water that normally is runoff due to impervious surfaces is allowed to filter into the groundwater. Porous pavement can only be used in low traffic areas, and can reduce the volume of water and pollutant loads during rain events.

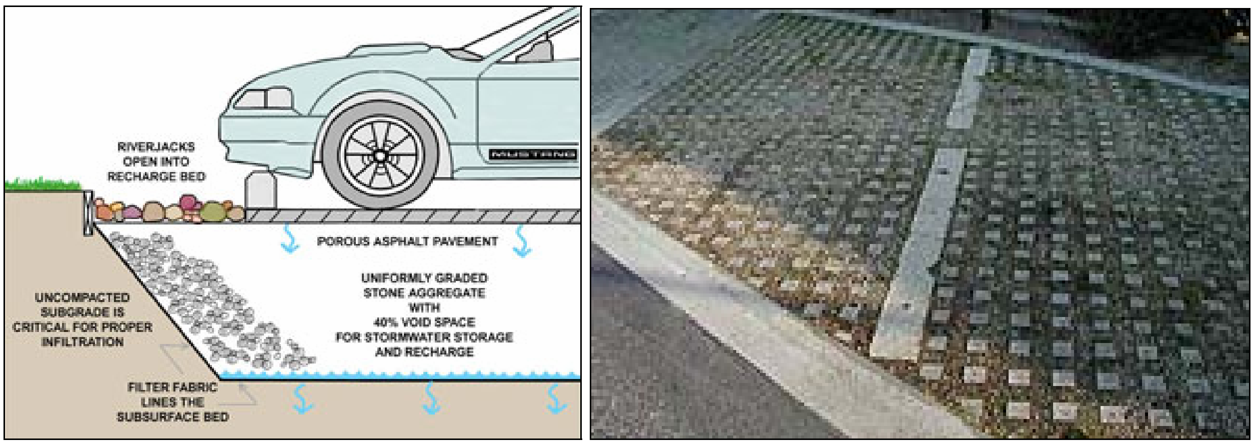
Function and method of construction - There are different methods to install porous pavement. The concrete mix itself may be designed to encourage a rapid infiltration of water. Fine particles and sand must be removed from the concrete mix to achieve increased levels of infiltration (U.S. EPA 2002c). Modular block may be placed below concrete or asphalt before being poured. Modular block is similar to concrete block in its structure. The zone of use is usually underlined with gravel, and a porous medium such as gravel or coarse sand is used to fill in the block spaces. Modular block needs to be place in a concrete grid to restrict the horizontal movement of infiltrated water. Thus, the infiltrated water is encouraged to percolate downward into the subsoil and/or groundwater.

Potential load reductions - The effectiveness of porous concrete is site-specific. The size, location, and design will determine potential pollutant load reductions

Costs - The U.S. costs range from $2-$3 per square foot (0.09 square meters). The costs translate to $45,000 - $100,000 per acre treated (U.S. EPA 2002c).

Potential obstacles - Modular block cannot be used in heavy traffic areas. Though up to 70% of slow moving water may be filtered to the ground, the block requires vacuum sweeping, maintenance, and replacement due to traffic stress (U.S. EPA 2002c).

Feasibility - Porous pavement, due to the high costs, may be used in a limited fashion in areas of low traffic, where there are high concentrations of pollutant and stormwater runoff.



Picture 6.6. Porous asphalt schematic (left) and infiltration concrete (right) (Guillette 2006).

Wetlands

Purpose - The use of wetlands, both natural and constructed, may help reduce the amount of pollutants in the water.

Function and method of construction - As wastewater flows through these low-lying areas, reeds and other aquatic plants act as natural filters. There is no oxygenation requirement. Treatment occurs at the soil-root interface of the wetland plants (Parr, *et al.* 2002). A wetland basin is similar to a retention pond (with a permanent pool of water) with more than 50% of its surface covered by emergent wetland vegetation or similar to a detention basin (no significant permanent pool of water) with most of its bottom covered with wetland vegetation (U.S. EPA 1999b). Retention ponds are also commonly known as “wet ponds” because they have a permanent pool of water, unlike detention basins, which dry out between storms. The permanent pool of water is replaced in part, or in total, by stormwater during a storm event. The design is such that any available surcharge capture volume is released over time. Retention of stormwater in the permanent pool over time can provide biochemical treatment. A dry weather base flow, pond liner, and/or high groundwater table are required to maintain the permanent pool (U.S. EPA 1999b).

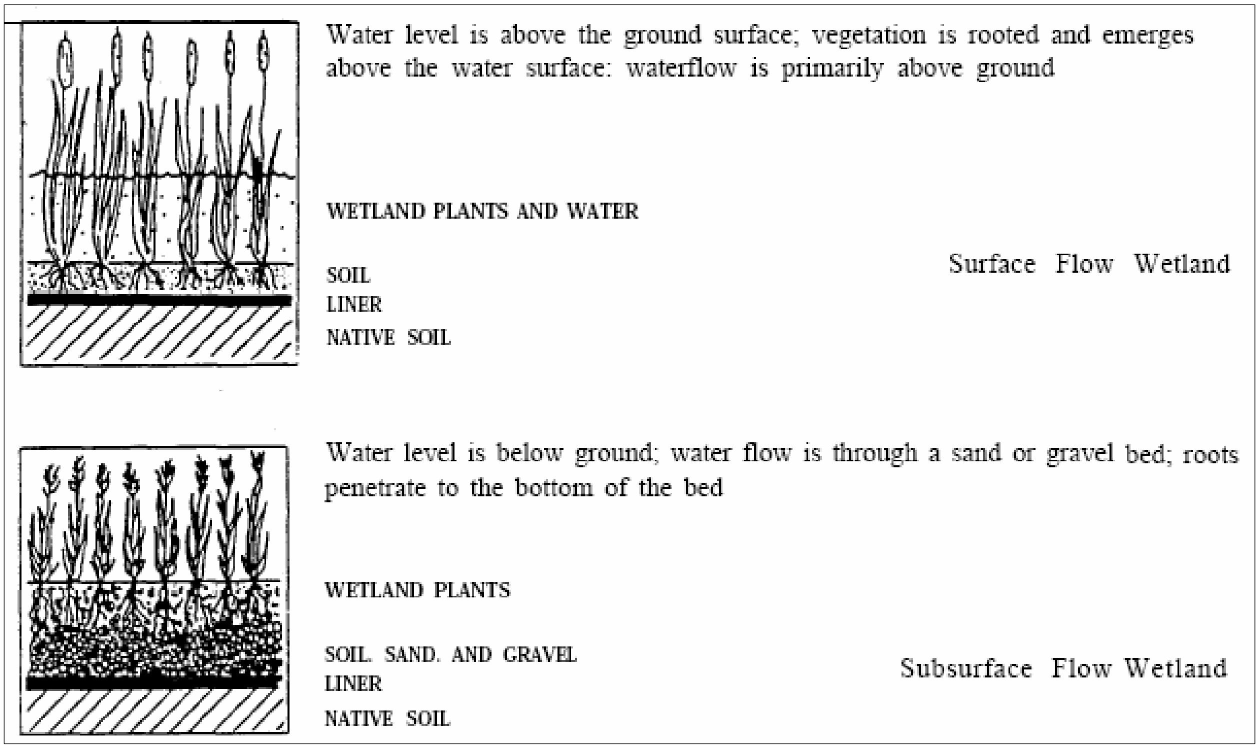


Figure 6.10. Constructed wetland diagram (DuPoldt, *et al.* 1999).

Potential load reductions - Effectiveness is site-specific for secondary sewage. Typical removal rates are as follows: 65% of suspended solids, 50% of phosphorus, 30% of nitrogen, and 75% of bacteria (U.S. EPA 1999b).

Costs - Costs include land acquisition and protection for the existing wetlands. For construction of new wetlands, U.S. costs are $65,000-$140,000/hectare (U.S. EPA 1999b). Maintenance costs are low once a wetland is established.

Potential obstacles - Additionally, for any constructed wetlands in karst topography, an impermeable layer is needed to line the bottom to prevent contamination of groundwater by untreated sewage (Iowa Association of Municipal Utilities 2000).

Feasibility - In San Cristóbal, the low-lying wetlands once acted as a natural filtering system. However, population expansion has limited the effectiveness of the wetlands due to increased pollutant loads and decreased wetland area. Due to the relatively large area of land necessary for effective wetland filtering to occur, only limited reliance on wetlands is recommended downstream of the city. Upstream from the city, the use of wetlands to filter limited sewage may be more applicable. Downstream from the city, native wetlands may suffer from heavy contamination from industrial sources. The existing wetlands in San Cristóbal cannot be relied upon to properly filter the sewage load from the city of San Cristóbal.

Contour Water Retention Trenches

Purpose - Water retention trenches facilitate the infiltration of surface runoff into the subsoil by filling up during rain events and slowly allowing water to percolate into the ground. The practice is also important for reducing the velocity of surface runoff. Reducing the velocity of surface runoff decreases soil erosion, especially in or down slope from agricultural fields (Natural Resources Conservation Service 2004).


Picture 6.7. Contour Trenches (Natural Resources Conservation Service 2006; Shaxson and Barber 2003).

Function and method of construction - Trenches are primarily employed along the contour of slopes in agricultural regions or near communities where there is sufficient open space. The construction process consists of first delineating the horizontal contour along a slope. Next, water retention ditches are dug, with the excess soil being used to form a berm on the downhill side of the trench. The width and depth of the ditch may vary depending of steepness of slope. Typically, a trench is dug at least 30-50 centimeters both in width and depth (Shapiro and Tran 1998). Depending on the slope, as well as the preference of the individual land owner, the trenches should be spaced between 16-40 meters apart. On the downhill side of the contour trench, permanent, and preferably deeply rooted, vegetation should be planted to stabilize the slope (Natural Resources Conservation Service 2004). It is important that the ditches are dug along the contour as to prevent the runoff of surface water. An 'A' frame (level) may be used to find the contour of the slope. Trenches need to be cleared of vegetative growth and loose sediment as part of the maintenance routine.

Potential load reductions - Effectiveness in reducing loads will depend on the onsite conditions and maintenance. Sedimentation in the surface water will invariably be reduced, though coarse particles will be reduced more than finer, clay particles. The literature suggests a potential runoff reduction of 75% and 70% for phosphorus and nitrogen, respectively (U.S. EPA 2006).

Costs - Costs are dependent on labor and land value. Also, there are additional costs of labor for maintenance.

Potential obstacles - Potential obstacles include the land requirement and labor costs.

Feasibility - Though the technology is appropriate for the region, potential problems with implementation of water retention ditches include hesitation of individual landowners to supply necessary labor and land, lack of perceived benefits by the land owners, and lack of maintenance.

Percolation Trenches and Dry Wells

Purpose - Percolation trenches and dry wells, similar to water retention ditches, facilitate the infiltration of surface runoff back into the subsoil. Problems addressed include stormwater management, surface water quality, erosion control, and groundwater recharge. Percolation trenches and dry wells augment the mitigation of stormwater runoff (compared to water retention trenches) during rain events, as well as contribute to aquifer recharge.

Function and method of construction - One difference between these techniques and the basic water retention trenches is the ditch depth. Percolation ditches are usually dug slightly deeper and wider, then partially refilled with a porous medium. The porous medium encourages the rapid percolation of surface runoff to the groundwater while maintaining subsoil integrity. A dry well is drilled through sub-surface impervious layers. Likewise, the dry wells are filled with a porous medium to further facilitate infiltration deeper into the groundwater (U.S. EPA 2006).

Potential load reductions - Effectiveness of the trenches depends on various factors including soil layer permeability, proper maintenance (see contour water retention trenches), vegetative cover, and frequency of application. The literature suggests a potential runoff reduction of 75% and 70% for phosphorus and nitrogen, respectively (U.S. EPA 2006). Sedimentation will be reduced, though over long time periods finer particles may fill in the porous medium.

Costs - Generally, these costs are higher than for simple water retention trenches. Costs are dependent on labor, and land value. Also, there are additional costs of labor for maintenance.

Potential obstacles - Potential dry wells need to be situated away from pumping stations and/or drilled to a shallower depth than from which the groundwater is pumped for human consumption.

Feasibility - Percolation trenches and dry wells may be more appropriate in marginalized zones closer to the urban area of San Cristóbal. The costs of drilling through impervious layers and filling with porous medium may be warranted only in critical areas where soil erosion and the volume and velocity of stormwater runoff cause severe stormwater management problems. One potential problem could be the direct influx of contaminated stormwater into a zone from which a SAPAM pumping station draws water.

Conservation Agriculture

Purpose - The purpose of conservation agriculture practices is to reduce the loads associated with traditional practices. Agricultural loads primarily consist of elevated nitrogen and phosphorus concentrations, as well as sedimentation. Conservation agricultural practices are designed to reduce erosion and nutrient runoff. The practices may be used in conjunction with contour trenches that facilitate water and pollutant infiltration to achieve improved load reductions.

Function and method of construction - Conservation agriculture includes leaving crop cover and plant residues on the field to control erosion and nutrient leaching from the field (Shapiro and Tran 1998). Runoff is increased when fields are cleared both before and after planting. Buffer areas may be left between tilled fields. Permanent strips of vegetation are intermixed between cropped areas to provide in-filed buffer strips. Fields on slopes may also be leveled prior to planting (conservation tillage) (U.S. EPA 2006).

Potential load reductions - Potential load reductions from a combination of conservation agriculture practices are between 25-45% for phosphorus, and 25-55% for nitrogen (U.S. EPA 2006).

Costs - Costs are site specific and depend on the intensity of implantation.

Potential obstacles - Potential problems include lack of education and implementation, maintenance, and monitoring.

Feasibility - Though a significant amount of education is required, conservation agricultural practices are feasible throughout the San Cristóbal watershed.

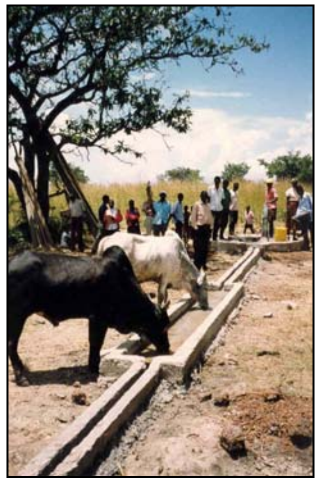
Table 6.8. Cost for BMPs that address stormwater runoff, nitrogen and phosphorus loading, erosion and sedimentation control, and limited groundwater recharge (Adapted from: (California Regional Water Quality Control Board Santa Ana Region 2004).

BMP	Typical Costs ($ per cubic feet of runoff)
Detention and Retention Basins	$0.50 - $1.00
Bioswales	$0.60 - $1.25
Bioretention	$0.60 - $1.25
Media Filters	$0.60 - $1.25
Constructed Wetlands	$0.60 - $1.25
Infiltration Trenches	$0.60 - $1.25

Animal Waste Management

Purpose - Animals in both urban and rural settings of the San Cristóbal watershed may contribute a significant amount of wastes to the stream network. Currently, much of the domestic animal and livestock population is allowed direct access to the streams. The problem arises from the animal wastes directly entering the water supply. The wastes in the water include BOD (animal manure has a high BOD), nitrogen, phosphorus, fecal pathogens, and potentially the Cryptosporidium parasite (parasite associated with human illness) (Bouwman 1997). The practice of fencing animals out of direct stream access and away from community or household water sources may help reduce the loads to be treated downstream.(Bouwman 1997)

Function and method of construction - Keeping animals out of the water network will require a significant amount of education, as well as fencing material, and small-scale water diversion infrastructure. First, a widespread education campaign will be needed to begin instituting behavioral change to the general population (urban and rural) regarding animal access to the streams and other water sources. Additionally, promoting the use of livestock wastes for manure composting can contribute to load reductions and improve the water and nutrient retention capacity of soil by building structure. Composting will become more feasible if feed is broken up for livestock in order to improve digestibility (Bouwman 1997).

Picture 6.8. The picture on the left shows how direct animal stream access can lead to soil erosion, bank destabilization, and water contamination (Wisconsin Department of Natural Resources 2005). The picture on the right illustrates how a water diversion project for livestock can help to protect stream water quality (Christian Engineers In Development 2002).

Potential load reductions - Load reductions depend on frequency of application and enforcement.

Costs - The costs will include fencing materials, coupled with the digging of small-scale water diversion gullies for animal access away from the streams. These costs are expected to be low to medium. The majority of the costs will come in terms of education, implementation, and enforcement of keeping animals out of streams.

Potential obstacles - The majority of the problems will come in terms of monitoring, compliance, and enforcement.

Feasibility - Only with significant attention to education and enforcement will reducing animal wastes be feasible.

Twin Chamber Composting Latrines

Purpose - Many of the new settlements on the periphery of San Cristóbal, and the smaller rural communities located upstream from the city, are not connected to the public sewer network. Dry Composting Latrines provide rural communities with a realistic alternative solution for managing human wastes. In many cases, pit latrines are used to deposit human waste. However, the waste in pit latrines may eventually seep into the groundwater and possibly contaminate the downstream surface water. Twin chamber and pit composting latrines prevent the release of harmful pathogens into ground and surface waters. The composting latrines may be constructed close to the home without concerns of subsoil or groundwater contamination. Composting latrines are particularly valuable in areas with a high water table.

Function and method of construction - Two separate chambers are constructed, with separate toilet seats for each one, and a tube to separate and drain out urine. The latrine is built approximately 1 meter above the ground level to allow for access to either chamber once composted material is ready for extraction and use. Only one chamber is used during any given period, to allow composting to occur in the inactive chamber without re-contamination from fresh wastes. After each waste deposit, earth, lime, and/or ash may be used to cover the waste in the active chamber before re-covering the toilet seat. Lime or ash additions serve to raise the pH level, producing more alkaline conditions which facilitate decomposition of pathogens. The latrine requires periodic mixing with a designated instrument to facilitate composting. Once the chamber is close to being filled, the entire remaining wastes are fully covered with a mixture of earth, lime, and/or ashes. The seat is sealed for a period of 6-8 months while the other chamber is utilized (Shapiro and Tran 1998). After this time period, the mixed material may be removed from the sealed chamber and used as a limited form of compost.

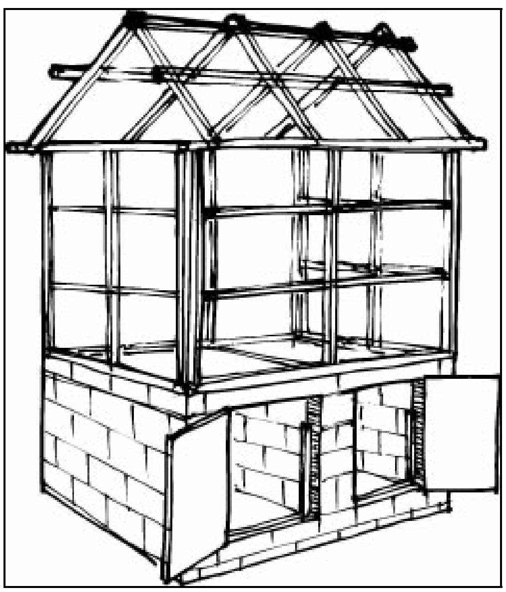


Figure 6.11. Twin pit composting latrines (Crennan 2005).

Potential load reductions - After a composting period of a few months, samples have shown a 70-80% die off rate for pathogens (Saywell 1996). Longer composting periods, improved temperature regulation, and additional earth, lime, and/or ash inputs will further reduce pathogen levels. Lab analysis after 6 or more months has shown typical moisture content to range from 12-16% and that *E. coli* and coliforms are absent in most cases (Farley and Kilbey 1999). In addition, the use of ventilation pipes and dry earth with twin pit composting latrines helps to significantly reduce odor compared to traditional pit latrines.

Costs - Costs for individual composting latrines are low. Installing latrines on a large-scale may have a medium cost due to transportation of materials, many organizations in the area have demonstrated their willingness and ability to fund small-scale projects throughout the watershed.

Potential obstacles - The major source of problems has proven to be poor maintenance and improper use.

Feasibility - Many communities around the San Cristóbal watershed have received composting latrine projects. However, interviews reveal that various community members do not properly maintain the latrines. Effectiveness will depend on adequate education, along with firm household and community commitments, in order to ensure the proper use of composting latrines.

Septic Tanks

Purpose - Septic tanks are located below the ground to collect wastes from individual households. Septic tanks are used to prevent human wastes from contaminating the groundwater and surface water. Though sludge from septic tanks must be extracted, the tanks may reduce human waste load events from stressing a wastewater treatment plant.

Function and method of construction - The primary function of septic tanks is to serve as a holding tank for human waste. Septic tanks are connected to standard or pour-flush toilets, and may be appropriate for individual household use, a group of households, or a small community. The tanks must be watertight, and may be constructed out of concrete, fiberglass, or plastic. Solids are settled in the main tank, while floatable overflow (grease, oil) water is allowed to fill up to an outlet pipe (U.S. EPA 2000). The outlet allows the grease and oil to drain through a leach field. All wastes should stay in the tanks at least 24-72 hours before they overflow to a leach field. The volume and flow rate of wastewater are critical to the recommended retention time.

Table 6.9. Minimum retention times for wastewater in septic tanks (World Health Organization 1992).

Wastewater Flow (m^3/day)	**Minimum Retention Time (hours)**
< 6 m^3/day	24+ hours
6 - 14 m^3/day	33+ hours
> 14 m^3/day	up to 72 hours

(Maximum sewage flow estimated between 0.1 – 0.2 m^3/person-day)

Wastewater may be allowed to overflow directly to a public sewer system designed to receive these loads. A portion of the solid wastes will decompose, while the remainder must be periodically removed by pumping trucks. The remaining sludge that does not decompose is pumped out and must then be transported to the proper waste disposal facility (U.S. EPA 2000). Tank size and design will depend on estimated load inputs (World Health Organization 1992). It is important to properly estimate these loads before installing a septic tank.

Potential load reductions - Properly used septic tanks will reduce non-point source pollution. Frequency of application will determine load reductions.

Costs - Costs are low to medium depending on the size of the septic system.

Potential obstacles - Potential problems include the proper installation and maintenance of the tanks. There is also no system to observe failures in the tank and/or excessive loads to the leach field. Users may have the tendency to throw household garbage into the tank which will cause clogging. Additionally, small leaks may cause contamination of shallow groundwater (U.S. EPA 2000). Septic tanks and the leach fields require a significant amount of space and may produce an unwanted odor.

Feasibility - The technology is only appropriate for low density housing areas.

Pit Latrines

Purpose - Pit latrines are designed to manage human wastes. The pits provide a low cost and immediate, though temporary, solution to human waste storage and disposal.

Function and method of construction - Pit latrines are simply a hole dug in the ground where human waste can be deposited. Generally, a floor or concrete slab is constructed over the pit, with a basic toilet and latrine structure built on top of the slab. Caution needs to taken to properly stabilize the structure to prevent collapse. Once the pit is nearly filled, the remainder is capped off with earth and sealed to allow for decomposition. The abandoned pits must be left undisturbed for a minimum of two years (usually, several more years) before wastes can be safely handled (World Health Organization 1992).

Potential load reductions - Properly used latrines will reduce non-point source pollution. Frequency of application will determine load reductions.

Costs - Costs are generally low, though require an initial investment.

Potential obstacles - The main problem is the potential contamination of the groundwater. The use of the pits is inappropriate in zones with a high groundwater table. Additionally, flies, mosquitoes, and odor may be a problem with the standard pit latrine.

Feasibility - The pit latrine is a widely understood technology, though it is recommended only as a temporary solution to human waste storage/disposal.

Pour-Flush Latrines

Purpose - Pour-Flush latrines operate as a combination between pit latrines and conventional sewerage. The pour-flush latrines are designed to manage human wastes.

Function and method of construction - The main difference between a pour-flush latrine and a standard pit latrine is the offset of the waste storage site. The pit for a pour-flush latrine may be equipped with a trap door providing a water seal, and is located nearby the toilet, though not directly beneath as a pit latrine. Thus, the ground supports the weight of the pour-flush latrine. Water is used to flush wastes through the pipes and into the storage/settling pit. The water seal prevents flies, mosquitoes, and bad odors from infecting the pour-flush latrine. The latrine can be located in house and may be attached to conventional sewerage as an upgrade when such infrastructure becomes available (World Health Organization 1992). Until sewer connections become available, wastes may decompose inside the pit. Once the pit is nearly filled, the remainder is capped off with earth and sealed to allow for decomposition. The abandoned pits must be left undisturbed for a minimum of two years (usually, several more years) before wastes can be safely handled (World Health Organization 1992). Until sewer connections become available, wastes may decompose in the pit.

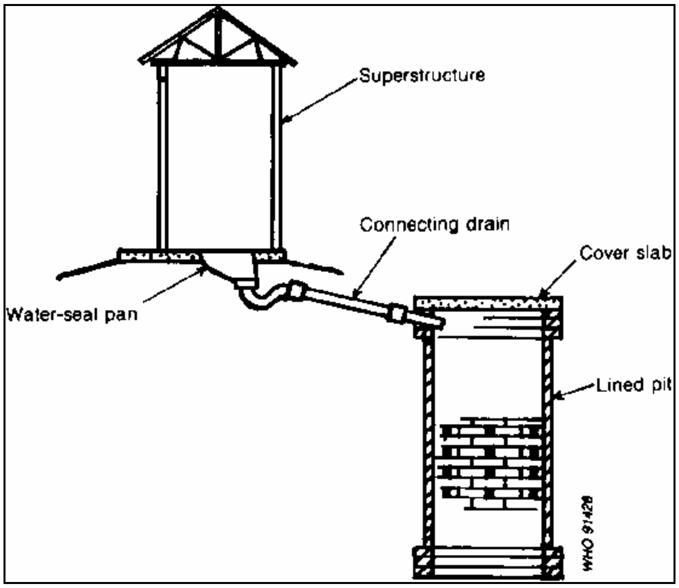


Figure 6.12. Pour-flush latrine schematic (World Health Organization 1992).

Potential load reductions - Properly used latrines will reduce non-point source pollution. Frequency of application will determine load reductions.

Costs - Costs are comparable to a standard pit latrine (low), and slightly less than a composting toilet.

Potential obstacles - Water availability may be a problem. A sufficient quantity of water is needed to flush the wastes through the pipes and into the storage pit. Pits may easily contaminate shallow groundwater.

Feasibility - Pour-flush latrines may be used as a temporary solution to sanitation problems where conventional sewerage is planned in the near future. Though the technology is feasible for the region, it is not recommended for long term use due to groundwater contamination.

Oxidation Ponds/ Waste Stabilization Ponds

Purpose - Oxidation ponds (or waste-stabilization ponds) are constructed lagoons in which sunlight facilitates algal growth. The purpose is to treat wastewater from small-scale human inputs. Solids must first be screened out before wastewater enters an oxidation pond. The disinfection of pathogens by solar radiation reduces the amount of chlorination required (Parr, *et al.* 2002). Often, the water can be reused for irrigation. Moreover, the algal growth may be collected and used as fertilizer, fodder, or as a source of energy via methane conversion (U.S. EPA 2000).

Function and method of construction - Ponds need to be constructed in an open area that receives an ample amount of sunlight. The treatment may consist of a single pond or a series of shallow ponds. These ponds can be anaerobic, facultative, and/or maturation ponds. One of the primary objectives of the technology is to stimulate algal growth in order to convert waste into algal cell material. The algal growth provides the oxygen required for bacteria to absorb pollutants using the anaerobic process (oxidation) (Parr, *et al.* 2002).

Potential load reductions - The oxidation ponds are 99.9% effective at treating pathogenic material. The ponds may dilute wastes sufficiently for water quality purposes. Ponds may also reduce nitrogen and phosphorus loads up to 75% (Shrivastava and Swarup 2001).

Costs - Though capital investments for construction of oxidation and waste stabilization ponds are relatively low, one drawback of the ponds is the large land requirement.

Potential obstacles - In addition to the land area requirement, another drawback is that solids need to be filtered out before water enters ponds for oxidation.

Feasibility - The oxidation ponds are best suited to sunny, semi-arid climates, though are effective in a wide range of areas. Climatic conditions in San Cristóbal vary considerably. Though cloud cover, even during the dry season, may limit the feasibility of oxidation ponds, the practice may still be applicable. Where conditions permit, oxidation ponds may be used to decrease loads from small communities or groups of households.

Grey Water Filters

Purpose - Grey water filters are used to save wastewater from sources other than the toilet (or other “black water” sources) for certain reuse activities. Grey water filters also help to reduce the amount of soaps and detergents released into open water systems. Grey water typically contains only 10% of the nitrogen that black water contains (Gajurel, *et al.* 2003). The availability of filtered grey water will depend on the desired use, as well as the intensity of the filtering system. However, because grey water must treated, or at least separated onsite, any technology must be employed over a large portion of any region to produce water savings. Average water savings are around 20% per household (Birks, *et al.* 2003). Grey water filtering will assist in reducing loads to wastewater treatment facilities.

Function and method of construction - There are a plethora of grey water technologies that exist for developing regions such as the San Cristóbal watershed. Different technologies may be appropriate for the urban center, while others may be more cost effective for rural use. Regardless of the technology employed, grey water must be separated from black water sources such as flush and pour-flush toilets (Birks, *et al.* 2003). For rural applications, grey water may be filtered through series of aggregates (rocks, pebbles, coarse sand, fine sand) before being discharged into open water systems or re-used for irrigation water. For more urban or sub-urban use, grey water may be used for household irrigation in addition to reducing the volume of wastewater in need of primary and secondary treatment. As irrigation water, grey water should not be sprayed directly onto vegetables, particularly below-ground vegetables (Lindstrom 2000).

Potential load reductions - Properly used grey water filters will reduce non-point source pollution. Frequency of application will determine load reductions.

Costs - Costs will depend on technology employed. Compared to other filtering technologies, grey water filters are usually low cost.

Potential obstacles - Potential problems include improper education, grey water storage, discharge directly to a natural water body, clogging, improper re-use, monitoring, and maintenance.

Feasibility - Grey water separating and filtering is somewhat feasible in the San Cristóbal watershed region. Implementation in rural communities may require significant education, training, and monitoring.

<u>Rain Water Harvesting</u>

Purpose - Currently, many residents do not have regular access to water. Small-scale rain water harvesting may increase the water supply for consumption, household use, and irrigation for various communities. Additional benefits come in the form of reduced erosion and stormwater impacts from increased storage of rain water (Krenn 2005). Increased water availability depends on size of storage tank(s) and quality of media filters.

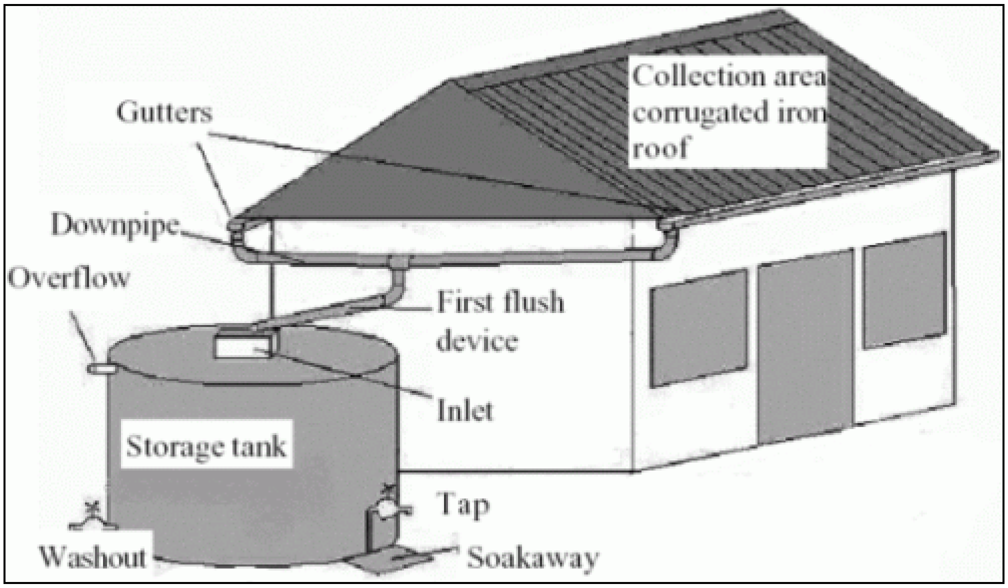


Figure 6.13. Simple rainwater harvesting schematic (Krenn 2005).

Function and method of construction - The system consists of mounting drainage canals alongside the roofs of houses. Rainwater is funneled to a storage tank. Multiple tanks can be used in conjunction with simple sand (or other media) filters to remove a percentage of pollutants. Individual households must receive education as to proper construction and maintenance of filters. Also, individual roof tops need to be periodically cleaned (especially after long dry periods) to prevent excess pollutant build-up from clogging media filters and contaminating the water (Krenn 2005). Simple filters are sufficient for household and irrigation use, while additional ones may be needed to ensure rain water is potable.

Costs - The costs for rainwater harvesting are relatively low. Materials are readily available, though education would be needed.

Potential obstacles - Potential problems may include improper maintenance, gutter failure, filter clogs, and lack of storage tank availability.

Feasibility - Rain water harvesting, in conjunction with storage tanks, may increase water availability in San Cristóbal. The practice is particularly suitable for rural communities.

<u>Small-Scale Water Tanks</u>

Purpose - Implementing water tanks would increase household water storage capability during periods of limited supply. Increased storage may increase water availability for human consumption, household use, and irrigation.

Function and method of construction - Small-scale, household water tanks are used for storing water. Individual households or community tanks may be provided where water connections are available.

Costs - Costs may be medium due to the high number of individual households in San Cristóbal.

Though the prices for individual tanks are low, the supply of tanks to individual households in densely populated areas would increase project costs due to the number of tanks to be purchased.

Potential obstacles - Potential obstacles include improper maintenance and use.

Feasibility - During times in which SAPAM supplies water, demand may increase due to attempts to fill up individual tanks.

Soil Aquifer Treatment (SAT)

Purpose - SAT involves artificially recharging underground aquifers with partially treated wastewater and withdrawing the water later for future use for irrigation purposes. SAT can increase the available supply of groundwater for pumping.

Function and method of construction - Prior to mixing with the groundwater, the wastewater undergoes natural treatment from unsaturated soil layers. The mixed water is later withdrawn, substantially free of pathogens (U.S. EPA 2006). SAT is usually implemented by allowing ponded wastewater to percolate through unsaturated zones and into the subsoil for mixing with the groundwater (Gungor and Unlu 2004).

Potential load reductions - Removal rates are highly dependent on soil type and saturation conditions. Under optimal conditions, SAT reduce total nitrogen in water supplies (Volkman 2003).

Costs - The initial costs of SAT are medium. Once drilling has been complete, costs are low. However, the research needed to confirm feasibility in addition to the possibility of treating water before artificial recharge may increase costs significantly.

Potential obstacles - Soil aquifer treatment is more appropriate for arid to semi-arid regions, and should not be used when high algal concentrations are present in the wastewater (Volkman 2003).

Feasibility - Though SAT is relatively inexpensive, the practice may potentially contaminate San Cristóbal's water supplies. Due to the karst geology, saturated soil layers, and unknown, potentially varied flow of groundwater, SAT would require significant research prior to implementation. Additionally, water used for SAT would most likely require significant treatment prior to either release for percolation into the ground or after retrieval for reuse as irrigation.

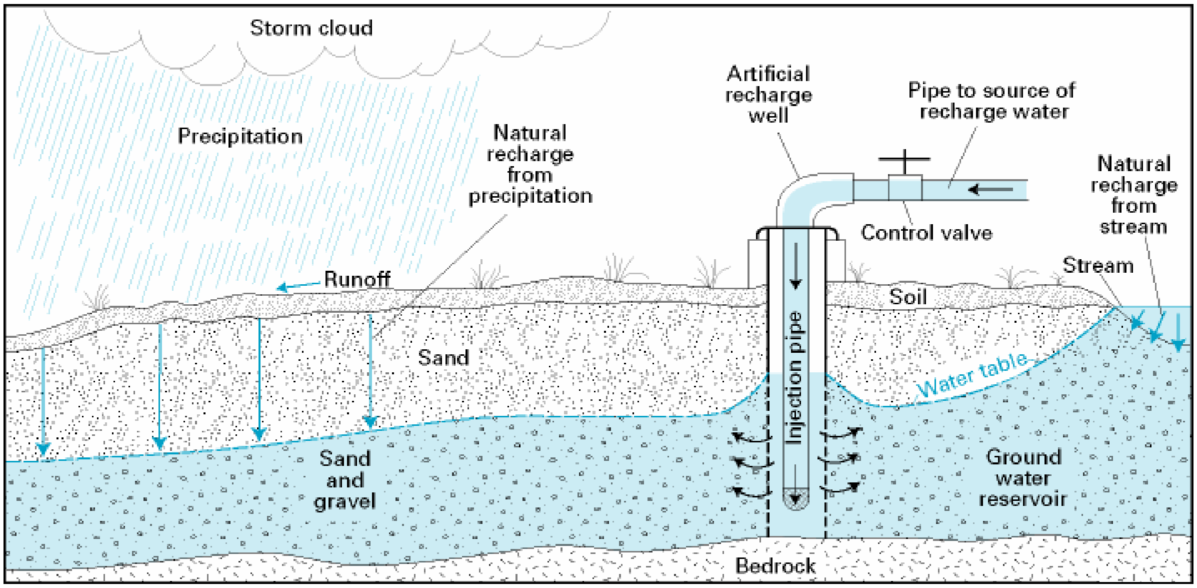


Figure 6.14. Artificial and natural recharge of an aquifer (U.S. Geological Service 2005).

<u>Artificial Aquifer Recharge and Vadose-Zone Wells</u>

Purpose - Much like soil aquifer treatment, artificial recharge wells such as Vadose-zone wells are specifically designed to facilitate aquifer recharge. The primary difference from SAT is that artificial aquifer recharge usually involves injecting water below impermeable soil layers. The wells may be implemented for use in zones where groundwater pumps encounter periods of reduced capacity, and in areas were there is sufficient unsaturated soil available to facilitate the purification of water (Gungor and Unlu 2004).

Function and method of construction - Similar to dry wells, Vadose-zone wells are drilled to re-introduce surface water to depths beyond impermeable layers. The wells usually require filtration through unsaturated zones before the introduced water mixes with groundwater. The unsaturated zone percolation is important as a step to remove contamination before mixing with the aquifer, from which water is extracted. Generally, the wells contain a perforated pipe (with diameter 1+ meter), to allow filtrating out in permeable, unsaturated zones (granular, sandy, etc). The length of the pipe is dependent on aquifer depth (Stephens & Associates 2002).

Costs - The costs of Vadose wells are relatively high compared to other technologies.

Potential obstacles - For wells that inject water directly (or close) into zones to be mixed with the groundwater, water quality becomes an issue for reuse, possibly requiring additional treatments. Costs are site-specific and will depend on the amount of pilot tests needed to determine artificial aquifer recharge well feasibility (Stephens & Associates 2002).

Feasibility - The karst geology and generally high subsoil saturation presents a significant amount of risk and additional costs for artificial aquifer recharge well implementation. For these reasons, the wells have low feasibility in San Cristóbal.

Education Campaigns

Purpose - Education campaigns are designed to provide information to address diverse problems. One major issue which can be addressed through education campaigns is sanitation: residents throughout the San Cristóbal watershed (and Chiapas) suffer from elevated rates of illness, due in large part to a lack of education. Improved education and information dissemination regarding sanitation practices can significantly reduce rates of illness and improve quality of life (WHO and UNICEF 2005). Other issues, such as trash in streams, watershed processes, and the linkages between human activities and water quality, can also be addressed through education campaigns.

Function - The function of the campaign will depend on the goals. For example, an educational campaign to deal with sanitation and health could disseminate information about various practices including washing hands, proper handling of human wastes, food handling, water treatment(s) (chlorination, filtering, etc.), basic medical issues, and a wide range of hygiene issues. Since people in the city of San Cristóbal frequently visit different health-care providers and use self-prescribed medications, training in how to treat illnesses should include doctors, drug vendors, traditional healers, and the general public (Flores, *et al.* 2003). This training should include health care professionals who provide services to people living in the rural areas of the watershed.

Potential load reductions - Reductions in hygiene-related illnesses may be difficult to quantify, although the literature suggests meaningful gains. A UNICEF study suggests that programs that promote hand washing with soap can decrease risks of diarrhea by 42 to 47%. Many programs have been successful in changing attitudes of communities by targeting school children, who return to their families and teach them about health and sanitation (WHO and UNICEF 2005). One of the biggest economic gains may come in terms of time savings associated with improved sanitation and access to water (WHO and UNICEF 2005).

Costs - Costs will depend on campaign intensity, provisions of educational materials, availability of trained staff and volunteers, as well as individual, community, and cultural acceptance.

Potential obstacles - Potential problems include implementation of behavioral changes, cultural biases, and the man-power required to reach a large and diverse population. Another potential problem is the lack of community adoption of improved sanitation practices. For example, in one community in San Cristóbal, composting toilets were installed but were not maintained, and therefore are no longer used. Because these toilets are not properly maintained, they have become a point source of pollution (Cruz García 2006). If this problem is due to lack of information about how to maintain the toilets, simple education methods such as painting the instructions on the walls of the toilet buildings can be effective.

Feasibility - Although it may be difficult to quantify the results, education campaigns can be very effective at achieving a variety of goals. Such campaigns are feasible throughout the San Cristóbal watershed.

6.3 Wastewater Treatment Options

In the urban center of San Cristóbal wastewater is collected in a combined sewage and stormwater conveyance system and discharged directly into the river system at various locations throughout and downstream of the city. As the municipality currently owes several million U.S. dollars in fines to CNA for being out of compliance with ambient surface water quality standards, one of their top priorities is construction of a wastewater treatment system to eliminate contamination by raw sewage. Construction is expected to begin sometime in 2007. However, the type of wastewater treatment system and where to locate it has yet to be determined by the municipality. Our partners at ECOSUR have asked that we evaluate a range of potential wastewater technologies, beyond just the conventional wastewater treatment plant, and make recommendations for wastewater treatment solutions that the municipality could realistically implement. For this analysis we considered a variety of lagoon treatment systems, constructed wetlands and floating aquatic plant systems, and intermittent filtration systems, in addition to conventional wastewater treatment.

6.3.1 Wastewater Treatment in Mexico and Chiapas

Before providing San Cristóbal with recommendations, it is useful to get an understanding of the state of wastewater collection and treatment around the rest of the country, and specifically in Chiapas. In Mexico, 22.8 million people, or 22.5% of the population, do not have a sewage connection in their home. Of this number, 7.1 million live in urban areas and are much more likely to need such coverage. Only 31.5% of the wastewater that is collected in Mexico receives some form of treatment. In total, there are around 1,300 treatment plants in Mexico. Of these 1,300 plants, 37% are only primary, 59% are primary and secondary, and 4% include tertiary treatment (Comisión Nacional del Agua 2005b). A summary of the specific technologies used in Mexico is given in Figure 6.15.

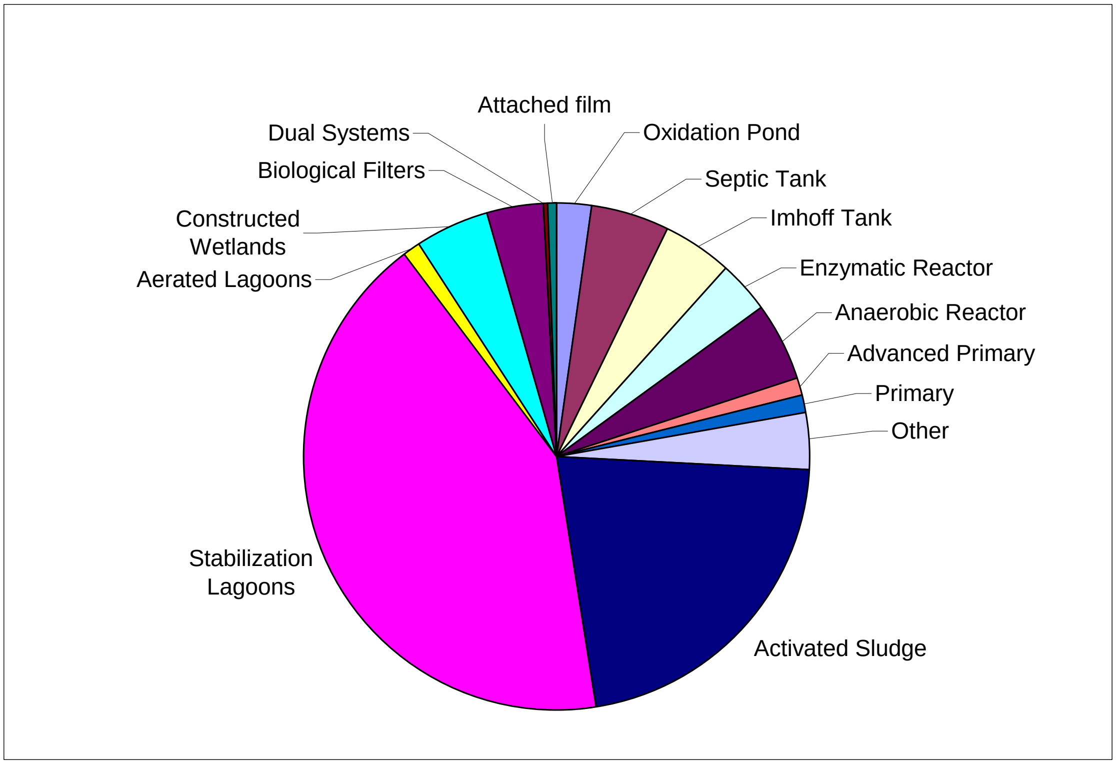


Figure 6.15. The types of wastewater treatment systems currently in use in Mexico as a percentage of total treatment systems (Comisión Nacional del Agua 2005b).

Activated sludge systems and stabilization lagoons are the most widely used technologies for wastewater treatment comprising 64% of all treatment plants in the country. It is also important to note the average flow that each system treats (Figure 6.16). Only dual systems treat more than 1 m^3/s of wastewater flow, with advanced primary and aerated lagoons having the next highest average flow capacities.

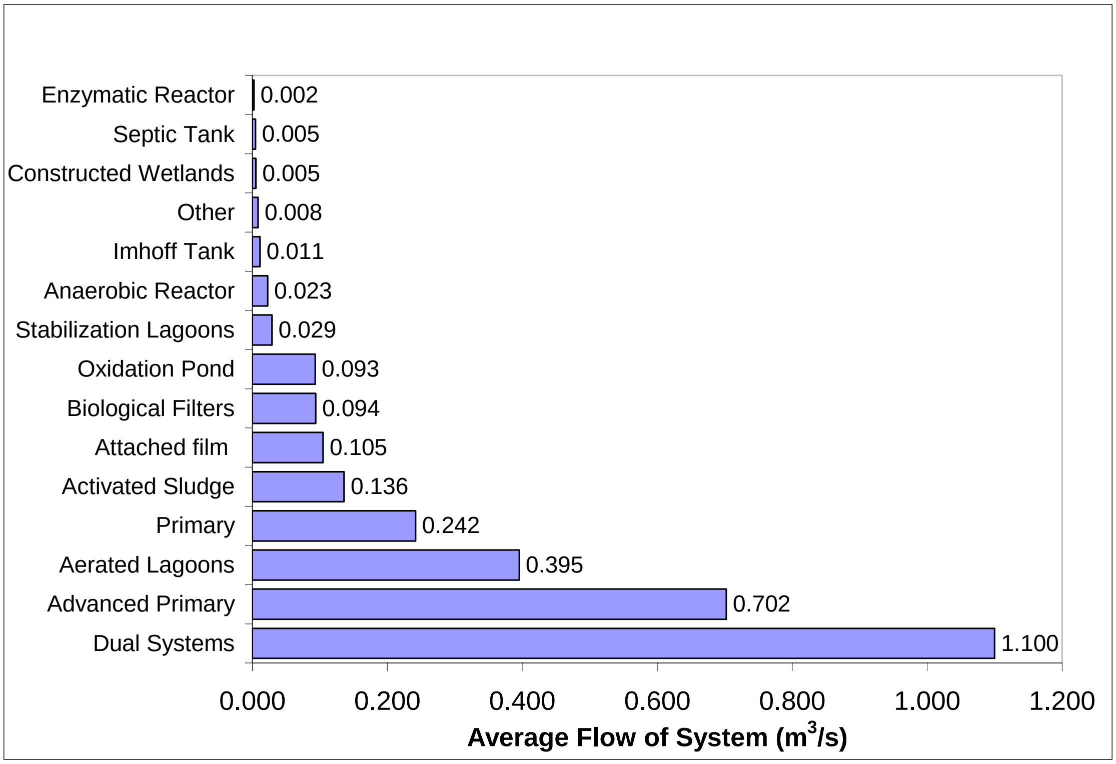


Figure 6.16. The average flow of wastewater treated by each type of wastewater treatment system used in Mexico (Comisión Nacional del Agua 2005b).

As compared to the rest of Mexico, slightly more than 40% of the population in the state of Chiapas is without a sewer connection. Of those that do have a connection, only 20.5% have wastewater treatment (Comisión Nacional del Agua 2005b). Though Chiapas is home to nearly six million people, there are only nine wastewater treatment facilities in operation throughout the state. The most popular system is the stabilization, or facultative lagoon; this technology is used at seven of the nine facilities (Comisión Nacional del Agua 2006b). Table 6.10 details the location, treatment technology, and capacity of all treatment facilities in Chiapas. Only the attached growth filter in Tuxtla Gutierrez is built to treat a flow similar to meet the expected needs of the future population of San Cristóbal.

Table 6.10. Types of treatments facilities currently in operation in the state of Chiapas (Comisión Nacional del Agua 2006b).

Municipality	Treatment Type	Installed Capacity (m^3/s)	Current Operation (m^3/s)
Chiapilla	Stabilization Lagoon	0.0064	0.0050
Comitan de Dominguez	Stabilization Lagoon	0.1400	0.1400
Paso Hondo	Stabilization Lagoon	0.0083	0.0060
Ocosingo	Stabilization Lagoon	0.0610	0.0180
Reforma	Stabilization Lagoon	0.0360	0.0360
Las Rosas	Stabilization Lagoon	0.0300	0.0210
Suchiapa	Stabilization Lagoon	0.0160	0.0140
Tuxtla Gutierrez	Attached Growth Filter	0.0110	0.0110
Tuxtla Gutierrez	Attached Growth Filter	0.8000	0.6000

6.3.2 Wastewater Treatment Options for San Cristóbal

To help the municipality assess their treatment options we answered several important questions: 1) What is the future population that needs to be planned for in sizing a treatment system; 2) Where is the most suitable location for the treatment facility given design requirements; 3) What is the wastewater flow produced; and 4) What is the load of pollutants being produced?

Population Projections

In designing a wastewater treatment system, it is important to look beyond the current population when estimating wastewater production rates. It is necessary to consider the typical life of a treatment option and design it specifically to accommodate for the size of the expected future population of the community it serves. For this analysis we assume a treatment plant life of 25 years and thus make an estimation of the population of the city in the year 2030 to plan for proper sizing of the facility. Given that several population growth scenarios have been predicted for San Cristóbal, this analysis considers both high and low wastewater production scenarios.

The low growth scenario was derived from San Cristóbal's city development plan. The plan estimated a higher growth rate until 2018 at which point it would slow down (Municipio de San Cristóbal 2004). From the estimates in the report, we interpolated that constant growth rate to be approximately 2.4%. With this growth rate, the estimated population in 2030 could reach 230,000 people (Figure 6.17).

For the high population growth scenario, we used estimates produced by ECOSUR (García García 2005). This scenario predicted population growth out to 2017. Again, we interpolated the data to determine a constant growth rate of 4.16%. At this growth rate the population could reach 375,000 people by the year 2030. These projections and the historical growth are shown in Figure 6.17.

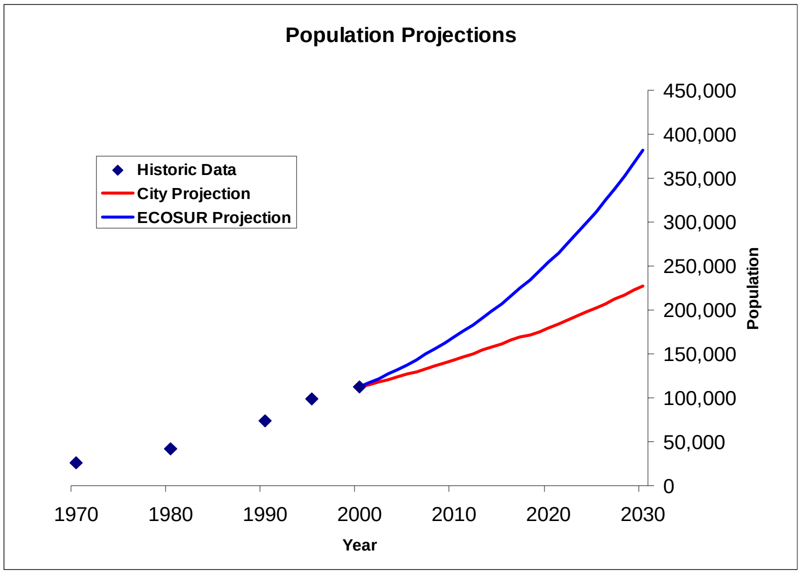


Figure 6.17. Population growth in San Cristóbal since 1970 and projections for growth projected out to 2030.

Treatment Option Scenarios

There are four scenarios under which each treatment option can be considered as depicted in Figure 6.18. The treatment facility can be constructed in two ways: 1) to treat only wastewater, conveyed in a collection system directly to the facility or 2) to treat the entire flow of the river, including both the natural flow of the river and the discharged wastewater. Additionally, there is the choice between treating wastewater before the tunnel entrance or at the exit of the tunnel, outside of the watershed boundary.

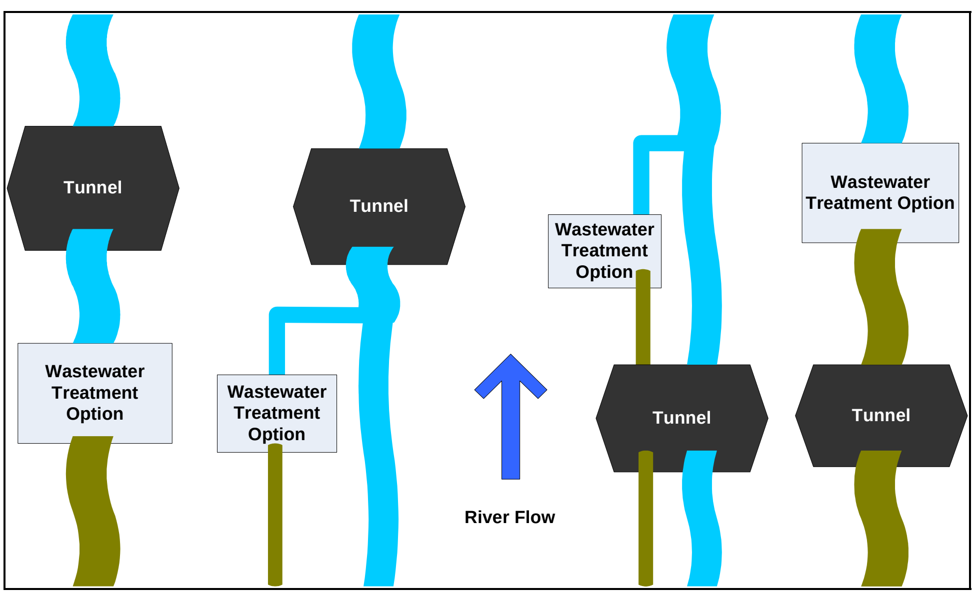


Figure 6.18. Four scenarios for planning a wastewater treatment system in San Cristóbal.

Ideal placement of the treatment facility will be a function of the flow being treated, the land area required by the treatment option, and the characteristics of the landscape on either side of the tunnel. The following summarizes the important factors to consider with regards to siting as each treatment option is evaluated.

Flow Considerations - The important factor to note about flow is that as the flow increases so does construction and maintenance costs. Higher peak flows will result in larger facility design requirements and higher average flows will result in higher day to day pumping and treatment costs. Estimates of wastewater flows are detailed in the following section.

Considerations for Before the Tunnel - The major limiting factor for siting a treatment facility within the watershed before the tunnel is the amount of land area available. Using GIS, it was estimated that there are approximately 1,250 hectares of open, undeveloped land within in the flat valley of the watershed. In addition, this land is considerably more expensive than the land on the opposite side of the tunnel, although actual values are unknown at this time.

Considerations for After the Tunnel - There are several important factors that need to be taken into consideration if wastewater is to be treated on the exit side of the tunnel. Land is expected to be cheaper than land within the watershed. However, there is also the issue of the slope of the land at the tunnel exit. Slope was calculated using the digital elevation model of the region in GIS. The average slope near the exit of the tunnel is 17%, with a maximum grade of 40%. Given that many treatment options require minimal slopes, the distance to the nearest track of flat land needs to be taken into account. This distance was estimated using a topographical map to be approximately 6 kilometers. Therefore, if the municipality wants to explore treating wastewater that is conveyed through a system of sewage pipes, it may be necessary to install an additional 12 km of sewer pipe infrastructure, 6 kilometers through the tunnel in mountains at the southern border of the watershed and 6 kilometers to the nearest flat landscape.

Treatment Options Considered[11]

For this analysis, a variety of treatment options were considered including lagoon treatment systems, constructed wetlands, intermittent filtration systems, and conventional wastewater treatment plants. A short description of each technology is given below. For each system, the biochemical oxygen demand (BOD) assimilation rate, pollutant load reductions of biochemical oxygen demand (BOD), total suspended solids (TSS), nitrogen (N) and phosphorus (P), ideal land slope, pre-treatment requirements (also called primary treatment), and any other important considerations that should be taken into account are discussed. The section concludes with a summary table that compares the important design considerations for each treatment option (Table 6.16).

<u>Lagoon Treatment Systems</u>

Lagoon treatment systems are earthen basins engineered for the purpose of treating wastewater through the process of settling and the breakdown of organic materials. This technology has been primarily used for small rural communities, but there are systems that have been built to accommodate mid- to large-sized communities as well. Typically, these systems operate without primary treatment, and they are often utilized for primary treatment in more advanced land

[11] This section is primarily summarized from Crites and Tchobanoglous (1998) unless otherwise noted.

treatment systems such as constructed wetlands and intermittent sand filters. To prevent seepage of only partially treated wastewater into the water table, lagoon bottoms are typically lined with either clays or plastic membrane materials. In addition, while a slight slope is necessary (0-3% is ideal) to allow natural flow in and out of the system, it should be minimal to allow for the required detention time. There are several types of lagoon systems which are differentiated by their use or source of oxygen to complete this breakdown. Lagoon options considered in this analysis are further described below.

Facultative Lagoons - Facultative lagoons, also known as oxidation ponds or stabilization lagoons, are the most common type of lagoon system in use. The surface of the lagoon relies on naturally occurring aeration while the deeper layers rely on anaerobic conditions for the breakdown of settled solids. These systems are typically designed based on BOD loading from the wastewater stream. In climates with average winter temperatures of 0 – 15 ºC, facultative lagoons can process approximately 22-45 kg/ha-day of BOD. Typical effluent values for this system are in the range of 30-40 mg/L for BOD and 40-100 mg/L for TSS.

Anaerobic Lagoon - Anaerobic Lagoons use anoxic conditions to breakdown wastewater, and are typically used to treat highly contaminated industrial wastewater. The advantage of this type of system includes low nutrient requirements and minimal production of biological sludge while the disadvantages include incomplete removal of BOD and potential for strong odor production, which is why they are often used in remote locations away from populated areas. Anaerobic systems are typically designed based on the surface loading rate, volumetric loading, and hydraulic detention time. They are built very deep to promote anoxic conditions, but require very specific conditions to achieve removal efficiencies. For example, 50% reduction in BOD can only be achieved in climates where the average temperature is greater than 22ºC.

Advanced Integrated Lagoon - The advanced system simply relies on a variety of lagoon types, aerobic and anaerobic, placed in series to treat wastewater. This system can treat up to 390 kg/ha-day of BOD if the influent concentration is around 300 mg/L. It also has high constituent removal efficiency achieving concentrations of BOD and TSS to 20-40 mg/L.

Constructed Wetlands and Aquatic Treatment Systems

Wetland and aquatic treatment systems rely on aquatic plants and animals to treat wastewater. These systems often require primary treatment and are lined to prevent seepage into the groundwater. To be effective, the land needs to be primarily level, with a slight natural slope (<3% is ideal) to facilitate natural flow through the wetland. Design of wetland and aquatic systems is typically based on combination of organic and hydraulic loading factors. It is important to note that in constructed wetlands and aquatic systems there is a natural process of vegetation decay. This adds to the BOD in the effluent of the system, which why effluent concentrations are often higher than with other wastewater treatment options.

Free Water Surface (FWS) Wetland - In this type of system, water is applied to the surface of the wetland through channels or basins so that emergent vegetation is flooded to depths of up to 450 millimeters. This allows the wastewater to be treated by attached bacteria and other physical and chemical processes as it flows through the wetland. Ideal sites for FWS wetlands have a slope of 0-3%, with underlying soils of low permeability. Liners can be used to prevent seepage in the areas with high permeability soils. These systems should be designed such that organic loading rates do not exceed 112 kg BOD/ha-day. These systems have typical BOD removal efficiencies of 60 to 80% and 50 to 90% for TSS removal.

Subsurface flow Wetland - In contrast to free-water-surface flow wetlands, wastewater flow is applied to the subsurface of the system where it flows through a porous media planted with emergent vegetation. The wastewater is treated by attached bacteria in the root zone of the vegetation. They also have the advantage of avoidance of odor and mosquito problems that are potential with FWS wetlands. However, the costs can be higher due to installation of gravel bed media. Ideal site locations have a slope of 0- 0.5%. Liners are also necessary to protect the groundwater from seepage. BOD loading rates are similar to FWS wetlands with capacity up to 112 kg BOD/ha-day and has the same removal capacities.

Floating Aquatic Plant System: Water Hyacinth - In these systems the roots of floating or suspended plants serve as the surface area for the growth of bacteria that breakdown wastewater constituents. The system can either be aerated or non-aerated. Aerated systems have higher costs but can achieve greater removal efficiencies. Ideal site conditions will have level to slightly sloping ground. Water Hyacinth systems can process up to 500 BOD kg/ha-day. However, loading rates above 225 BOD kg/ha-day are not recommended because of problems with odors and mosquitoes. Finally, pollutant load reductions of 90% for BOD and TSS and 55% for ammonia are possible with this treatment option.

Intermittent Filtration Systems

Intermittent filtration systems, or packed-bed filters, use biological and physical processes to treat wastewater. A large area is dug to a depth between 0.5 and 1.5 meters and filled with a filtering medium (sand or rock). Wastewater is applied to the surface through irrigation and is drained from the porous media from underground. The biggest drawback of this option is that it can fail if the hydraulic, solids, or organic application rates regularly exceed the limits of the filter.

Single-Pass - Single-pass systems have typically been used for smaller communities to treat septic tank effluents or improving other primary treatment effluents. In single-pass dosing, wastewater is applied to the packed filter bed only one time and then allowed to drain out of the filter. They are generally only economical for wastewater flows of up to 3,000 gallons per day. They can reduce BOD concentrations to below 10 mg/L and remove 55 to 75% of ammonia and nitrates. The type and size of the filter is critical to achieving these effluent values however. Single-pass filters can accommodate up to 100 kg BOD/ha-day.

Multi-Pass - The main difference between single and multi-pass systems is the recirculation of wastewater. In a multi-pass system a portion of the liquid that passes through the filter bed is returned to a recirculation tank where it mixes with untreated effluent and is re-applied to the filter bed. This constant dilution allows for a reduced organic load to be processed by the filter. In addition, it can accommodate higher BOD loading rates of up to 400 kg BOD/ha-day, but achieves similar effluent levels as the single-pass system.

Conventional Wastewater Treatment

A variety of conventional wastewater treatment options are available, the technologies of which are not discussed in this analysis. The important considerations for conventional treatment is that they require smaller amounts of land and are not usually limited by soil types, permeability, or slope. One can also achieve any combination of desired effluent concentrations, up to 95-100% removal. Primary treatment is typically a part of the technology and does not require extra land considerations. For this analysis, we suggest that a modular wastewater treatment be considered first before other conventional systems because it can be augmented in capacity over time to accommodate for growth. The drawback is that conventional wastewater treatment technology is more expensive and requires considerably more labor for operation and maintenance than the other treatment systems discussed in this analysis.

Wastewater Flow Calculations

An important part of wastewater treatment design is the amount of wastewater flow requiring treatment. Given that San Cristóbal has a combined sewer system, meaning that the system collects both wastewater and stormwater, we can determine the flow needing treatment by calculating the wastewater flow produced by the population and adding it to the maximum stormwater flow that is collected during a high intensity storm.

Wastewater Flow

To calculate the amount of wastewater produced per capita, we first need to estimate per capita water consumption. To do this we used the water pumping rates provided to us by the municipality. As detailed in Section 5.1 (Water Supply and Sanitation), the water consumption rate was estimated to be 143 L/capita-day. Approximately 60-80% of human consumed water becomes wastewater depending on the amount of water that is used for outdoor landscaping (Crites and Tchobanoglous 1998). For this analysis, it was assumed that 80% of water consumed for domestic purposes becomes wastewater as the amount of outdoor landscaping in San Cristóbal is limited. This results in a per capita wastewater flow of 114 L per day, or 41.6 m^3/capita-year.

It is important to consider, however, that as development of the city and its water resources continues there is the potential for increased per capita water consumption. The average per capita water consumption rate for Mexico is 715 m^3/year, and thus this amount was used to estimate a reasonable future consumption rate (Comisión Nacional del Agua 2005a). Of this amount, 14% is consumed for domestic use and therefore leads to a domestic consumption rate of 275 L/capita-day and a wastewater production of 220 L/capita-day, or 80.3 m^3/capita-year. Using both the current estimated consumption rate and the potential future consumption rate, the range of potential future wastewater flows were estimated for both population growth scenarios. The results of this analysis are listed in Table 6.11.

Table 6.11. Estimated average wastewater production scenarios for San Cristóbal in the year 2030.

Wastewater produced at current water consumption rate of 142 L/cap-day		**Wastewater produced if water consumption increases to 275 L/cap-day**	
	Estimated Wastewater Flow (m^3/s)		Estimated Wastewater Flow (m^3/s)
High Population Estimate	0.50	High Population Estimate	1.0
Low Population Estimate	0.30	Low Population Estimate	0.60

This analysis only considers the daily average flow of wastewater. We also need to consider the peak flow that is produced in a day because this will be critical in the sizing of conveyance pipes. In the absence of observed wastewater flow data, what is known as a peaking factor can be used to estimate the peak flow. The peaking factor for a population size between 200,000 and 400,000 is approximately 2.5 (Tchobanoglous, *et al.* 2003). Using this peaking factor we estimate peak wastewater flows as detailed in Table 6.12.

Table 6.12. Estimated peak wastewater production scenarios for San Cristóbal in the year 2030.

Wastewater produced at current water consumption rate of 142 L/cap-day		Wastewater produced if water consumption increases to 275 L/cap-day	
	Estimated Wastewater Flow (m^3/s)		Estimated Wastewater Flow (m^3/s)
High Population Estimate	0.75	High Population Estimate	2.5
Low Population Estimate	1.25	Low Population Estimate	1.5

Stormwater Flow

To determine the amount of stormwater flow that enters the conveyance system, we assume that all precipitation that falls on urban impermeable surfaces, ends up in the sewer. Using a GIS, we estimated the area of the urban center of the city to be 2,240 hectares in size and assume for the purpose of this analysis that all of the urban area is impermeable. Using this area and daily rainfall data, as measured at a rain gauge in the urban area of the watershed, we calculated the stormflows as a percentile over the 10 year time period between 1989 and 1999 to determine the "peak" and "average" flows that need to be planed for in facility design. We recommend that the peak flow that the facility is designed to hold be the 90 percentile flow (4.67 m^3/s) and the average flow the 50 percentile flow (1.04 m^3/s). The facility would need to be designed to have a spillway to accommodate flows over the 90 percentile. The percentile flows can be seen in Figure 6.19.

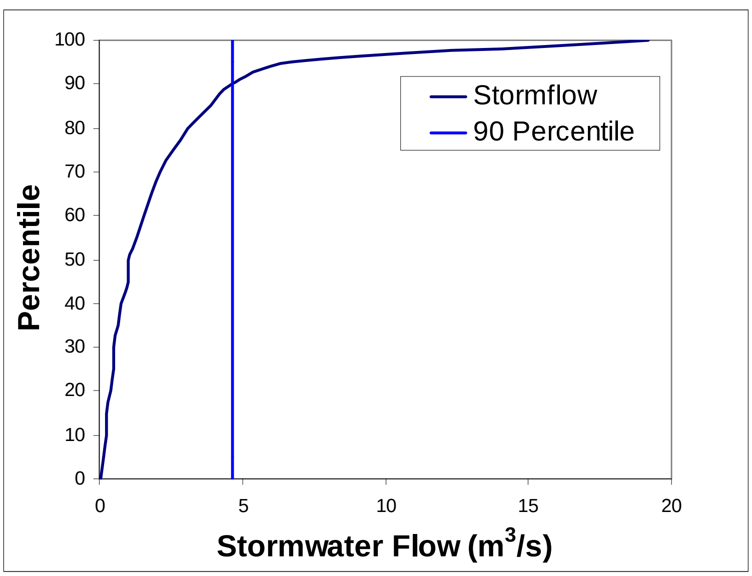


Figure 6.19. Estimated urban stormwater runoff over a ten year period (1989-1999) with percentile rank for each runoff volume [data source: (Servicio Meteorológico Nacional de México 2003)].

Combined Flow of Wastewater and Stormwater

Adding up the estimated peak and average flows for wastewater and stormwater production gives the total amount of flow that should be planned for in designing a wastewater treatment facility should the municipality continue with plans to construct further combined conveyance pipes. These flows are summarized in Table 6.13.

Table 6.13. Total estimated peak flow needing treatment within a combined wastewater and stormwater conveyance system.

Total flow at current water consumption rate of 142 L/cap-day			**Total flow if water consumption increases to 275 L/cap-day**		
	Average Flow (m^3/s)	Peak Flow (m^3/s)		Average Flow (m^3/s)	Peak Flow (m^3/s)
High Population Estimate	1.54	5.92	High Population Estimate	2.04	7.17
Low Population Estimate	1.34	5.42	Low Population Estimate	1.64	6.17

Pollutant Load Calculations

To calculate pollutant load, typical daily production values reported for persons living in the United States were used. These typical values are:

- 80 g/cap-day of BOD
- 7.6 g/cap-day of NH_3
- 3.2 g/cap-day of Total P
- 2.00 x 10^9 fecal coliforms/cap-day

Based on these loading rates, the total pollutant load was calculated for both high and low population growth scenarios. The loads are reported in Table 6.14. It is important to note that this load will be the same if the waste is conveyed in a sewer pipe or through the river flow. The only difference would be the concentration of the pollutant; the concentration would be significantly higher in the sewer pipe than in the river flow.

Table 6.14. Mass loading expected in 2030 based on typical BOD, NH_3, Total P, and Fecal Coliforms per capita production rates (Crites and Tchobanoglous 1998).

	BOD	**NH3**	**Total P**	**Fecal Coliforms**
Total production in 2030 for low population estimate (kg/day)	18,400	1,800	740	4.60E+14 (#/day)
Total production in 2030 for high population estimate (kg/day)	30,000	2,900	1,200	7.50E+14 (#/day)

Land Area Requirements
Given that the flow being treated has yet to be determined, for each treatment option considered, the amount of land needed to accommodate the facility was estimated based on typical process design values for assimilating biochemical oxygen demand. In the case of anaerobic lagoons, it was necessary to use hydraulic loading to calculate land area. For this option, it is assumed that wastewater is conveyed through piping infrastructure, giving a lower bound estimate of the land area needed for an anaerobic lagoon. It is important to note that these estimates also only represent a lower bound estimate. If the municipality chooses a combined wastewater system, the amount of hydraulic load may require more land area for proper treatment. The amount of land needed for each option under both low and high growth scenarios is displayed in Figure 6.20.

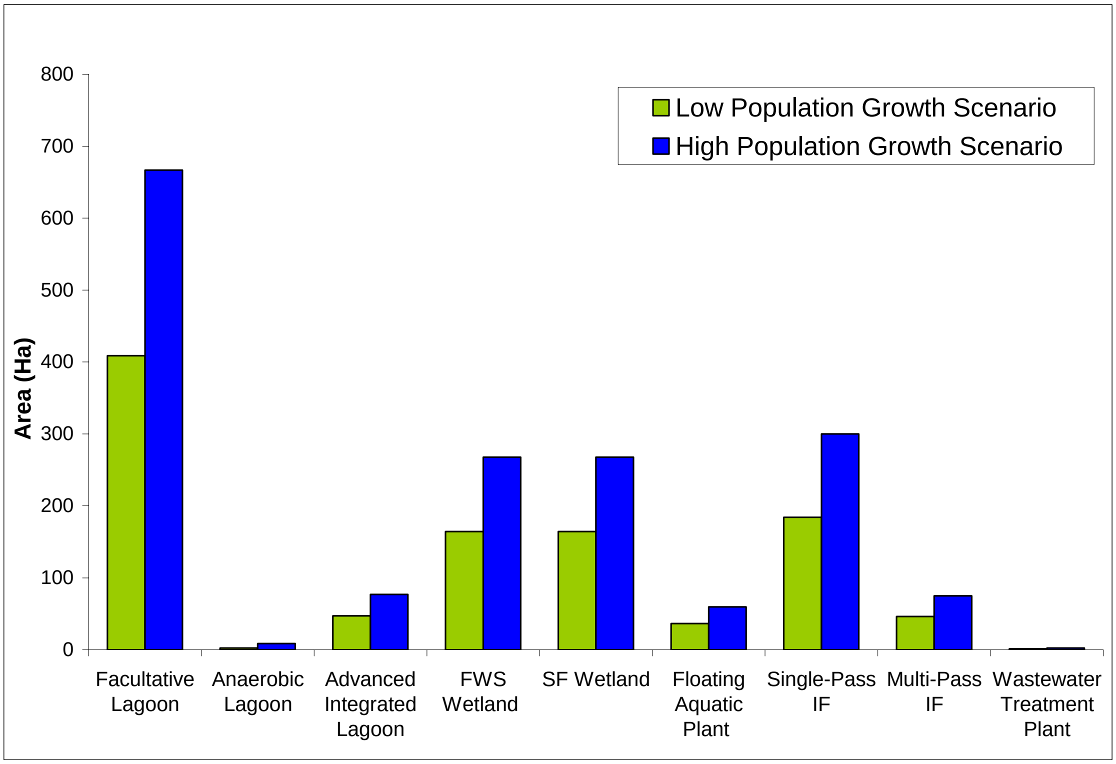


Figure 6.20. Land area required by a variety of wastewater treatment options based on estimated BOD loading rates in two future population scenarios for the year 2030.

Summary of Considerations
Table 6.15 is a summary of the treatment options considered in this analysis and how they compare in land area requirements, ideal slope, depth of system, the need for primary (pre)treatment, the potential load reduction of BOD, TSS, N or P, and relative cost. These comparisons will be set the basis for final recommendations, which are discussed in Section 7.3.

Table 6.15. Comparison of wastewater treatment options.

Treatment Option	BOD loading rate (kg/ha-day)	Area for low population estimate (ha)	Area for high population estimate (ha)	Slope	Load reduction	Lining requirement	Pretreatment requirement	Relative costs
Lagoon Treatment Systems								
Facultative Lagoon	45	409	667	0 - 3%	BOD to 30-40 mg/L	Yes	No	L-M
Anaerobic Lagoon	5 day retention time*	2.7**	4.3**	0 - 3%	50% BOD	Yes	No	L
Advanced Integrated System	390	47	77	0 - 3%	85% BOD 80% TSS	Yes	No	M-H
Constructed Wetlands								
Free Water Surface	112	164	268	0 - 3%	BOD to 20 mg/L TSS to 15 mg/L NH3 to 10 mg/L	yes, if permeable soil	Yes, primary	L
Subsurface Flow	112	164	268	0 – 0.5 %	BOD <20 mg/L TSS to 10 mg/L N to 10 mg/L	yes, if permeable soil	Yes, primary	L-M
Floating Aquatic Plant	230	80	130	level to slightly sloping	90% BOD 90% TSS 55% NH4	yes, if permeable soil	Yes, primary	M-H
Intermittent Filtration Systems								
Single-Pass	100	184	300	0 - 0.1	BOD < 10 mg/L N: 55-75%	Yes	Yes, primary	M
Multi-Pass	400	36	75	0 - 0.1	BOD < 10 mg/L TSS < 10 mg/L N: 40-50%	Yes	Yes, primary	M
Conventional Wastewater Treatment								
Modular Wastewater Treatment Plant	variable	1.5 ha	2.5 ha	variable	95-100% for all constituents	No	No	H

**Based on Hydraulic loading;*
***Based on lagoon depth of 5 m*

6.4 Watershed Model

To gain insight into watershed processes and explore the potential impacts of different management scenarios we chose a modeling approach to understanding watershed processes. Modeling allowed us to integrate the available information into a framework which offered insight into the watershed processes that we did not have information on. It also allowed us to explore the how the water quality within the watershed might change under a number of different development and management scenarios, including population growth, urbanization, and BMP implementation. We are delivering the model to our partners not as a finished product, but as a living tool, meant to be continually updated and utilized by our partners as additional data is collected or new management strategies suggested.

6.4.1 Model Set-up

Watershed Analysis Risk Management Framework WARMF, was chosen as the modeling tool for flow and pollutant loading (Chen, *et al.* 1996; Chen, *et al.* 1999; Systech 2000; Systech Engineering 2001). The model was developed by Systech Engineering in conjunction with the EPA to provide decision makers with the information necessary to make informed decisions about management of their watersheds. The tool is a GIS-based system which was designed to work seamlessly with the output of watershed delineations in Basins 3.1. It integrates topographic, land use, hydraulic cycle information, with a fate and transport model, to allow for simulations of water quality under a variety of conditions and management scenarios.

After the watershed extent has been delineated in Basins, two additional calculations, true aspect and slope, were required prior to importing the watershed into WARMF to begin modeling. Both measures are calculated on a per cell basis and averaged within each sub-basin for modeling purposes.

Land Use

Land use data for WARMF modeling was derived from an unpublished study done by an ECOSUR researcher (Zermologio 2005) and urban extent files provided by LAIGE. The study, whose primary purpose was identifying land use change in the state of Chiapas between 1993 and 2003, utilized a supervised classification algorithm with 30 meter LANDSAT TM data. Because the study's scale was much larger than the scope of this project, a portion of the study's output was inconsistent with higher resolution regional land use data. Of particular concern was the extent of the urban region surrounding San Cristóbal, which was known to be much larger than the region classified as urban in the study.

To incorporate this additional knowledge of the region, two datasets of greater resolution were used to modify the original land use file. An urban extent layer for the city of San Cristóbal served as the base layer for the development of the new region to be classified as urban. This layer was overlain on an IKONOS image of the downtown region captured in 2001 that was provided to us by our partners at LAIGE. The urban layer was then modified using heads-up digitizing to include all areas that appeared to be urban in the image. All land use within the resulting area was set to urban before the layer was merged with the study's land use classification to generate the final watershed land use file.

WARMF requires users to assign each land use within the watershed to a specific category. For the purpose of this study, ten different identified categories of land use were assigned to six different WARMF land use categories (Table 6.16). After importation land use within each sub-basin is treated as an average of all land uses within that sub-basin.

Table 6.16. Land use classification for modeling purposes.

Primary Classification	WARMF Classification
Primary Forest	Mixed Forest
Secondary Forest	Mixed Forest
Pine and Oak Forest	Mixed Forest
Urban	Urban
Scrubland	Cropland/Pasture
Grasslands/Pasture	Cropland/Pasture
Milpa	Cropland/Pasture
Cleared-Tilled / Non-vegetative	Barren
Water	Water
Rangeland	Rangeland

Meteorological Data

Both air quality and precipitation data are required to run a WARMF simulation. Because we were unable to obtain reliable air quality data, we instead used a dummy file from another watershed[12]. To assure that atmospheric deposition did not introduce any bias into our simulations the atmospheric deposition multiplier was set to zero for all simulations. Setting the multiplier to zero has the same effect as instructing the model to ignore any atmospheric deposition, allowing us to run a simulation that remains unbiased by the dummy air quality file.

Precipitation data for model was gathered from Climate Computing Project (CLICOM) data records, a project of the World Climate Data and Monitoring Program (Servicio Meteorológico Nacional de México 2003). The project includes monitoring stations for the entire state of Chiapas, and contains precipitation and temperature data on a daily basis. Seven monitoring locations were located either within the watershed or within close proximity of the watershed and were thus considered as potential sources for climate data. Records from the stations being considered spanned the period from 1951-2000, however station activity and measurement consistency of active stations varied significantly between stations. Station 7067 was selected for modeling purposes, because of its location within the watershed, and because of the relative abundance and consistency of measurements. Records for the station were available from 1964 through 1999, however only a subset of this period was used to run scenarios because of large gaps in earlier periods of the data record. The eleven year period from 1988-1999 was selected as the base precipitation dataset because it offered a contiguous dataset with relatively few gaps.

In addition to precipitation and temperature data, WARMF simulations require data sets for air pressure, cloud cover, dew point temperature and wind speed. No actual measurements were available for the above parameters. Air pressure was estimated using the air pressure for the

[12] WARMF comes pre-packaged with default data for the Brier Creek watershed in Georgia, USA. Included in this base data is the Brier.air file which was used as the air quality file for all simulations.

mean elevation of the watershed. The pressure was then held constant over the course of the modeling period at 942 mbar. Given the conditions of the watershed, the wind speed was assumed to be a constant 7 m/s over the course of the modeling period. Cloud cover was estimated using a simple decision tree, which classified the percentage of cloud cover based on the precipitation records of the present and previous day (Figure 6.21).

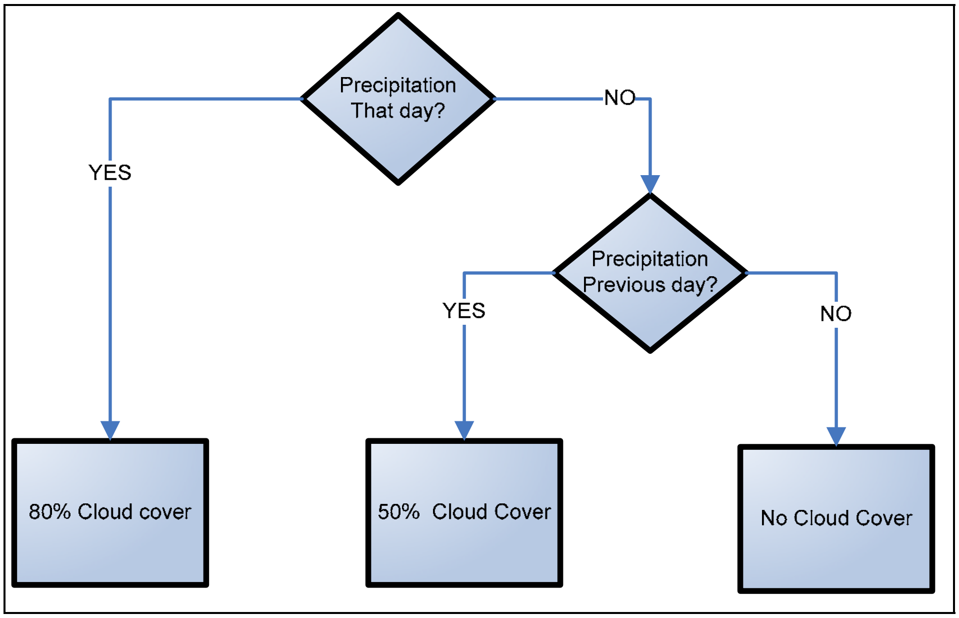


Figure 6.21. Cloud cover decision tree.

In order to calculate daily dew point temperatures, we solved for saturation vapor pressure using equation 6.1, then used saturation vapor pressure to solve for dew point temperature using equation 6.2 (Bras 1990).

Equation 6.1	$E_s = 33.8639[(.000738T+0.8072)^8 - 0.000019\ \lvert 1.8T+48 \rvert + 0.001316]$
Equation 6. 2	$E_s = 6.11 + 0.339(T_d - 32)$

Subsurface Profile

There is significant spatial variation in soil composition and profile within the watershed. Low lying mild slopes are characterized by thicker topsoil layers, while the valley walls, with increasing slopes, have almost no topsoil. Although detailed information about profile variability was not available, some of the variability was incorporated into the model. All sub-basins within the watershed were assigned to one of two groups based on surface conditions. Sub-basins with an average of slope 15% or greater were assigned to the 'Shallow Soil' group or the group where surface soil was more likely to be heavily eroded. Sub-basins with an average slope of 15% or less were assigned to the 'Typical Soil' group (Table 6.17). Nine of the 31 sub-basins were placed into the shallow soil group and the other 22 were placed in the typical soil group. The basin was divided in this manner based on the on-site observation that in areas of the watershed with higher slopes, shallower surface soil profiles were also present. This distinction was made at the sub-basin level, because WARMF aggregates subsurface composition at the same sub-basin level at which it aggregates land use data.

The depths of subsurface unit were assigned based on change points in soil resistivity as reported in Fuentes, *et al* (2003). Values from the Fuentes study were used to assign unit depths to the typical soil layer group because the resistivity measurements were taken within the central flat region of the watershed. To assign depths to each unit within the higher sloped regions, the depth of the corresponding typical soil layer was decreased significantly.

Table 6.17. Soil thickness of the two soil layer profiles used for modeling.

Soil Layer	**Thickness**	
(#)	(cm)	
	Shallow Soils	**Typical Soil**
1	50	100
2	100	200
3	800	1,600
4	100	2,750
5	150	3,000

Soil Characteristics

The subterranean profile of the watershed was divided into two primary groups for soil characteristic estimation. The first group was the topsoil layer, which was modeled through the first two soil layers in WARMF. The second group was the underlying geologic units, which were modeled with the lower three WARMF layers.

No information was available about the actual soil characteristics available for the site, other than a rough soil classification map provided to use by LAIGE. The map divided the topsoil into seven broad categories based on dominant regional topsoil. Topsoil composition was roughly estimated using examples provided in the FAO topsoil characterization for sustainable land management (Food and Agriculture Organization of the United Nations 1998) . Based on the composition estimated above, hydraulic conductivity for each soil type was estimated using average values for saturated hydraulic conductivity for soil types as reported in Rawls, et al. (Rawls, *et al.* 1998). Initial values assigned to each soil type are displayed in Table 6.18. WARMF models conductivity at the sub-basin level and thus these individual values had to be converted to a single value for each sub-basin. An aggregate value for each sub-basin was assigned based by calculating the average conductivity, weighted by the area within the basin covered by each soil type. Horizontal conductivity was assumed to be 1/10 of vertical conductivity.

Table 6.18. Initial top soil layers vertical hydraulic conductivity

Soil Type	Vertical Sat. K (cmd^{-1})	Horizontal Sat. K (cmd^{-1})
Acrisol	2,880	288
Feozem	6,000	600
Gleysol	12,480	1,248
Luvisol	8,400	840
Redosol	4,560	456
Rendizna	6,000	600
Vertisol	4,560	456

Hydraulic conductivity for the lower three layers was estimated based on representative ranges for the formation type. The bottom three layers consisted of a clay layer at the shallowest depth, underlain by volcanic and karstic limestone deposits. A midpoint value was selected for the clay layer, and the bottom two layers were assigned a value in between Karst Limestone and Volcanic deposits (Table 6.19).

Table 6.19. Hydraulic conductivity ranges for lower deposits (Freeze and Cherry 1979).

Rock/Deposit Type	Vertical K High (cmd^{-1})	Vertical K Low (cmd^{-1})
Marine Clay	0.00864	0.00000864
Karst Limestone	86400	8.64
Volcanic	0.000864	0.000000864

After initial simulations were completed with the above conductivities it was clear that these estimates were too low. Initial run-off rates were too high, and recharge was insufficient to maintain the observed base flow through the dry seasons. A possible reason for this is the fracturing known to occur in the region, which would produce areas with much higher conductivity, resulting in sub-basin averages far higher than would normally be expected. Because these initial estimates produced such unlikely results, a trial and error approach was taken with respect to likely vertical and horizontal conductivities in order to achieve flow rates within the expected ranges. Recognizing the amount of uncertainty in the initial estimates of hydraulic conductivity, and in an attempt to limit additional sources of spatial error, the soil and ground characteristics of the watershed were treated as a uniform block. When output for flow and depth were consistent with observed conditions, the baseline conditions for the model were established (Table 6.20).

Table 6.20. Baseline subterranean hydraulic conductivity.

Layer	Vertical Sat. K (cmd^{-1})	Horizontal Sat. K (cmd^{-1})
1	6,625	662.5
2	6,625	662.5
3	100	10
4	1,500	150
5	1,500	150

Initial Model Simulation

The initial model simulation consisted of running the model with the eleven years of climate and precipitation data. The model was run numerous times and estimated flow and river depths were compared with empirical observations made during the three trips to the site (Table 6.21). When simulation output was within the expected range, the initial conditions for soil moisture were re-set to reflect the average soil moisture during each season.

Table 6.21. Flow estimates for the Río Fogótico based on three sampling events.

Río Fogótico Above City		
Month	Flow Estimate(m^3/s)	Stage (m)
June	2.91	0.27
December	0.60	0.08
March	0.33	0.05

Municipal Pumping File

Monthly pumping rate data for 19 pumps (Table 6.22) within the municipality, from December 2004 to October 2005[13], were provided by SAPAM.

Table 6.22. Active SAPAM pumps serving the city of San Cristóbal.

Name	**Size (H.P.)**	**Number**
San Felipe Motor	40	02-0764
Maria Auxiladora Motor	75	MA-804030
Maria Auxiladora Motor	30	MA-604797
La Kisst Tanque Zona Sur Motor	75	02-2341
La Kisst Tanque Zona Sur Motor	75	02-2402
La Kisst Tanque Zona Sur Motor	75	02-2308
La Kisst San Ramon Motor	75	00-3301
La Kisst Tanque Chico del Cerrito de San Cristóbal	N/A	02-1952
Explanada del Carmen Motor	30	02-0812
La Kisst Tanque de Fatima Motores	40	MA-807102
La Hormiga Motor	20	02-1350
La Hormiga Motor	40	02-1938
La Hormiga Motor	20	02-4008
Peje de Oro I Motor	60	02-2403
Peje de Oro I (sin equipo)	N/A	02-1930
Peje de Oro II	40	02-1934
La Almolonga	60	02-2373
La Almolonga	60	02-2371
La Almolonga	100	02-0829

[13] SAPAM records indicate that there are additional smaller pumping stations, however our partners in San Cristóbal explained that the regions served by these pumps and thus the total pumping was negligible in comparison with the pumping rates provided.

In addition to monthly pumping rates, the data consisted of a well location identifier for each pump. By comparing the pumping location identifier with a SAPAM map of well and tank location (SAPAM 2002), we were able to aggregate all pumps into five primary locations. These locations were verified through a field survey of pumping sites which recorded GPS points for each pumping location. To determine the total extraction rate from each location, the pumping rate for all pumps operating at that location were added together.

To model yearly extraction from a location, the missing November pumping rate was estimated using the average pumping rate for the previous eleven months. This provided us with twelve contiguous months of pumping data. It should be noted that this year represents pumping rates for 2005, with December of 2004 substituted for December of 2005 (Table 6.23).

Table 6.23. Monthly pumping rates for major SAPAM wells (m^3).

	Pumping Location					
Month	La Kisst	Maria Auxiladora	La Hormiga	Peje de Oro	La Almolonga	Total
Jan	274,163	80,160	26,038	263,640	121,044	765,045
Feb	242,721	83,655	22,450	226,570	142,696	718,093
Mar	333,621	86,272	42,449	259,180	170,607	892,129
Apr	335,461	82,253	26,596	241,612	273,878	959,799
May	328,986	76,228	25,804	240,439	302,121	973,579
Jun	327,883	74,410	598,251	235,817	321,160	1,557,521
Jul	345,117	84,981	713,702	324,832	323,422	1,792,055
Aug	440,537	74,295	624,150	199,890	253,818	1,592,689
Sept	430,611	86,349	587,416	257,810	257,580	1,619,765
Oct	346,055	61,902	615,688	215,901	242,543	1,482,089
Nov	344,330	78,424	302,731	249,097	223,416	1,197,998
Dec	382,472	72,164	47,494	274,380	48,709	825,219
Total	**4,131,956**	**941,093**	**3,632,769**	**2,989,168**	**2,680,993**	**14,375,980**

Verbal communication with SAPAM officials indicated that pumping rates had remained constant for the past five years, from 2000 to 2005. In order to simulate pumping for all modeling scenarios, the yearly extraction rate was assumed to be static over the 11 year course of all simulations. WARMF models pumping as on a daily basis, based on cubic meters extracted per second. In order to accommodate this, it was assumed that within a given month, extraction was constant in every day and throughout each day.

Industrial Pumping

The only known industrial pumping in the region is that of a FEMSA bottling plant. The plant currently operates two wells at approximately the same location. The pumping rates for both wells were aggregated to estimate the total extraction rate. Because monthly pumping rates were not available, extraction was assumed to be constant over the course of the year. Extraction was assumed to be constant on a daily basis, in accordance with the city well assumptions.

Fate of extracted groundwater
Extracted groundwater is returned to the system within the model in three different ways (Figure 6.22):

1. Forty percent of the pumped water is returned to the river system as point source discharges to the stream system in which it is consumed. The quantity of water returned to the surface waters of each sub-basin was calculated in accordance to proportion of the urban population living in that area. It was assumed that per capita production of wastewater was constant across the entire municipality.
2. Fifty percent is assumed to be lost during the pumping process and returned to the upper soil layers of the regions. This extracted ground water is returned in an unpolluted state. This estimate is based upon city estimates of system losses, which estimated a 43% loss within the municipally run conveyance system and additional losses in the independent conveyance systems utilized in the region (Arreguín, *et al.* 1997). It was assumed that water loss was spatially constant across the entire conveyance network.
3. Ten percent is consumed and not returned to the system. The 10% consumption rate includes, but is not limited to, water transported out of the system through plants shipped outside of the region or water bottled within the region but not consumed within the region.

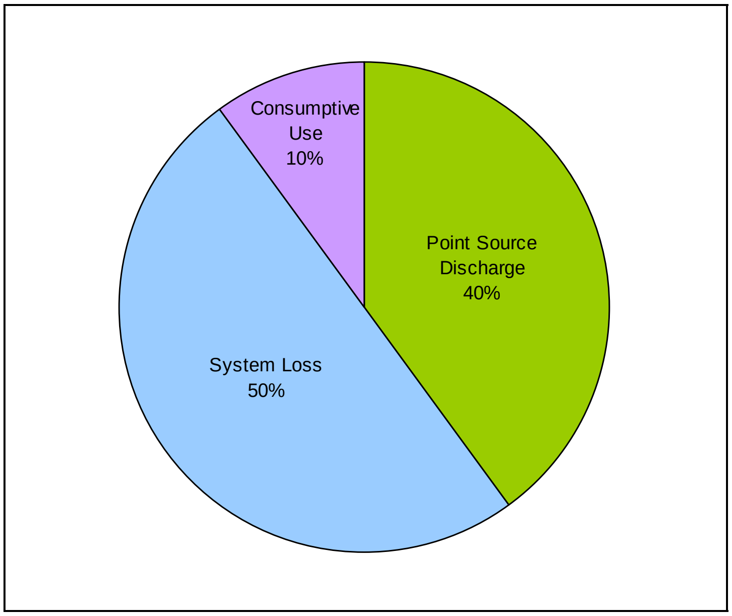


Figure 6.22. Estimated fate of extracted groundwater.

Municipal Wastewater Point Source Discharges
The domestic wastewater for the residents of the city of San Cristóbal is conveyed through a sewerage system to numerous discharge points along the rivers that traverse the city. At the present time, the exact locations of the discharge points and the urban users served by the sewerage systems are unavailable. Without precise knowledge of the above mentioned items, two critical assumptions were made:

1. All inhabitants of the urban center are served by the sewage conveyance systems. Underestimation of the users served by sewerage would have meant a decrease in the total point source load and a likely improvement of water quality. The assumption that

all inhabitants are served by the system is thus a conservative, or worst case scenario, assumption.

2. Wastewater is discharged into the rivers within the sub-basin that it originates. Without knowledge of the actual conveyance system, any aggregation of wastes from different districts would have been arbitrary and counterproductive. Discharging wastewater within the basin is the conservative assumption because it assumes a minimal conveyance system.

Total municipal wastewater volume was determined based on the total amount extracted, divided by the 40% that becomes domestic wastewater, or 114 L/Cap*day. The amount of discharge within each sub-basin was determined based on the total number of inhabitants served by municipal sewer system within that sub-basin. All waste was added as an untreated point source directly into the surface water within that sub-basin.

To determine the urban population of each sub-basin, the modified San Cristóbal neighborhood layer, developed in the land use section, was used to estimate the total population of that sub-basin. The urban population of a sub-basin was determined by the following formula:

$$\frac{\textit{Urban Area of Sub-basin}}{\textit{Total Urban Area}} \times \textit{Total Urban Population} = \textit{Urban Sub-Basin Population}$$

The estimate of urban population served by sewerage within the sub-basin assumes that the population density of urban areas within San Cristóbal is constant across all neighborhoods. A final map displaying the number of municipal users that contribute to point source discharges is included in Figure 6.23. The population used in all modeling scenarios was the 2005 population estimate, and it was assumed that the population remained constant across all years within the scenarios.

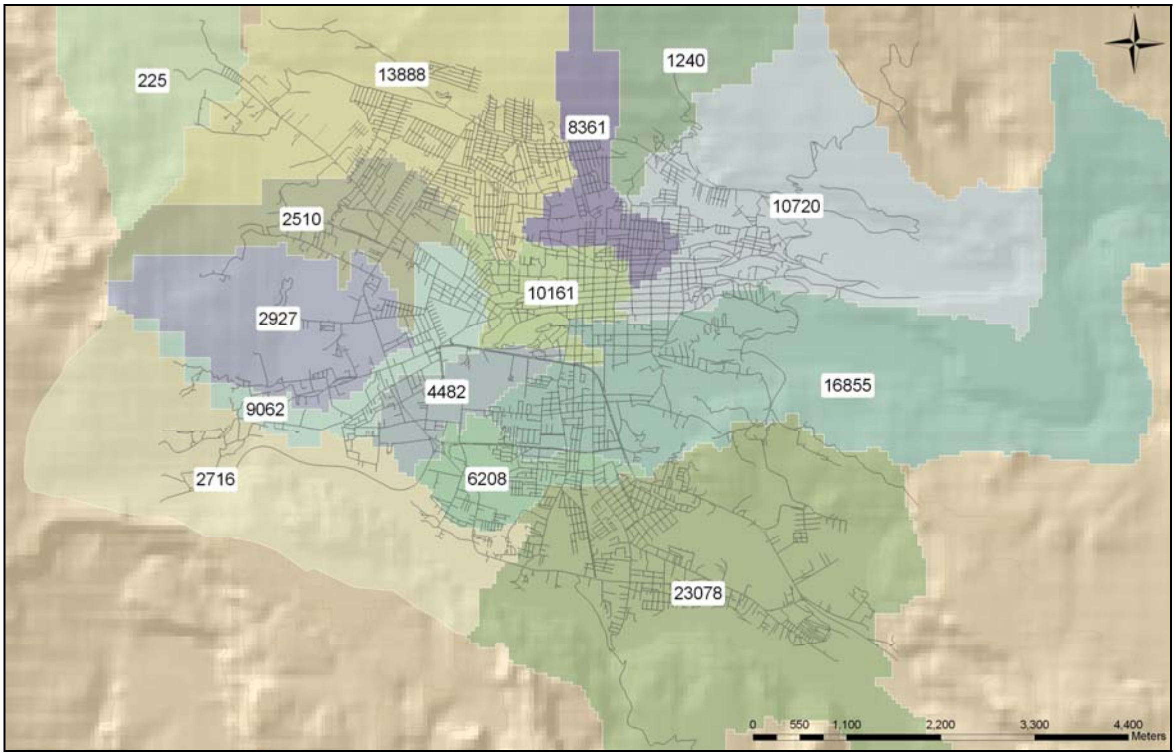


Figure 6.23. Population by sub-basin, whose waste is added as a point source to the surface water within that watershed.

Modeling efforts focused on four contaminants commonly found in domestic sewage: Ammonia, Phosphate, Fecal Coliforms, and Biological Oxygen Demand (BOD). Values of the amount of each contaminant were derived from values reported as standard, per person production rates in Mexico (Crites and Tchobanoglous 1998). The per capita value was then multiplied by the number of people in the sub-basin to obtain the sub-basin load for each pollutant (Table 6.24). Flow from each sub-basin was calculated as a fraction of the total number of inhabitants served by municipal sewerage within the sub-basin.

Table 6.24. Point source discharge of urban wastewater.

Sub Basin	Population	Flow	Temp	Ammonia	P	Fecal Colifroms	BOD
(#)	(#)	(m^3/s)	C	kg/d	kg/d	(#)*10^9/d	kg/d
11	1,523	0.00201	18	12	5	3,046	122
8	277	0.00037	18	2	1	554	22
14	17,045	0.02252	18	130	55	34,091	1,364
13	10,262	0.01356	18	78	33	20,524	821
21	3,082	0.00407	18	23	10	6,163	247
12	13,157	0.01738	18	100	42	26,314	1,053
24	12,471	0.01648	18	95	40	24,942	998
22	3,593	0.00475	18	27	11	7,187	287
23	11,123	0.01470	18	85	36	22,246	890
27	5,501	0.00727	18	42	18	11,002	440
28	20,687	0.02733	18	157	66	41,374	1,655
29	7,620	0.01007	18	58	24	15,240	610
30	28,325	0.03743	18	215	91	56,650	2,266
31	3,334	0.00441	18	25	11	6,669	267
Total	138,000	0.18234	18	1,049	442	276,000	11,040

Non-point Source Discharges

The population that lives outside of the center of the urban area of San Cristóbal was not included in the point source discharge described above, because there is no known conveyance system outside of the city center. The population included in the non-point discharge includes all of the named communities[14] within the watershed other than San Cristóbal. There are no known treatment facilities serving any of these communities, thus the load is assumed to reach the system in its entirety. The difference between non-point load and the urban point source load is the point of entry to the system. The non-point load is applied to the land surface, and thus some natural attenuation can occur prior to entering the surface water. The point source load enters the surface water system directly.

The population of each sub-basin was estimated by applying a constant growth rate to the 2000 INEGI census. To estimate the 2005 population of each rural community, it was assumed that rural population growth occurred at the same rate as growth occurred in the city of San Cristóbal between 2000 and 2005. Population estimates for each sub-basin that are not served by sewerage conveyance are reported in Table 6.25.

[14] The 2000 INEGI census provided population information for 57 named communities within the San Cristóbal watershed.

Table 6.25. Sub-basin population not served by the municipal sewage conveyance system.

Rural Population		
Sub Basin	2000 Population	2005 Estimate
1	3,057	3,184
2	1,086	1,131
3	3,941	4,104
4	0	0
5	3,590	3,739
6	508	529
7	2,010	2,093
8	1,600	1,666
9	1,071	1,115
10	200	208
11	561	584
12	562	585
13	0	0
14	2,237	2,330
15	1,979	2,061
16	0	0
17	1,945	2,025
18	0	0
19	445	463
20	195	203
21	0	0
22	417	434
23	0	0
24	0	0
25	2,398	2,497
26	804	837
27	0	0
28	1,644	1,712
29	0	0
30	128	133
31	419	436
Total	**30,797**	**32,069**

The per capita discharge for each person was estimated using values derived from estimates of per person contaminant production rates in Mexico (Crites and Tchobanoglous 1998).

System Water Loss

Loss of water through system leakage was returned to the soil layers in proportion as a fraction of the urban population inhabiting the sub-basin. No water was returned to basins without an urban population because there is no known water delivery infrastructure through which it would be lost. The return rate for each basin was held constant for the entire year, in effect balancing the water use for the year rather than for the month. For the purpose of this analysis, the constant assumption is justifiable because the water returned to the system accounts for less than 3% of average river flow. No water quality information was available for this water, so we assumed it was returned to the system with a similar quality as the background levels. Future work may consider returning water at a constant monthly rate, thus accounting for the seasonal differences in pumping rates and the expected accompanying differences in water loss.

Additional Sources of Pollutant Load
Additional sources of the modeled pollutants within the watershed include agriculture and livestock. In lieu of an accurate assessment of the number of livestock per unit area or the types of crops being grown or fertilizers being applied to the agricultural land, the default loading values for the other land uses were used.

Our partners in San Cristóbal have suggested that pesticide loading, especially from the tributaries and the main stem of the Arroyo Chamula may be an issue. The WARMF framework can be easily extended to provide modeling of such compounds if and when they are identified. However such work has not been done at this time.

6.4.2 Baseline Scenario
The baseline scenario was used to approximate the total flow and temporal fluctuations within the watershed, based on the limited dataset available at the time of this study (Table 6.25). The scenario is an un-calibrated model because there were not enough data points available to truly calibrate the model. Baseline estimates for pollutant loads could not be compared at this time because not enough information was available about pollutant concentrations.

The scenario was able to provide some basic insights into the function of the watershed that furthered our understanding of the processes present within the system. For example, the model predicted a relationship between the quality and quantity of the water that was consistent with the local understanding of the systems as explained to researchers. During informal interviews, numerous residents living in the outskirts of the city explained that during storm events the water was dirtier. Figure 6.24 shows the estimated relationship between quality and flow at a point prior to water passing through the urban center. In the figure, peak flows (shown in blue) are positively correlated with higher pathogen levels (shown in red). This suggests that the runoff from storm events contributes a significant amount of the total load, at least in headwater reaches. The opposite phenomenon is predicted for a reach of the stream after passing through the urban center. In Figure 6.25, flow is again shown in blue and fecal coliform concentration is indicated by the red. In this reach the inverse relationship is predicted, when flow is higher, fecal coliform concentration is lower. This observation suggests the primary importance of urban point sources to downstream pollutant loads. During storm events the impact of increased loads from the headwater areas reaching the downtown area is an order of magnitude smaller than the input from urban point sources. The greater volume of water reaching urban during storm events is sufficient to offset the additional nutrient delivery, and dilute the normally more urban load.

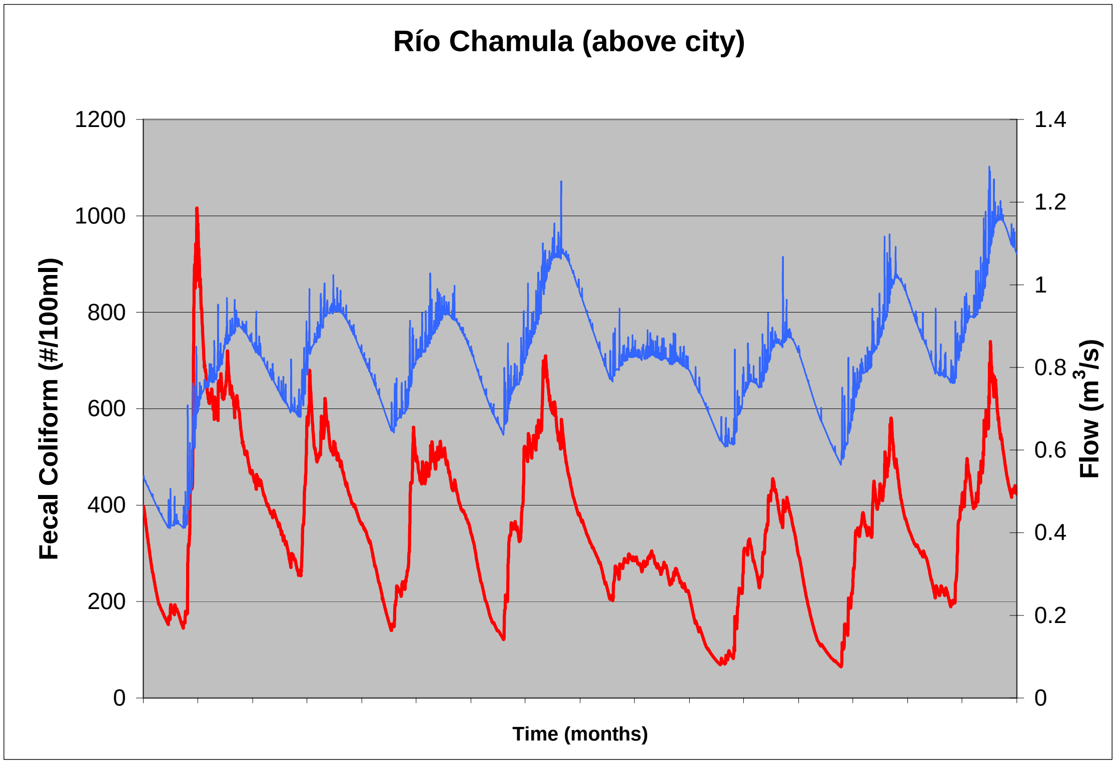


Figure 6.24. Relationship between water quality and flow in a headwater stream.[15]

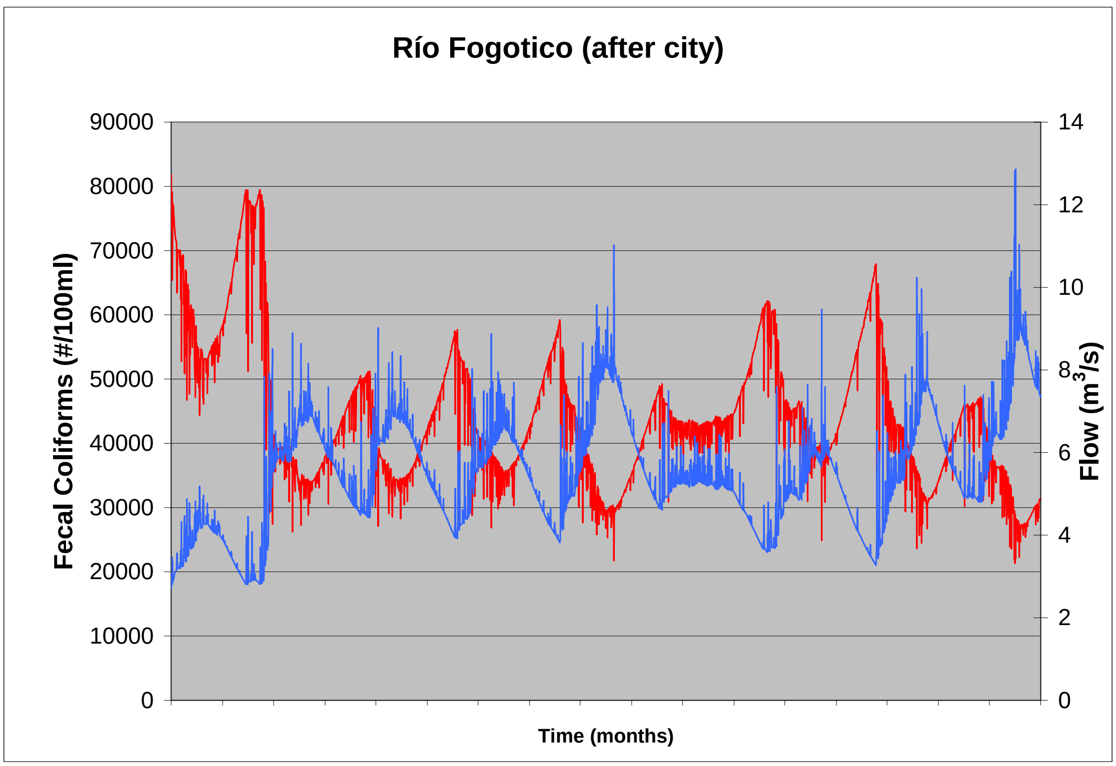


Figure 6.25. Relationship between water quality and flow near the exit of the watershed.[16]

[15] Values reported are the estimates from the uncalibrated model.

On a very simplified level the model can also be used to explore the seasonal relationship of groundwater availability within the watershed. Figure 6.26 displays the seasonal flow (averaged over a two year period) for the fourth subterranean unit. The graph clearly indicates that recharge occurs during the rainy season, and drawdown occurs during the dry season in the sub-basin that contains the La Hormiga pumping station. The relationship is simplified because no research has been done on the extent of the aquifer system, and we recognize that aquifers do not normally follow the physical contours of the surface used to delineate watersheds.

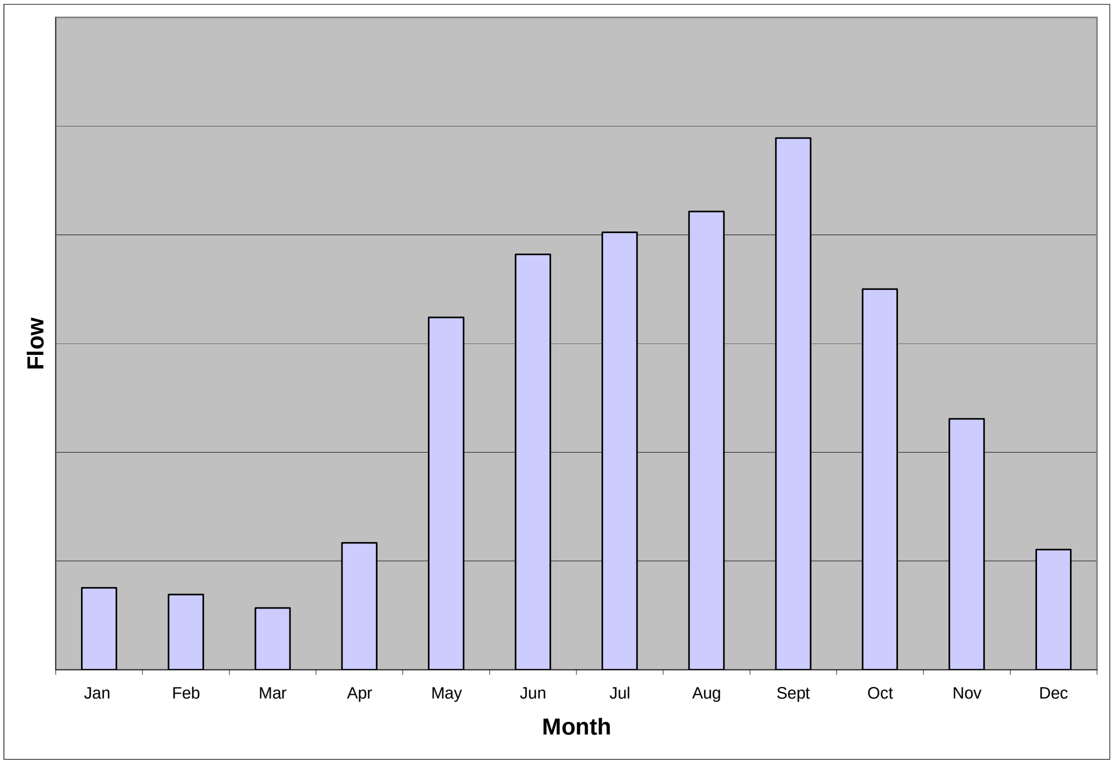


Figure 6.26. Seasonal variation in subsurface flow[17].

Rainfall is known to be variable through the watershed with higher elevations displaying strong orographic effects. In the baseline scenario rainfall was held constant in all sub-basins in the watershed. To explore the potential impact of orographic effects on stream flow, a scenario was generated in which the sixteen sub-basins with a mean elevation of greater than 2,300 meters were given a rainfall multiplier of 1.9. A rainfall multiplier of 1.9 indicates that these sub-basins will receive 1.9 times the rainfall as the basins with a multiplier of 1. A rainfall multiplier of 1.9 was selected using estimated differences in rainfall by elevation (Espiritu 1998, see Appendix 8.1) and with the understanding that the rainfall monitoring station used to establish baseline rainfall amounts is located in the central low valley of the watershed. In the scenario with orographic effect included, the mean flow at the outlet of the watershed increased from 6.21 m^3/s to 9.44 m^3/s, and mean exiting the Chamula sub-watershed increased from 1.19 m^3/s to 2.13

[16] Values reported are the estimates from the uncalibrated model.
[17] Actual values for flow are not reported because there is no basis for the overall storage area being measured, thus reporting a numerical value offers little insight.

m^3/s[18]. These dramatic increases in flow suggest that a better understanding of the rainfall patterns is essential for understanding watershed processes and future modeling efforts.

6.4.3 Future Management Scenarios

The model, as implemented above, served as the baseline analysis for which to compare future model outputs. Because the model is un-calibrated, the amount of change should be viewed primarily in terms of percentage change rather than looking at the absolute difference of the change. With this in mind we explored a number of scenarios to look at the potential effectiveness of different management scenarios.

Exploration of Future Population Growth

The one certainty in the San Cristóbal region appears to be that the population will continue to grow. The rate of the growth however remains open to debate and speculation. This scenario explored the potential impact of two different population growth scenarios over a 25 year planning horizon. The first estimate is based on projection made by the city of San Cristóbal, which assumes the growth rate of the city will continue to decline from the peak rates experienced in the mid-nineties. This is the lower of the two estimates and approximates the 2030 population of the city to be approximately 230,000. The second estimate is the higher of the two, and is based on ECOSUR population growth predictions, which assumes a constant growth rate. Based on ECOSUR estimates, the population of the city in 2030 will be approximately 375,000.

The goal of the model was to offer the stakeholders a glimpse into what could be expected if a business as usual scenario (no sewage treatment) occurred, but with increased population size. In order to model growth, a number of additional assumptions were made across all scenarios:

1. Rural population growth occurred at the same rate as the urban growth.
2. Urban population growth was evenly distributed across all sub-basins that currently contain a portion of the urban area.
3. No change in the rate of per capita water consumption.
4. No change in per capita sewage generation.
5. No change in land use (land use changes are explored separately later).
6. Pumping rates increased in proportion with per capita growth.

The 2030 population for each sub-basin was calculated through the following formula:

$$\frac{\textit{2030 Urban Pop Est.}}{\textit{2005 Urban Pop}} \times \textit{2005 Sub-basin Population} = \textit{2030 Sub-Basin Population}$$

After the 2030 population was established for the scenario, the point and non-point source discharges, septic system discharge, and system water loss files were updated to reflect the new population estimates for the region. The scenarios were then run with the same ten year climatologic cycle period that the baseline scenario used. Figure 6.27 graphically illustrates how such growth under the business as usual scenario would further exacerbate the watershed's quality problems.

[18] Average values reported based on a nine year average from 1991-1999. The first two years of flow are omitted from average estimates to reduce bias introduced by initial conditions.

Figure 6.27. Fecal Coliform concentration in two different growth scenarios.[19]

Urbanization

Urbanization, the process of converting alternative land uses (agriculture, forest, wetlands, etc.) to urban cover, has occurred rapidly over the last two decades and the trend is likely to continue as the population of the urban center increases. To explore the effects of future urbanization on the water cycle within the watershed, a likely urbanization scenario was created by converting the area currently classified as cropland/pasture to urban within the 14 sub-basins that currently contain part of the population of San Cristóbal. The conversion had little effect on the annual or monthly average stream flow, but had a significant impact on the hydrograph during storm events. Figure 6.28 displays the hydrograph for the main stem of the Fogótico during a typical month within the rainy season. The figure displays a number of storm events, including a larger event which occurs around the 10th day of the month. This larger event creates the runoff spike which can be observed in both scenarios. The spike in the urbanized scenario is almost 20% higher than the spike currently predicted by the model. This increase suggests the importance of the non-urban area in current flow attenuation, and suggests that converting even a fraction of the total watershed area can have a large impact on peak flow. In a city in which flooding is already a problem, the use of the model to explore how different land uses or land features might attenuate flow or increase peak flow could be of use when siting residential or commercial projects. In interpreting Figure 6.28 it is important to note that the greater peak predicted in the urban scenario is not accompanied by a more narrow (shorter duration) event window as might be expected. WARMF reports flow as an average daily value, and the line fitted through the average flow in Figure 6.28 is a smoothed line through average daily flow. Thus the compression of the storm event that would be expected, would not be captured in WARMF. It is

[19] Values reported are the estimates from the uncalibrated model.

also important to note that baseline flow in the urbanized scenario was lower during the dry season.

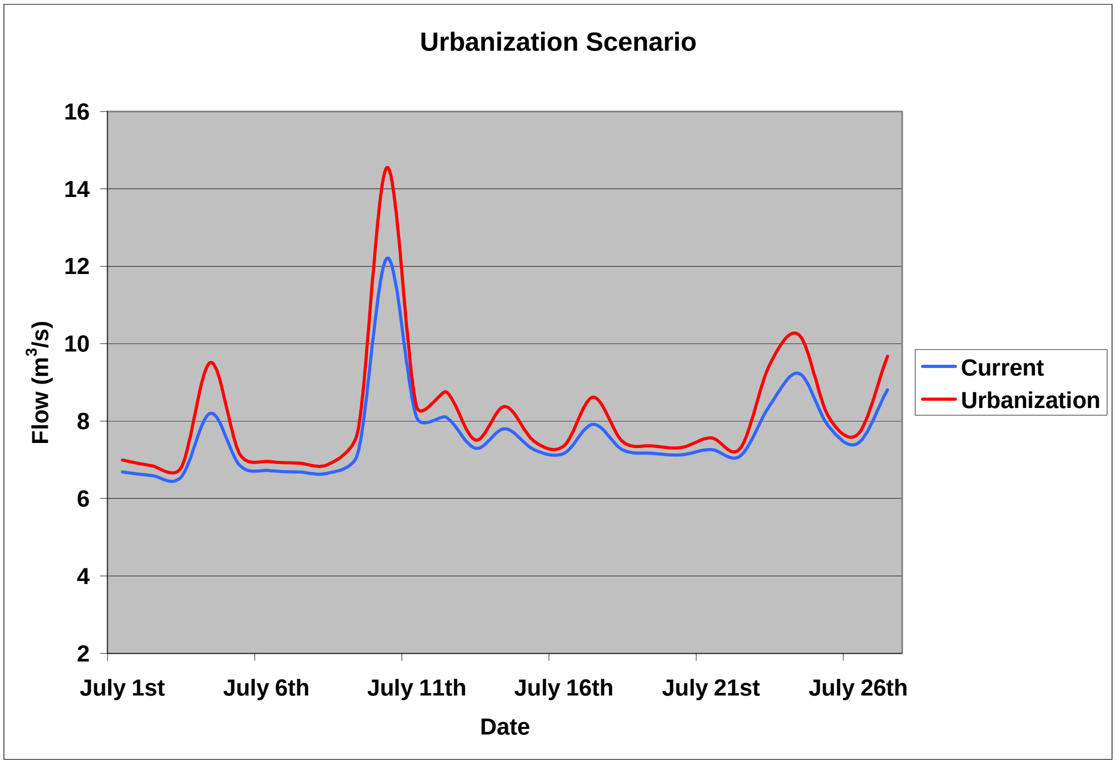


Figure 6.28. This graph indicates an increased spike in the storm event hydrograph as a result of land use conversion.[20]

Upstream Sewerage Treatment Systems

Modeling of the effectiveness of an individual sewage treatment technology in WARMF is beyond the capability of the application. What WARMF can do is model the overall effect of a treatment technology on the receiving water body. The difference is subtle but important to understanding the output from pollutant load reduction scenarios. If we assume that per-person production of waste remains constant across all scenarios (an assumption we adhere to), then WARMF allows users two avenues through which to manipulate the amount of pollutant load reaching the water body. The first is manipulating the effectiveness of the treatment process. Initial treatment scenarios assume zero treatment of human waste. The second is through adjusting the percentage of the population being served by the treatment process.

The impact on surface water quality was explored when all upstream inhabitants of the Chamula sub-watershed were provided with a treatment technology that would reduce loading by 75%. The scenario predicts that the implementation of such a program could have a dramatic impact on water quality within the headwater systems. However, once the water reached the urban area, the magnitude of the reduction would be dwarfed by the magnitude of the urban load.

[20] Values reported are the estimates from the uncalibrated model.

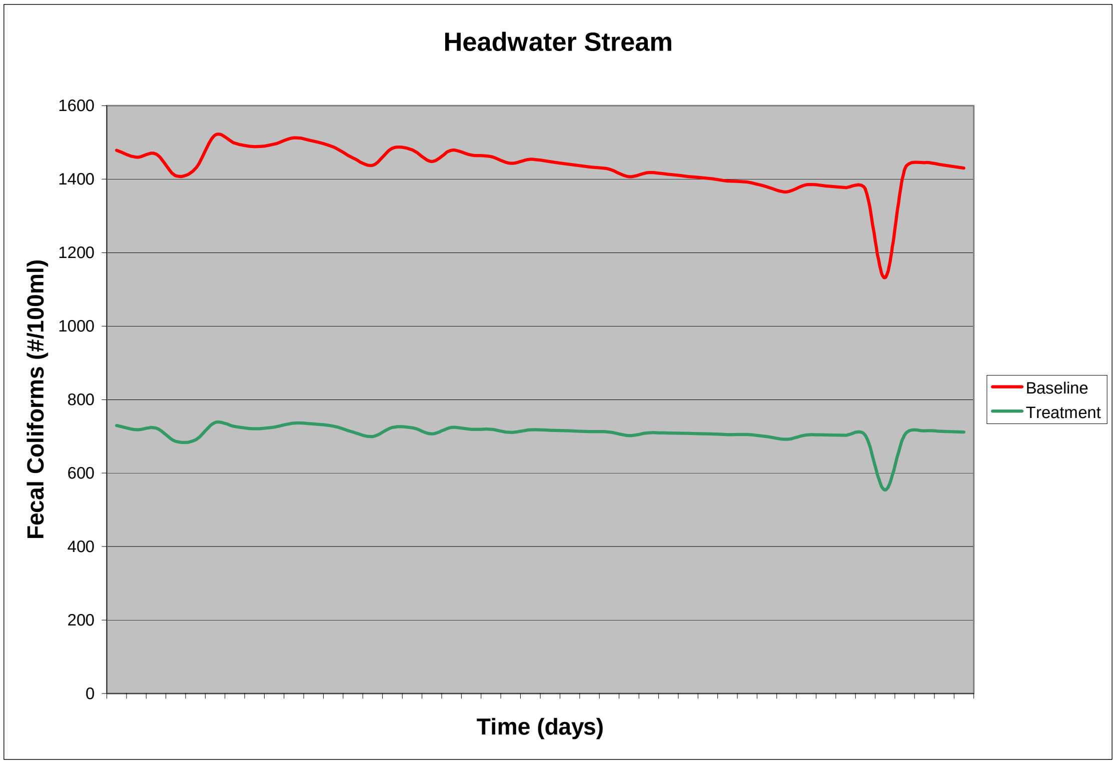


Figure 6.29. Fecal Coliform reduction in a headwater stream through upstream domestic sewage collection and diversion to a treatment system.[21]

[21] Values reported are the estimates from the uncalibrated model.

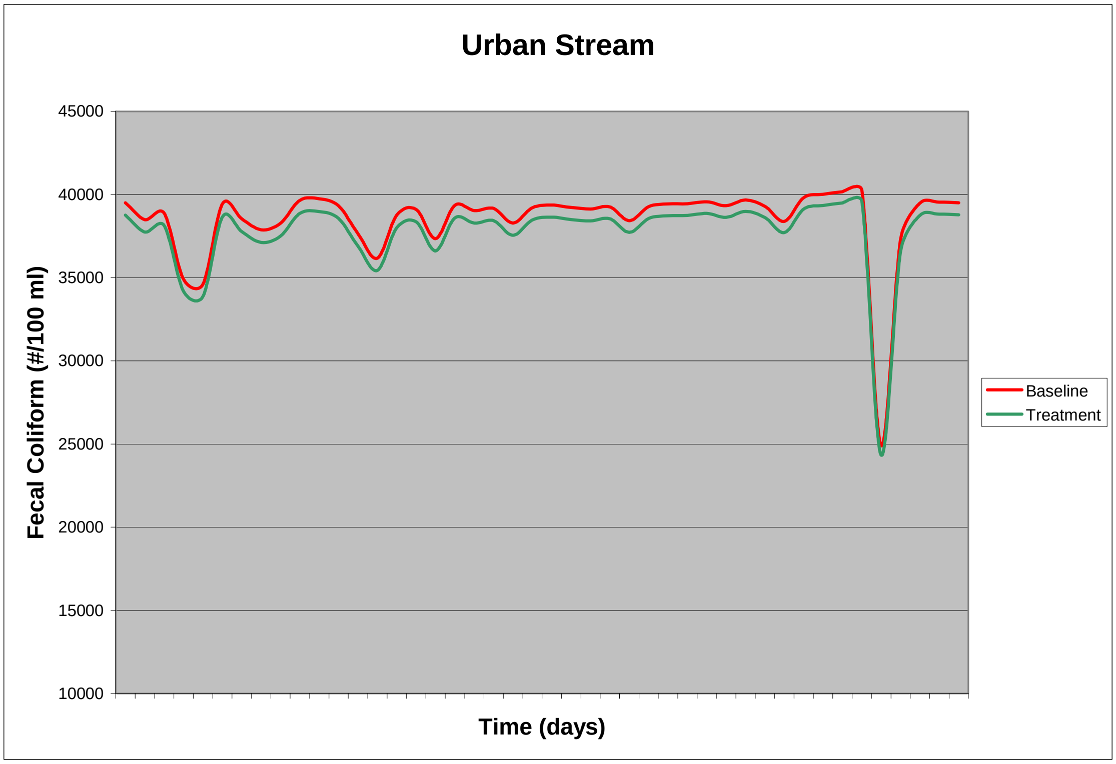


Figure 6.30. Fecal Coliform reduction in an urban stream through upstream domestic sewage collection and diversion to a treatment system.[22]

Riparian Buffers
Numerous attempts were made to model the impact of installing buffer zones along various portions of the rivers in the headwater regions of the watershed; however, such attempts did not yield the expected results. No buffer size or slope produced significant decreases in the load of the pollutants being modeled. Because there are no point sources in the headwater systems we speculate that the failure of buffer zones to achieve even a modest decrease in load is likely a model failure rather that an indication that buffers will not work in the area.

6.4.4 Sensitivity Analysis
In using models to evaluate management decisions it is important to recognize which parameters the model is most sensitive to and how this sensitivity affects model output. The primary output of the model used during this phase of the analysis was the flow estimation. Flow predictions and calculations were used to explore the wastewater treatment options, while soil moisture content through seasons was used for a rudimentary examination of aquifer recharge.

To explore the sensitivity of this WARMF implementation we explored the relationship between four soil characteristics and their impact on flow through the system. The analysis divided the subterranean system into two units: 1- the upper two layers (soil layers); and 2- the lower three

[22] Values reported are the estimates from the uncalibrated model.

layers (geologic features) and explored the impact of doubling or halving of the assigned baseline value on the flow throughout the system (Table 6.26)[23].

Table 6.26. Soil parameter ranges for sensitivity analysis.

Variable	Low	Baseline	High
Horizontal Conductivity (cm/d)			
1st Layer	3,312.5	6,625	13,250
2nd Layer	3,312.5	6,625	13,250
3rd Layer	50	100	200
4th Layer	375	750	1,500
5th Layer	375	750	1,500
Vertical Conductivity (cm/d)			
1st Layer	331.25	662.5	1,325
2nd Layer	331.25	662.5	1,325
3rd Layer	5	10	20
4th Layer	75	150	300
5th Layer	75	150	300
Field Capacity			
1st Layer	0.2	0.4	0.5
2nd Layer	0.15	0.3	0.45
3rd Layer	0.11	0.22	0.35
4th Layer	0.1	0.2	0.35
5th Layer	0.08	0.15	0.35
Saturation Moisture			
1st Layer	0.25	0.5	0.75
2nd Layer	0.22	0.45	0.675
3rd Layer	0.17	0.35	0.525
4th Layer	0.17	0.35	0.525
5th Layer	0.17	0.35	0.525

To compare change in flow across scenarios the output from each scenario was compared individually against three different reference flow values. The first reference flow amount was the flow given in the baseline scenario (see Section 6.4.1). Recognizing that output from the baseline scenario was that of an un-calibrated model, and not wanting to place too much emphasis on the output from the baseline scenario, we also compared each scenario's output to the mean value of all scenarios and to the median value of all scenarios (Tables 6.27 and 6.28).

The difference is reported as the percent difference between the observed and the expected value:

*Difference = (Observed – Expected / Expected) *100*

Because the observed value was not an actual observed value, the observed value used in difference calculation is that model output for that scenario. The expected value is the reference

[23] If doubling or halving the base value resulted in a value outside of the reasonable range for a parameter, then the highest/lowest reasonable value was used.

value for the comparison group. For example, if the model output is compared to the mean of all model output, then the expected value would be the mean.

The difference in flow was compared across four different one month periods, representing different stream flow conditions.

1. Low flow period: Low flow period with little to no precipitation.
2. High flow period: High flow period with constant flow.
3. High flow during rising hydrograph: High flow period with sufficient precipitation events to increase flow over the course of the period.
4. High flow during falling hydrograph: High flow period with little to no precipitation, and steady decrease in flow.

Bias in different flow regimes can have dramatically different effects on management strategies and approaches to watershed management. For example, a slight under estimation of flow during a low flow period, may be the critical difference between adequate water for aquatic life and inadequate supply. While a slight underestimation during high flow may have no net effect.

Field Capacity

Total flow in both the headwater stream and along the main stem of the Fogótico was very sensitive (~100%) to increases in the field capacity. In all conditions a doubling of the field capacity of either the upper two layers or the lower two layers lead to reductions in overall flow. A possible explanation for this prediction is that increasing the field capacity of a region will result in an increase in water stored within the soil system of that area, and less leaving the region as run-off. It is interesting to note that reductions in field capacity did not result in corresponding changes in flow in the opposite direction.

Saturation Moisture

Saturation moisture proved to be the second most sensitive variable in terms of flow in both systems. Within the different conditions drastic differences were predicted based on the season of the change. Of particular interest is the dramatic increase in flow predicted during the low flow/low precipitation condition that accompanied a decrease in the saturation moisture of the lower 3 layers. In both stream systems this reduction resulted in a predicted flow that was over 100% higher. This prediction is in line with expectations because as saturation moisture is reduced, the total capacity to retain groundwater is diminished. Reduced underground storage capacity results in a forcing of the water into the surface water system, increasing river flow. Flow was also predicted to be higher in both the high precipitation/high flow and the high precipitation/rising hydrograph condition, while flow was predicted to be lower in the low precipitation falling hydrograph condition. The estimated lower flow in the falling hydrograph condition, leads one to speculate that in this saturated condition, additional water ran-off as quick flow during the storm events (as suggested by higher flows in both the high precipitation conditions). This observation seems to be at odds with the increased flow predicted in the low flow/low precipitation condition.

Horizontal Conductivity
Model output for flow does not appear to be very sensitive to changes in horizontal conductivity of any of the soil layers. The notable exception to this was the higher flows predicted in the headwater stream, in the high precipitation/high flow condition that accompanied increases in the horizontal conductivity of the lower three layers. In this condition flows greater than 25% above expected were predicted. This suggests that this reduction in horizontal conductivity prevents water from traveling horizontally through from the upper reaches of the lower areas of the watershed, instead forcing this water into the surface water system.

Vertical Conductivity
Overall total flow was least sensitive to changes in vertical conductivity, with predicted flow within 7% of the expected value across all conditions. While this may seem to suggest the relative unimportance of vertical conductivity to the system, we would caution that it not be overlooked in future modeling efforts. As currently constructed, the model estimates that vertical conductivity decreases with increasing depth. While this assumption may be reasonable for most subterranean systems with more permeable soils underlain by geologic units with lower permeability, the presence of karst geology in the region means that it may not be appropriate in this watershed. Karst formations are typified by large fractures and fissures which act as macropores dramatically increasing the rate of low through the unit. The location of these macropores could dramatically affect flow within the region, resulting in changes in conductivity much larger than the doubling used here for sensitivity analysis.

Table 6.27. Flow variability in the main stem of the Río Fogótico with soil parameter variation.

	JULY 98 - LOW PRECIP - LOW FLOW															
	Field Capacity				Saturation Moisture				Horizontal Conductivity				Vertical Conductivity			
	Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Baseline	-93.9%	0.1%	-94.0%	-7.5%	-93.9%	0.1%	-7.6%	127.5%	0.0%	-2.7%	0.0%	19.3%	0.0%	0.2%	4.5%	-6.2%
Mean	-93.4%	10.2%	-93.5%	1.8%	-93.4%	10.2%	1.6%	148.8%	10.1%	7.1%	10.1%	31.4%	10.1%	10.3%	15.0%	3.3%
Median	-93.9%	0.1%	-94.0%	-7.5%	-93.9%	0.2%	-7.6%	127.6%	0.1%	-2.6%	0.1%	19.4%	0.0%	0.2%	4.5%	-6.1%

	OCTOBER 95- HIGH PRECIP - HIGH FLOW															
	Field Capacity				Saturation Moisture				Horizontal Conductivity				Vertical Conductivity			
	Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Baseline	-97.0%	0.0%	-97.0%	-9.6%	-97.0%	0.0%	-17.9%	12.5%	0.0%	-22.5%	0.0%	17.4%	0.0%	0.0%	0.4%	-2.3%
Mean	-96.3%	22.7%	-96.4%	10.8%	-96.3%	22.6%	0.6%	37.4%	22.6%	-5.0%	22.6%	44.0%	22.6%	22.6%	23.1%	19.8%
Median	-97.0%	0.2%	-97.0%	-9.5%	-97.0%	0.1%	-17.8%	12.6%	0.1%	-22.4%	0.1%	17.6%	0.1%	0.1%	0.5%	-2.2%

	JULY 94- HIGH PRECIP - RISING HYDROGRAPH															
	Field Capacity				Saturation Moisture				Horizontal Conductivity				Vertical Conductivity			
	Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Baseline	-96.5%	0.3%	-96.6%	-5.0%	-96.5%	0.0%	-11.8%	38.3%	0.0%	-8.5%	0.0%	14.5%	0.0%	0.0%	1.9%	-4.4%
Mean	-95.9%	18.8%	-96.1%	12.5%	-95.9%	18.5%	4.4%	63.3%	18.5%	8.3%	18.5%	35.7%	18.5%	18.5%	20.7%	13.3%
Median	-96.5%	0.4%	-96.6%	-4.9%	-96.5%	0.1%	-11.8%	38.4%	0.1%	-8.5%	0.1%	14.6%	0.1%	0.1%	2.0%	-4.3%

	JANUARY 99- LOW PRECIP - FALLING HYDROGRAPH															
	Field Capacity				Saturation Moisture				Horizontal Conductivity				Vertical Conductivity			
	Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Baseline	-98.5%	-0.1%	-98.6%	0.7%	-98.5%	-0.1%	-3.8%	-77.9%	0.0%	-8.1%	0.0%	-2.0%	0.0%	-0.1%	-3.0%	3.2%
Mean	-98.1%	29.4%	-98.2%	30.4%	-98.1%	29.4%	24.6%	-71.4%	29.5%	19.0%	29.5%	26.9%	29.5%	29.3%	25.6%	33.7%
Median	-98.5%	0.1%	-98.6%	0.8%	-98.5%	0.0%	-3.6%	-77.9%	0.1%	-8.0%	0.1%	-1.9%	0.1%	0.0%	-2.9%	3.4%

Table 6.28. Flow variability in a headwater stream (Arroyo Chamula) with soil parameter variation.

	JULY 98 - LOW PRECIP - LOW FLOW															
	Field Capacity				Saturation Moisture				Horizontal Conductivity				Vertical Conductivity			
	Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Baseline	-93.1%	0.2%	-93.3%	-2.5%	0.1%	-93.1%	-3.5%	114.0%	0.0%	0.0%	6.1%	-2.6%	0.0%	0.1%	3.5%	-4.2%
Mean	-92.4%	11.2%	-92.6%	8.2%	11.1%	-92.4%	7.1%	137.0%	11.1%	11.0%	17.8%	8.1%	11.0%	11.2%	15.0%	6.4%
Median	-93.1%	0.2%	-93.3%	-2.5%	0.1%	-93.1%	-3.5%	114.0%	0.1%	0.0%	6.1%	-2.5%	0.0%	0.2%	3.6%	-4.1%
	OCTOBER 95- HIGH PRECIP - HIGH FLOW															
	Field Capacity				Saturation Moisture				Horizontal Conductivity				Vertical Conductivity			
	Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Baseline	-95.8%	0.3%	-96.2%	-5.9%	-5.9%	-95.8%	-16.5%	39.2%	0.0%	0.0%	24.9%	-10.3%	0.0%	0.0%	1.0%	-3.0%
Mean	-95.1%	18.3%	-95.5%	11.0%	11.0%	-95.1%	-1.6%	63.7%	18.0%	18.0%	47.3%	5.7%	17.9%	18.0%	19.1%	14.4%
Median	-95.8%	0.4%	-96.2%	-5.9%	-5.9%	-95.8%	-16.5%	39.3%	0.1%	0.1%	25.0%	-10.2%	0.1%	0.1%	1.1%	-2.9%
	JULY 94- HIGH PRECIP - RISING HYDROGRAPH															
	Field Capacity				Saturation Moisture				Horizontal Conductivity				Vertical Conductivity			
	Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Baseline	-95.3%	1.0%	-96.1%	3.2%	3.2%	-95.3%	-11.1%	51.2%	0.0%	0.0%	9.8%	-10.8%	0.0%	0.0%	1.7%	-2.7%
Mean	-94.5%	18.0%	-95.5%	20.6%	20.6%	-94.5%	3.9%	76.2%	16.8%	16.8%	28.3%	4.1%	16.8%	16.8%	18.8%	13.7%
Median	-95.3%	1.0%	-96.1%	3.2%	3.2%	-95.3%	-11.1%	51.2%	0.0%	0.0%	9.8%	-10.8%	0.0%	0.0%	1.7%	-2.7%
	JANUARY 99- LOW PRECIP - FALLING HYDROGRAPH															
	Field Capacity				Saturation Moisture				Horizontal Conductivity				Vertical Conductivity			
	Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers		Upper 2 Layers		Lower 3 Layers	
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
Baseline	-98.4%	0.0%	-98.6%	-2.4%	-0.1%	-98.4%	-8.2%	-63.4%	0.0%	0.0%	6.2%	-13.2%	0.0%	-0.1%	-1.7%	0.8%
Mean	-98.0%	28.5%	-98.2%	25.5%	28.4%	-98.0%	18.1%	-52.9%	28.5%	28.6%	36.5%	11.5%	28.5%	28.4%	26.3%	29.5%
Median	-98.4%	0.2%	-98.6%	-2.2%	0.1%	-98.4%	-8.0%	-63.3%	0.2%	0.2%	6.4%	-13.1%	0.2%	0.0%	-1.6%	0.9%

7.0 Recommendations

The recommendations listed in this section are suggestions as to how the deliverables of this project fit into the larger scope of improving the water quality of San Cristóbal. The section outlines the next steps which should be taken in order to maximize the benefit of each deliverable.

7.1 Water Quality Monitoring Program

We recommend that the monitoring program for surface and drinking water quality be implemented as soon as possible. The results will provide a profile of the current state of water quality parameters in the San Cristóbal watershed - information that is essential for the proper management of the local water resources.

The monitoring programs described in Section 6.1 reflect our view, incorporating input from our partners, of what is necessary to characterize regional water quality. However, in addition to the sampling points described there, we also recommend sampling water in the areas outside of the city as part of the surface water quality monitoring program.

Since the majority of the pollutant load is thought to occur inside the urban region, due to the large discharge of untreated wastewater, it is expected that most of this water is already highly contaminated. Only monitoring urban areas would provide a profile of the water quality as it moves inside the city, but not include information on the outer reaches of the watershed. These additional points would assess the changes in the water quality as the water moves through the watershed, from the headwaters to the watershed outlet. The points were identified using the multi-criteria analysis described in this report (Section 5.4), which provided a rapid assessment of potential non-point sources of pollution. The comparison of the pollutant constituents from one point to another would identify the areas that cause the greatest impairment in the water outside of the urban area.

In order to achieve this objective, points were grouped based on location and potential information inferred from monitoring at that location. Three primary groups where established, which were further subdivided by priority (Figure 7.1 and Table 7.1):

- Headwater stream and rural area points – Provides data on background nutrients present in the water before any contamination occurs.
- Periphery of the urban areas – Provides data on the amount of non-point sources of pollution (agricultural and livestock loads) present, prior to water entering the urban area.
- Inside of the urban area – Provides data on the amount of point sources of pollution (urban loads).

These points were grouped in order of priority, to provide our partners with a suggested implementation timeline maximizing impact of monitoring effort, given limited resources (Table 7.1). The sampling sites were classified as high, medium, or low priority. Whenever possible the sampling points were located in close proximity to roads in order to facilitate the ease of sample collection.

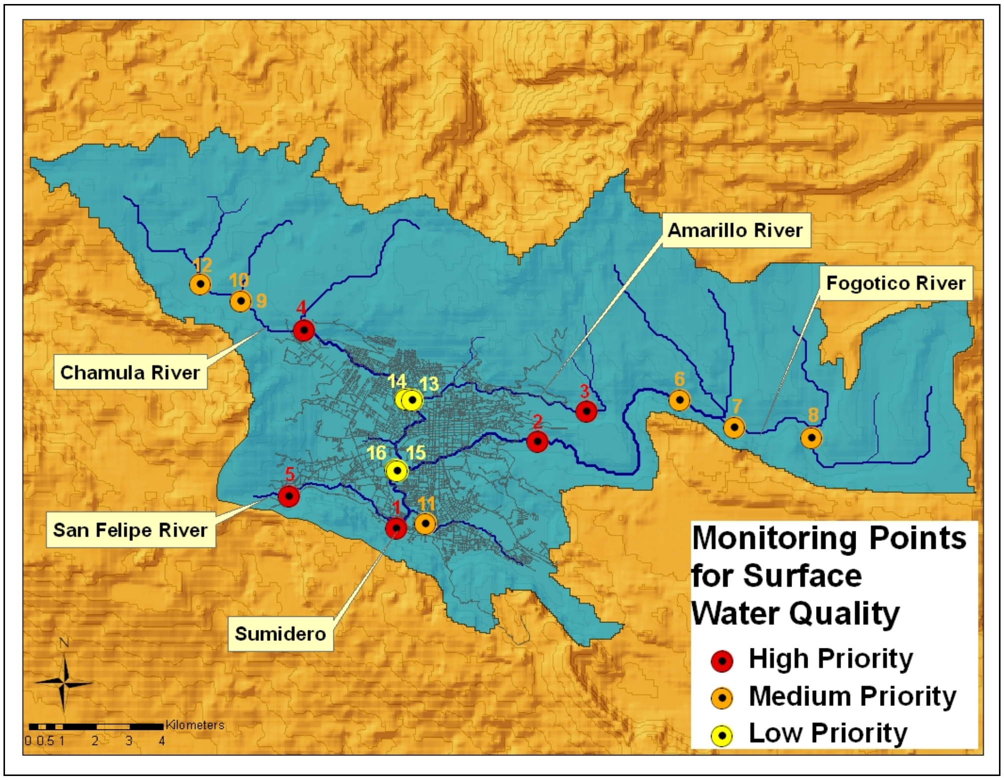


Figure 7.1. Suggested monitoring point in the San Cristóbal watershed with their respective priorities (Source data: ECOSUR, see Appendix 8.4).

Table 7.1. Proposed points, site code, river, and the criteria used to justify the water samples.

Sampling Point #	Location	Priority	Criteria
1	Sumidero	High	Total nutrient flux and flow from the watershed
2	Fogótico - Above city	High	Flow and load prior to urban inflow
3	Amarillo - Above city	High	Flow and load prior to urban inflow
4	Chamula - Above city	High	Flow and load prior to urban inflow
5	San Felipe - Above City	High	Flow and load prior to urban inflow
6	Fogótico	Medium	Load after probable non-point source based on MCA
7	Fogótico	Medium	Load before probable non-point source based on MCA (does not need to be monitored if point 6 meets standards)
8	Fogótico	Medium	Load before point 7 based on MCA (does not need to be monitored if point 7 meets standards)
9	Chamula	Medium	Load after the probable non-point source based in MCA (on the Chamula before the confluence with tributary from the town of Chamula) (does not need to be monitored if point 4 or 14 meet the standards)
10	Chamula tributary	Medium	On the tributary that runs from the town of Chamula, right before confluence with the Chamula based on MCA (does not need to be monitored if point 4 or 14 are clean)
11	Cinco de Marzo stream	Medium	On the tributary that runs through Cinco de Marzo, water quality prior to Sumidero and wetlands
12	Chamula – Up stream	Medium	Necessary only if point 10 does not meet standards
13	Amarillo – Inside city limits	Low	Flow and load of urban load (before confluence with the Chamula)
14	Chamula – Inside city limits	Low	Flow and load of urban load (before confluence with Amarillo)
15	Fogótico – Inside city limits	Low	Flow and load of urban load (before confluence with Amarillo)
16	Amarillo – Inside city limits	Low	Flow and load of urban load (before confluence with Fogótico)

The drinking water quality monitoring program is independent of the surface water quality monitoring plan, and its implementation should not be dependent on that of the surface water plan. The drinking water quality plan is a preliminary effort to assess the quality of the water currently used to the meet San Cristóbal's drinking water needs. The plan calls for monthly assessment of water at the each of the municipally run pumping stations. Ideally, sampling would occur monthly at each pump; however, if resources are limited, the monitoring focus should be on the pumping stations withdrawing the largest quantities of water or on those serving the greatest number of people.

7.2 Recommended Best Management Practices

Our partners in San Cristóbal have indicated that a large wastewater treatment plant will eventually be built to treat urban wastewater. This plant will require significant financial investment and outside funding. These BMPs are meant to offer low cost alternatives to address water contamination before wastewater enters the surface waters, reduce pollutant loads requiring treatment, and augment regional water supply (Table 7.2).

Table 7.2. Recommended set of BMPs and the problem it addresses in the watershed.

Recommended BMP	Problem Addressed
Rainwater capture and collection system	Water supply
Composting latrines	Human waste disposal
Retention basins	Stormwater runoff, nitrogen and phosphorous loading
Contour water retention trenches	Sedimentation, nitrogen and phosphorous loading, erosion control, groundwater recharge, stormwater runoff
Buffer zones and bioswales	Stormwater runoff, pollutant filtering, groundwater recharge
Education campaign	Poor sanitation, wastewater, human waste contamination

We recommend that pilot projects for these BMPs be implemented in order to establish their local cost, feasibility, and effectiveness. The BMPs are described in more detail in Section 6.2, though additional site-specific research would be required before undertaking development. In addition, to being low cost options, the recommended BMPs have additional benefits that warrant their adoption as pilot projects (see Section 7.2.3 for a discussion of each recommended BMP).

7.2.1 Assumptions Used in Best Management Practices Selection

In order to provide the recommendations outlined above we had to make a number of assumptions. The critical assumptions that guided the selection process are outlined below. The water-related concerns in San Cristóbal can be broken into two broad categories: water supply to consumers and surface water quality.

<u>Water Supply Assumptions</u>

For water quality, it is critical to note the extent of the SAPAM water supply network. SAPAM is currently developing an extensive database of water users and contracts. SAPAM's delivery network is primarily responsible for supplying water to urban users. The number of contracts continues to increase every year despite supply-related problems. Moreover, this network suffers from significant leakages, thus further reducing the amount of water available. Our project assumed that SAPAM is undertaking all feasible infrastructure improvements and we therefore did not consider these in our analysis.

Water users separate from the SAPAM network obtain water from surface flow, shallow wells, and/or local springs. The quality of this water is not monitored and, thus, we cannot state whether or not the quality meets the official Mexican standards. Because there are water users not supplied by the SAPAM network, these users may require a separate set of solutions. Additionally, we assumed that the drilling of new wells to extend the coverage of the current system is not feasible. This assumption was reinforced during our last trip to San Cristóbal in March 2006. SAPAM officials conveyed their reluctance to drill more wells due to high costs, uncertainty regarding aquifer structure and interconnectedness, and the recent encounter of high sulfur content in the water from a newly drilled well.

Perhaps most importantly, cost is assumed to be the limiting factor in the potential implementation of any project. Thus, low cost solutions are given a high preference in the BMP recommendations.

Stream Water Quality Assumptions

Urban surface water contamination is addressed separately from the outlying communities. The primary water quality impairment in the urban area is the influx of untreated wastewater from the urban area. The size of this load is orders of magnitude greater than that of the potential non-urban sources, and thus treating up-stream influent would have relatively little impact on the quality of water within the urban area. Additionally, stormwater mixes with this municipal wastewater in the current conveyance system, increasing the volume of contaminated water requiring treatment. The urban load can only be treated by a large-scale wastewater treatment plant; this is considered separately from the BMP selection process.

Target reductions are difficult to quantify due to insufficient data to establish baseline levels. To be conservative, high contamination levels, as well as potential sources, have been assumed. Given this uncertainty, ideal solutions would address a number of potential sources and types of contaminants. The two most likely sources of pollutants are from municipal and residential development within the urban and semi-urban areas and non-point runoff from agriculture outside of the city.

Community development outside of the primary urban area is assumed to be at a low density. Given this assumption, waste can be treated on a household or community basis in these areas.

Finally, costs were assumed to be the limiting factor in BMP selection. Low cost solutions are given a higher preference in the BMP recommendations.

7.2.2 Methodology for Evaluating Best Management Practices

In addition to the recommended set of BMPs, we suggest the following methodology for evaluating BMPs based on specific criteria that will help our partners in selecting appropriate strategies for the San Cristóbal watershed.

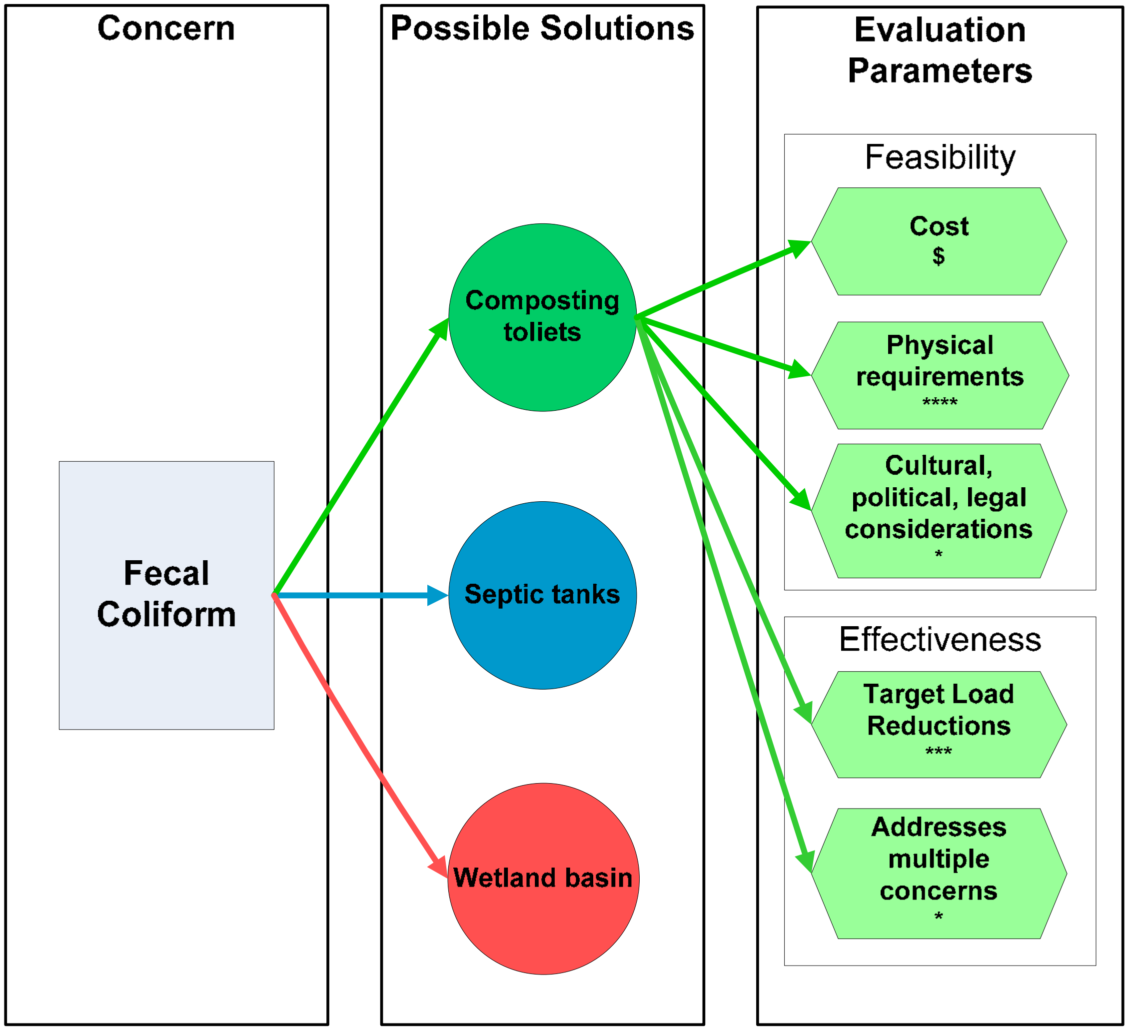


Figure 7.2. This flow diagram illustrates the suggested methodology for evaluating BMPs using the example of the presence of fecal coliform as the problem to be addressed by a BMP.

The methodology allows for inter-BMP comparison by deriving a composite score for each BMP. In order to derive this composite score, critical concerns are broken down into two primary categories: feasibility and effectiveness.

Feasibility includes all attributes of a BMP that relate to its implementation at a specific location, including cost, physical requirements and other cultural, political, and legal considerations. Every BMP receives an individual score for each of the three feasibility attributes, which are then turned into a composite score for overall feasibility. The three feasibility attributes are described below.

1. Cost: It is assumed that all projects seek to minimize costs, thus higher const BMPs would receive lower scores, while lower cost BMPs would receive higher scores.
2. Physical Requirements: Many BMPs are land intensive and require large swaths of land to be effective. Projects that require larger amounts of space would receive lower physical requirement scores, while projects which have a smaller foot print, would receive higher scores.
3. Other: This category encompasses all cultural, political, or legal issues surrounding potential project implementation. Projects would receive a lower score if specific local customs could potentially affect BMP effectiveness. A project might receive a higher score if similar projects had been successful in nearby communities or if local customs might contribute to BMP adoption.

Effectiveness includes all attributes that measure the benefit of implementing a strategy. This rating is composed of the BMP's effectiveness at addressing the problem, as well as potential additional benefits of implementation. Again individual scores would be derived for each BMP and then aggregated into a composite score.

1. Target Load reduction: The target load reduction score measures the BMP's effectiveness at addressing the primary or driving concern behind project implementation. It is expected that this score would be weighted higher than the secondary benefit attribute.
2. Secondary benefits: Secondary benefits include all benefits of the project unrelated to the primary project objective. For example, rainwater harvesting might have a primary benefit of providing additional water supply, but it will also have a secondary, unintended benefit of providing some flood mitigation.

How the composite score for each objective is derived is a decision we have left up to our partners. We do not propose a specific aggregation methodology within each objective or a way to combine the two objectives into a final score. By proposing such a weighting system we would have made the evaluation scheme more brittle and less adaptable to the individual needs of each project. Explicit in the methodology is that each BMP's score is dynamic and project specific – recognizing that a single static score for a BMP would not allow for project specific criteria to be taken into account.

7.2.3 Discussion of Recommended Best Management Practices

Educational Campaigns

There appears to be a substantial opportunity to improve both the quality of life of residents and the environmental quality of the region through the implementation of a watershed-based education campaign. Through our experience in San Cristóbal and from speaking with our partners, it is clear that the community as a whole does not understand how their individual actions are linked to water quality in the region.

Education campaigns should be initiated to improve community awareness of several different areas relating to watershed processes, including how sanitation and trash disposal affect water quality. A few recommendations follow, although more research is needed to determine which methods would best suit the population of San Cristóbal:

- Ask stakeholders what education they feel they could most benefit from in terms of water and sanitation (Center for Affordable Water and Sanitation Technology 2006).

- Target children for education efforts by establishing water-related education in schools (WHO and UNICEF 2005).
- Target health care professionals for sanitation education (Flores, *et al.* 2003).
- Include education with technology: when installing composting toilets, make sure that information about their maintenance is disseminated to the people who need it.

Our partners at SYJAC and ECOSUR understand the importance of education, and have indicated strong support for the development of targeted educational campaigns.

Water Supply
Rainwater harvesting systems will help to meet both immediate and long term water supply needs. The rainfall record for the watershed suggests ample average rainfall for the majority of the year, though most is lost due to rapid runoff. Rainwater collection systems may help to augment supplies to both urban and rural areas without SAPAM connections year-round. They can also act to alleviate demand for municipally supplied water.

Key Attributes of Rainwater Collection Systems:

- Ample rain falls in the region that is not currently utilized by the population.
- Rainwater quality is generally of higher quality than shallow groundwater or stream water.
- Water supply solutions are best if they supply water to the user at the point of use.
- Many houses in the region already have storage tanks.

Surface Water Quality
To address surface water quality, we suggest the implementation of composting latrines, retention basins, water retention trenches, buffers, and bioswales.

Composting latrines are recommended to decrease the contamination of surface and groundwater by human waste. Dry composting latrines are above ground, and if managed properly, produce a form of usable fertilizer for small-scale agriculture. While they are a viable solution, they do require significant education, maintenance, and monitoring.

Key Attributes of Composting Latrines:

- Address human waste not currently targeted for collection and treatment in the wastewater treatment plant.
- Easy to use.
- Low cost.
- Partners are already familiar with implementing the technology.

Retention basins can address multiple impairments in the watershed through stormwater management and pollutant load reduction, as well as contribute to shallow groundwater recharge. Basins may be constructed at multiple locations and be of various sizes depending on land use and desired water volume retention. Retention basin can be designed to regulate stream flow, allowing for timed water release.

Key Attributes of Retention Basins:

- Variable design structures, sizes, and functions.
- Readily available materials for construction in San Cristóbal.

Contour water retention trenches address many of the same concerns as retention basins, though on a widespread and dispersed scale. Contour trenches may used near the urban periphery and in rural areas where agricultural practices are dominant.

Key Attributes of Contour Trenches:

- Address multiple concerns including soil erosion, sedimentation in streams, nitrogen and phosphorus loading, and stormwater mitigation.
- Does not require a large amount of contiguous land for implementation.

Bioswales and vegetation buffer strips may provide mitigation for non-point runoff from both urban and rural areas. These BMPs could address the large pollutant loading that is thought to occur during storm events. It is thought that this flow is sufficient to move nutrients and fertilizers from fields into the surface water system. Both bioswales and vegetation buffer strips create areas which promote entrapment and settling of pollutants prior to reaching the stream.

Key Attributes of Bioswales and Vegetation Buffer Strips:

- Variable size allows for flexibility in implementation.
- Substrate content can be altered to allow for slow or rapid infiltration.
- Low cost (primary costs are thought to be opportunity cost of land).

7.3 Wastewater Treatment Options Recommendations

Based on the analysis of wastewater treatment options for San Cristóbal, as detailed in Section 6.3, we recommend the following actions by the municipality to address the issue of raw domestic sewage inputs in the urban region of the watershed.

Determine the Population Growth Rate

We recommend that the municipality consider the most recent census data and determine which population growth rate is most likely for the city. As they have a more detailed knowledge of the number of people moving to the city, they will need to decide which population growth rate is appropriate in order to allow for the accurate planning and designing of a wastewater treatment facility.

Dual Conveyance Systems

Given that large amounts of untreated sewage are being directly discharged into the rivers and streams in San Cristóbal, it is crucial that the municipality alter the current sewage conveyance system in order to reduce the health affects of pollution on communities within the watershed that depend on these waters. The conveyance pipes need to connect directly to a treatment facility rather than be discharged into a river to be treated by a downstream facility.

The municipality is currently designing a combined wastewater and stormwater conveyance system; however, our preliminary analysis suggests that the combined system might not be the most efficient strategy from a treatment perspective. It will be more cost-effective in the long-run to separately collect storm and sewage flows. This will greatly reduce the size of peak flows and eliminate the need for designing spillways for wastewater overflow which can lead to short periods of high contamination during large rain events. We therefore recommend that further consideration be given to implementing a sewer system that collects only wastewater. While the initial investment in this strategy is greater, the long-run savings in treatment costs may outweigh the costs of having to accommodate for large, stormwater flows. In order to make a final decision, these costs should be compared with the cost of setting up separate infrastructure for both storm and wastewater.

Determine Costs and Benefits of Location Options
We suggest that the facility be located inside of the watershed prior to the tunnel. This would eliminate the difficulties of siting a treatment facility on steeply sloping land or extending the conveyance system to the nearest flat land area at the exit of the tunnel. In order to accurately determine the costs and benefits of either location, a comparison of the local costs of sewage infrastructure, land, and labor needs to be conducted.

Further Consider Treatment Options
As far as specific treatment technologies, we recommend that more detailed design considerations be used to further explore the following treatment options (see Table 6.16 for a comparison of all the treatment options considered in this analysis):

- Advanced integrated treatment lagoons – While an advanced integrated lagoon requires more land (47 – 77 hectares) than an anaerobic lagoon (2.7 – 4.3 hectares), there is a \ greater degree of pollutant load reduction with the advanced system. Additionally, installing a pre-treatment or preliminary system is not necessary, as this technology includes that step of the treatment process.
- Multi-pass intermittent filtration system – This system requires a relatively small land area (36 – 75 hectares) and can be very effective in reducing pollutant loads. Construction costs are likely to be similar to an advanced lagoon system as are the operation and maintenance requirements. This facility would, however, require pretreatment of the wastewater. This could be done with an anaerobic lagoon, requiring only an additional 3-5 hectares of land. Therefore, it could still remain smaller in size than the advanced lagoon system. This technology also has very high pollutant load removal rates.
- Modular wastewater treatment plants – Given the potential for rapid population growth and the resulting potential for large hydraulic flows, a modular wastewater treatment facility would be very efficient, especially if land area is an issue. The value of preserving land space for future growth could potentially make the greater costs of this advanced system worthwhile to the municipality. Additionally, this would allow for a more specified design to meet effluent goals and standards.

Collect Additional Data
Finally, we suggest that the following data be collected to allow for a detailed analysis of the above treatment options:

- Cost of land, labor, and construction. Looking specifically to the costs of implementation for similar treatment technologies in other regions of Mexico.
- Data on actual constituent concentrations in the municipal effluent.

- Advanced design considerations necessary to treat wastes such that the facility effluents meet national effluent standards.

7.4 Watershed Modeling

Models can be a valuable tool in the watershed planning process because they can offer insight into what might happen if conditions in the watershed change. The present version of the model is intended to be a tool for future use by our partners. We have incorporated the available information about the watershed, but we recognize that the model has significant shortcomings. The current output of the model, and thus its ability to evaluate management scenarios, is limited by a lack of physical information available. Other recommendations, such as the water quality monitoring program, specifically address this lack of physical information. By continuing to augment the model with the data collected, the model's predictive capability will become more robust, and thus its value to stakeholders will increase. To this aim we are passing the model along to our partners and intend to provide them with the training and support necessary to continue the model's development.

The monitoring plan was designed to collect the required data for the model and augment the model's predictive ability. However, the most important measurement that can be taken at this time to augment the model is simple flow measurements. A single flow monitoring station at the output of the watershed would offer dramatic improvements in model flow calibration efforts.

Additional measurements not recommended within the monitoring plan could also play an essential role in augmenting the model. Of primary importance is further definition of the extent and location of the series of aquifers that underlie the region. Sensitivity analysis suggested that the single largest variable affecting total flow in the region was the size and storage capacity of the aquifers. Further definition of the aquifers is also necessary to address the questions surrounding the sustainability of the current groundwater pumping and aquifer recharge.

8.0 Appendices

8.1 Watershed Delineation

Basins 3.1 was used as the primary watershed delineation tool. Basins 3.1 is an application based on extensions of Arview 3.2 that was developed for the United States Environmental Protection Agency. Our partners at ECOSUR provided us with a 50 meter digital elevation model (DEM), with coverage for the entire state of Chiapas. This 50 meter DEM was used as the base data layer for watershed delineation. To reduce Basins processing time and improve accuracy, the DEM was clipped to a regional extent that included San Cristóbal and the surrounding municipalities. The clipped DEM was compared visually to a map with contour lines in order to ensure that all areas likely to be part of the watershed were included. The second pre-processing step performed prior to importing the DEM into Basins was the filling of potential holes in the DEM. These artifacts of data collection can cause water accumulation in incorrect locations and prevent proper flow routing in the delineation. The fill function provided in the Spatial Analyst extension of ArcGIS was used to identify and correct these cells.

After the pre-processing of the DEM was complete, the DEM was imported into Basins using the automatic delineation function. This function also allows users to specify a river network to burn in, and a region of focus. The river network provided by our partners at ECOSUR was burned into the DEM and the watershed of focus was specified by using the best estimate of watershed extent using contour lines. After burning in the river network and specifying the region of interest, the default values were used for definition of the stream network, and an outlet was selected at the known watershed outlet. The final watershed boundaries of two sub-basins were expanded using heads-up[24] digitizing to include regions which were obviously located within the watershed.

The physical nature of the San Cristóbal region contains two unique features which may have introduced error in the watershed delineation process. The first is the relatively flat central area of the basin, where the city of San Cristóbal is located. Elevation differences within this central region were less than approximately 10 meters between cells. Therefore, flow routing and accumulation using a 50 meter DEM was difficult. The low resolution of the DEM with respect to differences in elevation in the central part of the watershed, made routing water through this area particularly difficult.

The second unique feature of the San Cristóbal watershed is that the natural outlet for the watershed is through a natural tunnel through the mountains in the southwest portion of the watershed. Because any delineation that relies on a DEM for routing and accumulation of water is restricted by the surface characteristics of the landscape, the Basins delineation could not have accounted for this feature of the watershed. To accommodate for this shortcoming, a GPS point was taken at the current outlet (a man made tunnel approximately 25 meters from the natural location) of the watershed, and the stream network was extended to this point. All flow was then manually routed so that it would exit the watershed at this location.

[24] "Heads-up" digitizing refers to the technique were boundaries are digitized by hand using available features to guide new boundary extents.

Comparison of the Delineation to Prior ECOSUR Delineations
During the course of our project our partners at ECOSUR provided us with two different delineations of the San Cristóbal watershed which had been used previously by two different researchers. One delineation (herein after 'Espirtu Delineation') was based on 60 meter DEM data and physical maps of the region with 1:250,000 resolution (see Appendix 8.4). The second (herein after García García Delineation) was the result of using a combination of LANDSAT images and tracing the topography of the region (García García 2005). The three delineations shared many similar characteristics, including general shape, but significant differences existed at the margins of the delineations. The total extent of the watershed was estimated to be the largest in the García García delineation, approximately 27,473 hectares. The Espiritu delineation estimated the extent at 24,413 hectares, and our delineation (herein after Basins delineation) placed the watershed size at approximately 20,056 hectares. Here we discuss some of the differences between our Basins 3.1 watershed delineation and the Espirtiu delineation in greater detail[25].

The majority of the variation between the Basins watershed and the Espiritu watershed occurred in two specific regions (Figure 8.1):

1. Along the southeastern boundary, where the Espiritu watershed extends in a spur like shape in a southeasterly direction beyond the bounds of the Basins watershed. The spur is approximately seven kilometers long and two kilometers wide.
2. Along the northwest margin of the watershed, where the Basins delineation extends for approximately 3.5 kilometers in a primarily western direction beyond the bounds of the Espiritu delineation.

[25] The Garcia Garcia watershed was not available in digital in format and thus further comparison is omitted at this time.

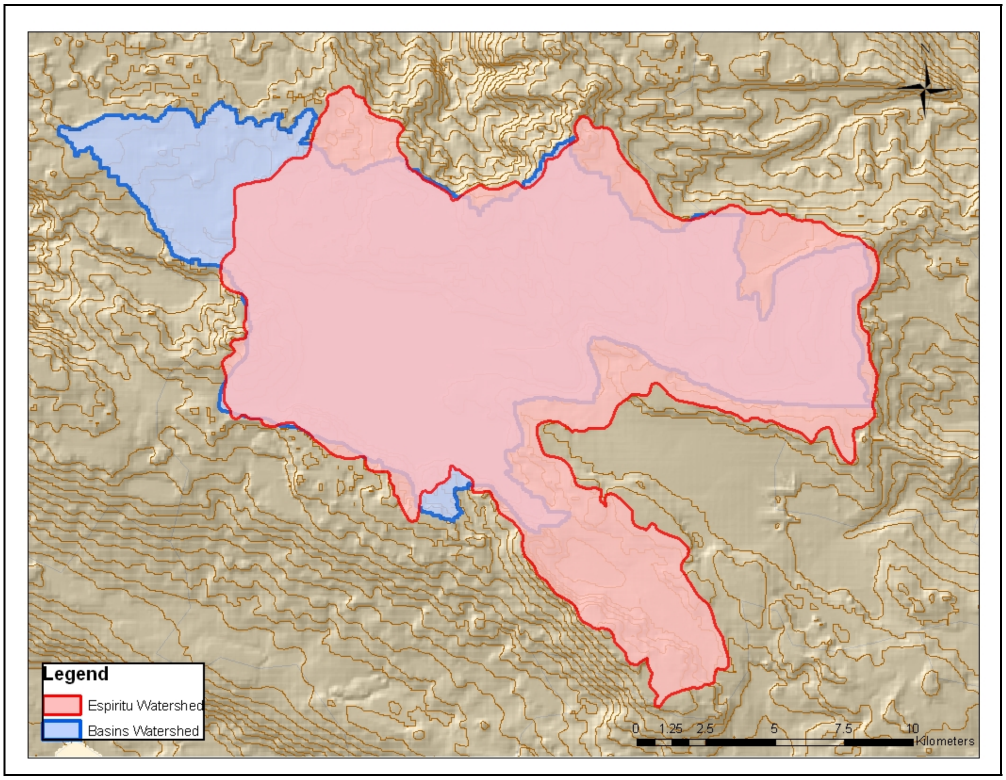


Figure 8.1. Comparison of the Basins delineation with the Espiritu delineation.

Southeastern Difference

In the southeastern portion of the watershed, the difference between the delineations appears to be based on whether or not a smaller basin to the south of the main San Cristóbal basin is a part of the watershed or is a separate drainage. The Basins watershed ends along what appears to one of the lower ridges of this basin. The ridge rises from the central San Cristóbal basin, at approximately 2,200 meters to an elevation of approximately 2,400 meters (where the Basins watershed approximates the edge of the watershed) before dropping down to approximately 2,300 meters in the smaller southeastern basins. The other bounding ridges of this basin are slightly higher, rising to approximately 2,400 meters to the south, approximately 2,500 meters to the west, and approximately 2,700 meters to the east. This area is contained primarily in the sub-basins that Espiritu labels, 'El Aguaje' and 'Rancho Nuevo.' There are no major rivers or tributaries that drain from this portion of the watershed, and the inner portion of the region, which is included in both delineations, is primarily wetlands.

Northwestern Difference

The sub-basins in the northeastern portion of the Espiritu delineation, ('Chamula', 'Petej') align very closely with the boundaries of sub-basins (5, 8) of the Basins delineation. Beyond the boundary that these sub-basins share, the Basins delineation extends to the northeast in a triangular shape, which includes 5 additional sub-basins with a total area of approximately 1,063 hectares. This region contains the headwaters of the Río Chamula.

Watershed Selection
For the purposes of this investigation, the Basins delineation was used as the primary unit of watershed investigation. The Basins delineation was selected primarily because it was delineated using the highest resolution digital elevation data of the three delineations. In addition, after comparing the Basins delineation to the Espiritu delineation, the Basins delineation appeared to most closely approximate how water might be expected to move across the land's surface. Based on visual observation of the 50 meter DEM, the Basins delineation appears to underestimate southeastern portion of the watershed, which the Espiritu delineation appears to more accurately portray. This region contains the origin of a small unnamed stream which runs through the 'Cinco de Marzo' neighborhood of San Cristóbal. The northeastern difference, which the Basins delineation appears to more accurately portray, contains the headwaters of the Chamula, and was thus deemed important to consider.

The Basins delineation also most closely approximated the size of the San Cristóbal watershed as referenced in a review of the area by SEDSOL (SEDSOL 2003). The Basins delineation was also selected because its stream network most closely mirrored known regional flow patterns. The Basins stream network was distilled from the stream network provided by Espiritu and ECOSUR in which vernal streams were removed, and all streams were funneled through the man made outlet of the watershed.

8.2 Questions for Informal Interviews and Table of Responses

Below is the list of questions that was used to get a sense of the socio-economic situation of the citizens living in the settlements on the periphery of San Cristóbal's city center. The responses we received are summarized in a table following the list of questions. The informal interviews were carried out with assistance of SYJAC who helped us create the list of questions to ask, took us to a variety of communities that would serve as examples of the living situations in San Cristóbal, and acted as mediators and sometimes as translators during the actual interview. The interviews were conducted in December 2005.

General

1. Where do you live?
2. How long have you lived there?
3. In addition to Spanish, do you speak another language?
   How many people live in the how? Where do they work?
4. How much do you make in one month?
5. Do your children attend school?
6. Does your family attend church?
7. Do you have animals?
8. Do you grow fruits or vegetables to eat or sell at the market?
   Do you use pesticides or fertilizers
9. What type of bathroom do you have in your house?
   Are there community bathrooms?
   Do they have a drain?
10. How much do you pay for electricity?
11. Are there trash removal services in your community?
    What do you do with your trash?

Health

12. Have you been sick recently?
    What types of illnesses?
    What do you think causes these illnesses?
13. What do you think is the main cause of diarrhea?
14. What do you think is the main cause of stomach aches?
15. Do you go to the doctor when you are sick?
    Where do you go?
16. Do you take medicine when you are sick?
    Do you take something else?
17. How much does a doctor's visit cost?
18. How much do the medicines cost?
19. Have you ever had to go to the hospital?
20. Are there days that you cannot go to work because you or your children are sick?
21. Do you have *Seguro* Popular (insurance)? Do you know what it is?

Access to water

22. Where do you get your drinking water from?
23. Do you have a tap in your house?
    Do you drink water from the tap?
    Do you receive potable water from the municipality?
    How much do you pay for the water?
    Do you know where the tap water originates from?
24. Do you have a water tank?
25. Do you have a well?
26. Are there days when water is not available from the tap?
    When was the last day that this happened?
27. Are there periods of time without water?
    When?
    How many times a year?

Water use

28. Do you use the same water to drink and for other domestic uses?
    For example, to wash clothes and bathe with. If you use another source of water for this, where does it come from?
29. Do you use water from the rivers?
    For what uses?
    Are there periods of time when you do not use this water?
    Why don't you use it?

Water quality

30. Are there periods of time when the water smells or looks bad?
31. Are there times when it tastes bad?
    Do you get your water from another source during these times?
32. Are there times during the year when you do not drink or use the water? Why?
33. What do you think about trash in the rivers?

34. Do you clean or treat the drinking water?
35. Do you drink bottled water?
    How many bottles do you use per week?

Other

36. What do you think about the wastewater that flows from the houses into the rivers?
37. Would you support a community project to improve the water conditions in your community? With time and/or money?
38. Would you pay to be connected to water pipes? How much would you pay?
39. Do you know what an ecological reserve is? Have you visited one?

Table 8.1. Interview responses.

	Location	Gender	Age	Years living in current location	Language in addition to Spanish	Number of people in the household	Job	Earnings (in Pesos)	Do the children attend school?	Does your family attend church?	Do you have animals?	Do you grow fruits or vegetables?
1	El Vergel	F		9		4	Artisan	1500/month	Yes	Baptist	Dog and cat	Peaches, apples
2	El Vergel	M		8	No	2	Works for the Catholic diocese	3000/month	Children are grown up	Catholic	Two dogs	Herbs to flavor food
3	El Vergel	F		1	Tzotzil	4	Merchants	300/week	Yes	Small church	Dogs	No
4	Nueva Maravilla	M	15	7	Tzeltal	5	Merchants		Yes	Christ Church	Pigs and dogs	Squash, peaches, and apples to eat
5	Cinco de Marzo	F		11	Tzotzil	5	She stays at home, the family sells cement blocks	400/month	Son does	No	Dog	No
6	Cinco de Marzo	F		10	Tzotzil	7	Carpenter/ block builder	300/week	Yes	Yes, different ones	Chickens	No
7	Cinco de Marzo	F	27	11	Tzotzil	7	bricklayer	600-700/week	Yes	No	Dogs	Vegetables
8	Cinco de Marzo	F	49	11	Tzeltal	7	Husband is day laborer, they have a store in the house	450/week	Yes- 2 don't because of develop-mental problems		No	No
9	Cinco de Marzo	F	35	11	Tzotzil / Tzeltal	9	Car service	Little bit	Yes	Catholic	No	No
10	Cinco de Marzo	F	27	10	Tzeltal	6		1200/month	Yes	Yes	Chickens	Peaches
11	Primero de Enero	M	35	8	Tzotzil	6	Merchants and café worker	3000/month	Yes	Yes, Catholic	Dog	No because the spaces are too small where they live

12	Primero de Enero	F		11		6	Husband is a bricklayer, she works at home	90/day	Yes	Yes, Catholic	Chickens, pigs, duck, horses, keeps them around the house	No
13	Primero de Enero	F		11		8	Works at home	80/day	Yes	Yes, Catholic	No	No, there is no space
14	Primero de Enero	F and M	27/29	10		4	Merchants	200-250/week	Yes	Yes, Catholic		
15	El Vergel	F	28	Not her home		9	Husband works		Yes	Yes	Two dogs	Yes
16	El Vergel	F	18	10	Tzotzil	9	Construc-tion	800/week	Yes	Yes, Presby-terian	Dogs	No
17	El Vergel	M/F	37/34	10	Tzotzil	6	Store in house	400/week	Yes	Yes, Presby-terian	No	No because no land
18	El Vergel	F	22	4	No		Store in town	4000/ 15 days	Yes	Yes, Catholic	Chickens and dogs	Corn for fun in the garden
19	El Vergel	F		5	No	4	Bricklayer	650/week	No	Yes	Chickens and dogs	No
20	Nueva Maravilla	F	43	5	Tzeltal	8	Bricklayer	400-450/week	Yes, but five kids washing clothes with her	Catholic	No	No

	Do you use pestici des?	**What type of toilet do you use?**	**Do you pay for electri-city?**	**Do you have trash collection services?**	**Have you been sick recently?**	**What type(s) of illness?**	**Do you or your children have diarrhea or stomach aches?**	**What do you think causes this?**	**Do you ever go to the doctor?**	**How much does it cost?**	**Do you take medicine?**
1	No	Normal with drain	50/ 2 months	Yes	Yes, often, but Not her children	Gastritis, diabetes		Food	All the time	60 pesos per visit, 70 if they take blood	Pills

2	No	Normal with drain	80/ 2 months	Twice a week	Mostly no	Flu, stomach ache		The food they eat is not natural, the water is contaminated and they use a lot of fertilizers	No because he doesn't have enough time, there is one doctor for all illnesses	200 pesos	Not really, he will take what he thinks he needs
3		Drain	Expensive	Twice a week	No	Allergies, stomach aches		Does not know	Yes, clinic	Free	Yes, depends; can pay 80 pesos for penicillin
4	No	Normal with drain	No	Yes, learning about it in school, have to throw it somewhere else once or twice a month	When it is cold	Diarrhea and stomach aches when it rains			Yes, private doctors	300 pesos	Sometimes
5	No	Provision-al latrine with a drain	No- Not officially connected	Twice a week	Yes	Headache, stomach ache		Does not know	Yes, health centers	20 or less	Pills
6		Latrine without drain	No	Twice a week	Yes	Backaches, feet, stomach, kids have the flu		Does not know	Yes, health centers	20	Pills
7		Latrine without drain	No	Twice a week	Yes	Cough, 1 kid is very sick, bad throat problem, sometimes problems with stomach ache		Does not know	No		Only small pills
8		Latrine without drain	No	Twice a week	No	One girl with stomach problems		Does not know	No, kids don't want to go		

9		Latrine without drain	No	No	Yes	Flu	Yes to both	Does not know	Yes	The doctor comes to the house and its free	
10		Latrine without drain	No	Twice a week	Yes	Cough	Yes to diarrhea	Bathrooms because there is no drain	Yes		Yes
11		Drain	Yes, 28/month	No service in the colony, have to take it to a deposit station	Yes	Flu, cough, depends on the season	Yes to diarrhea, stomach ache sometimes	The water, including the fact that water in the bottles doesn't always come clean	Yes	200 or 50	Pills
12		Drain	Rate is same for whole comm-unity		No not often	Flu	No	Because her kids eat in the street and sometimes they get sick	Yes, to a consultant		
13		Drain	Rate		Yes	Stomach ache, headache	Yes	Not washing hands causes infections	Yes	Normal consultation doesn't cost	
14		Drain	Rate		Yes	Headache and throat					
15		Drain	Yes but not sure how much		Yes	Cough and fevers	Yes	Does not know	Yes- traditional local treatment and medicine		Buy it in the market
16		Drain		Twice a week	Almost never		No		No		
17		Drain	40-50/month, depending on use	Twice a week	Almost never	Children often cough or have flu	Yes	Bad nutrition; does not know of other reasons	Only if the illness lasts more than 2 days		
18		Drain			No		No				
19		Drain			No	No	No				

20		Drain	60-70/month	Yes	High blood pressure for mom		Yes	Does not know	Yes	30 for the consulta-tion	Free

	How much does it cost?	**Have you or someone in your family had to go to the hospital?**	**Are there days when you cannot go to work because you or someone in your family is sick?**	**Do you have health insurance?**	**Where do you get your drinking water?**	**Do you have a tap in your house?**	**Do you drink tap water?**	**How much does the tap water cost?**	**Where does this water come from?**	**Do you have a tank and/or a well?**
1	Free		For months at a time	Seguro popular	Pipe, tank, tap	Water comes once a week, the children know that it comes from SAPAM	No, buy water to drink			Well
2		Once because he got in an accident	Sometimes when the kids were sick	From his job	From the city, buys jugs of water	Yes	No, buy water to drink	350/year	City's pipes	Cistern
3				No	Well	Yes, comes once a week	Yes, but mostly from the well	300/year	Doesn't know	No
4	500, when his dad was sick	No	No	He has it through school	8 jugs/week	Yes, to wash with	No		From a well	No
5		No		Seguro popular	Pipe, tap on the street	No	From street tap	Don't pay-provisional	Doesn't know	Well for bathing and wash-don't drink it
6		No		No	Pipe	No		No		No
7			Yes	No	Pipe	No				No
8		Yes, girl had stomach surgery	Sometimes	No	Pipe	No				No
9	Free	No	Yes, once a month		Small pipe	No				No
10		No	Once a month	Seguro popular	Pipe	No				No

11	50	No	4-5 times a year	No	Tap in house, from the municipality	Yes		42/month	Yes from the river, specifically from the Amarillo where it is not contaminated	Tank
12				Yes, so they don't have to pay much	Pipes and tap	Yes				
13	Diarrhea medicine costs 5 pesos		Yes, more in April, May, and June		Tap in house	Yes		42/month		
14						Yes	Yes			
15					Tap	Yes				Yes, tank
16					Tap	Yes	Yes	Doesn't know	Doesn't know	Tank and cistern
17		No	Yes, but almost never	Yes	From SAPAM, tap in house	Yes		Not being charged yet, but soon	SAPAM	Tank
18				Yes, her parents do	Large jugs	Yes				Well for washing house and store, tank also
19					Large jugs sometimes when the water doesn't come	Yes				Well , only used for washing
20		Mom had to stay there once for high blood pressure	Husband couldn't when she was sick	Seguro popular		No				Well, used for drinking when they can't afford large jugs

	How many jugs of water do you use per week?	Are there days when there is no water available from the tap?	Are there periods of time with no water available at all?	Do you use the same water to drink, bathe, and clean your house?	Do you use water from the rivers?	General thoughts on river quality
1			If it doesn't come in the tube they get it another way	Use water in house to wash	No, one time she had to have a neighbor wash her clothes and her children got rashes because they were washed in the river	
2	1	Once a week	Yes, when the pumps don't work	Uses water from the city to wash and bathe	No	Dirty
3			Yes, April, when it is not sent	Yes, to wash and bathe	No because she has the well	Dirty
4		No	No		No	Would be clean except for the things that people put into it
5	None	Yes, but can store it in tanks when there is water	No		Only before she had a well in her house	Very dirty
6		Yes, they buy bottled water if there is no water	There are weeks without water in January and February	Washes clothes in the river	Washes in the river, when river is dirty she uses well water to wash clothes	
7			There are weeks without water	Yes	Yes, to drink and wash (throughout the year)	Contaminated and dirty with all the trash
8			Two days	Wash clothes in river, use street tap for drinking and bathing	Washes clothes in river, but not when it rains	
9		Fill buckets to cover the times when the street tap doesn't work	Fill buckets to cover the times when the street tap doesn't work	Washes clothes in the river; tap water for bathing	Washes clothes, doesn't drink	Very dirty
10		Water comes every other day	River dries in April	Uses tap to drink and bathe, wash in the river	Washing only	Don't drink the water in the river because its dirty and people throw their dead dogs in the river
11		Every other day without water	February and March for weeks at a time	Yes, all from the tap	No because it is not necessary because they have a tap; daughter said that she knows people who do wash in the river	Bad quality- never uses because it is so dirty

12		Once a week	Sometimes there isn't water for a week or 15 days at most	The community wells used to be used for everything	No, only to wash if there is no other water	
13		5-7 days at most		Uses the wells to bathe and wash the clothes because it is cheaper	Never	
14	Sometimes they buy 1	1 day on, 1 day off		Use the tap to wash food and to bathe and wash clothes, use chlorine if they are going to drink it. But she doesn't trust the chlorine to kill the bugs in the water.	No because of the dead animals- before all the people moved here you could bathe there but now it is filthy	
15		Comes everyday, but some days there is only a little		Tap for everything	No because it is dirty	It's clean- there are times when it smells a little bit bad
16		Doesn't come about once a week	No	No- wash water comes from the tap but is kept in cistern and taken from there to wash	No because they are dirty and smell bad	No problems with the water
17		Once a week (if it doesn't come on Saturday, then next week it won't come on Sunday)	Sometimes they can't wash their clothes because there isn't enough water	Yes	Yes, once a week to wash, never to drink, sometimes it runs dry and they can't wash	Dirty, everyone washes and throws stuff in it
18	2-3 (cost ~40 pesos each)	3 is the most		No	No	Its contaminated, especially the Amarillo
19		Only have water 1 day a week, and its at night		No	No because it's far, bad and things drain into it.	Not very good because of the drainage into there
20			Well doesn't always work, February-May there isn't water, when it does rain they can wash clothes in the house		Yes they wash their clothes in it, but never for drinking	There's tons of trash in the rivers

	Are there times during the year when you do not use water from the rivers?	Does it ever look, smell, or taste bad?	What do you do during these times?	What do you think of trash in the rivers?	Do you clean or treat the water that you use?	Do you use bottled water?
1		Sometimes smells of chlorine and they won't drink it		Contaminates the water, lots of animals are near the water	No, because it is clean when it arrives	
2		Yes, when there is not a lot of water in the springs	Buy more bottled water	People should throw their trash in the street because it contaminates the water	Little bit of chlorine	1 jug a week
3		No		Bad	Little bit of chlorine	1 jug a week
4		No because they get the water from the well			No, they keep it in a well for awhile to let it filter before they use it	
5					They let the water sit to treat it	No, no money
6	Rivers are bad when it rains		Use wells when it rains and when it doesn't rain she uses the rivers	Makes her sad that there is trash in the stream		
7	No	It comes dirty			Sometimes	No
8	When it rains		Treat water	Doesn't think its dirty, because it is clean where she washes her clothes		
9	Don't wash in the river when it smells bad			Bothers her		No
10		Sometimes it looks bad because there is dirt and little rocks in it, it is bad in April, and when it is hot it smells bad				Buy purified water, 1 every 3 days
11		Yes - February, May, and June	Buy large jugs, but still use pipe to wash and bathe	Its bad		Yes, 2/week when they use it
12		It is dirty when it rains			Yes, chlorine	No because it is really expensive, and only if there was no water would they buy one
13					Yes, chlorine	

14				They offered to pay for it, but not enough people in the community agreed, so the service didn't get started. Sometimes people just have to dump it to get rid of it.	Yes, chlorine	Large jugs if they need it but not bottles
15		Sometimes			Yes, boil	No
16		No		Its bad	Yes, chlorine for all drinking water all the time	No
17					Yes with chlorine, but they had to get used to the way it smells	No
18		Yes, in April and May			Add chlorine to the large jugs	Large jugs
19	No					
20					Yes	

	Do you know where the wastewater from your house goes?	Would you support a community project to improve the water conditions in your community?	Would you pay for piped water?	Do you know what an ecological reserve is?	Other
1	Doesn't know anything about it	Would work with community			
2	Bad because it contaminates, flows to the sea and hurts the fish; it flows through the tunnel to where they grow fruits and vegetables; he sometimes asks where his food comes from; the water should be clean for the people who are growing food	Yes this would be good, support with his time not his money		Has visited 3 different ones a few times	In the future the city won't have any water, if you have a well you might have water; Coke has a deep well that is taking water from the city and selling it back - this is due to the political relationship between Coke and the national government (not state or local government); government needs to protect the people, they have the right to enjoy the rivers and the mountains, nature should not be a business
3	Bad	Yes with time and money		Kind of knows about them	
4	It all flows to the river	He doesn't think that his family would, but he does, definitely with his time, but		Knows what it is, but hasn't	He tries to tell his neighbors how to care for the water but they don't seem to care; knows a lot about the water cycle

		only maybe with money		visited	
5		Would pay to be connected, and she thinks the whole community would support getting water in pipes to their houses		Doesn't know what they are	
6		Yes with time and money (called it a cooperation project)	Yes but was skeptical about possibilities	Her daughter knew about them	Quality is more important than quantity, doesn't like having flood water in her house
7		Yes, with time, not money, but maybe help to buy materials if it was to get water in the house, and they'd like to have drainage			
8		Yes, for a cooperation project			Like a drain; problems because the tap only come on at night and so she can't get the water; the drainage is more important than a pipe to the house
9	If it was actually draining into the river then she couldn't use the river to wash the clothes	Yes, with money and time			She would like a drain and to have piped water in the house
10		Yes with time and money		Yes, but only kind of	Quality is more important than access but they'd also like to have water in the house
11	Bad	Of course, with time if they have time, but no money			Quality is the most important for everyone, state government got them piped water and drainage in 2004 (~2 years ago), before this they had latrines only. They have been in this colony for 11 years. When it rains the situation gets worse. Before the piped water, people drank well water, many got sick and died, and many children would fall in the wells. In 2000, they got ownership of their property.
12		Kind of, more or less			They need more pipes to houses because the river is so dirty and the wastewater flows to the rivers.
13		Yes			The quality of the water in the tubes is the most important to her
14		Yes, but she is busy so it depends on timing. Yes to money because the drainage is so bad.			The drainage is really terrible, when it rains it all gets backed up. The drains and street floods. You can see the wastewater come up into the street. Playa del Carmen is the worst. Her kids get sick from the smell of drainage. They have called SAPAM to come fix the problem, but they won't do it, and even if they did, SAPAM

					doesn't know where exactly the drains are to fix them. Before the drainage the problems was worse though because the latrines wouldn't get rid of the waste. The river becomes dirty with little rocks (sediment). Some people do everything in the river and this is bad because it is so dirty. While we were interviewing her daughter got bit by a rat that came out of the drain- she didn't seem compelled to go to the doctor even though Hilda said rats have rabies.
15		No			
16	Doesn't know anything about it	Yes with time, not money		Doesn't know	
17	Yes they know it flows to other rivers, but people need to use water	Yes, because they want more water. With time but not money			
18		Yes, time depends on hours, maybe with money but more likely with her time		Knows what they are, but hasn't visited	
19		Yes, her husband could help with time, and if it was cooperative they might give money			
20	She doesn't think drains into the rivers, but people with latrines have their wastewater flow into the river	Wouldn't support a project	Yes		Thinks that the kids might get sick from the river water because its so dirty.

8.3 Methods for Cost of Illness Analysis

The methods for analyzing the costs of illness and the benefits of improved water supply and sanitation are based on Hutton and Haller's (2004) analysis for the World Health Organization. In this study, the authors made general statements about costs and benefits of providing water and sanitation services in broad geographic ranges. Using the general numbers from epidemiological sub-region AMR B (which consists of 26 countries in Latin America and the Caribbean, including Mexico), we calculated the expected costs and savings per capita for a person in this region who is not currently receiving improved water and sanitation. We then applied these numbers to the affected population of San Cristóbal de Las Casas.

For this analysis, we estimated that today there are approximately 40,000 people who are not served by SAPAM, based on their estimation that 123,000 people are recipients of their services (SAPAM 2002). In addition, Velázquez-Velázquez and Schmitter-Soto (2004) states that 24% of homes, or approximately 40,800 people, do not have connections to the sewerage system. While we do not have more specific data for the costs and benefits of improved water and sanitation for San Cristóbal, we expect that the Hutton and Haller regional estimates will be reasonably accurate for estimating these values, given the similarity of the proportion of the total population without improved services in the entire AMR B region as compared to San Cristóbal (Hutton and Haller's analysis predicts that 40,659 would not have these services).

We calculated the costs and benefits of providing improved water and sanitation to the population that does not currently have these services (Table 8.2).

Table 8.2. Definitions of improved and unimproved water supply and sanitation.

Intervention	Improved	Unimproved
Water supply	• House connection • Standpost/pipe • Borehole • Protected spring or well • Collected rain water • Water disinfected at the point-of-use	• Unprotected well • Unprotected spring • Vendor-provided water • Bottled water • Water provided by tanker truck
Sanitation	• Sewer connection • Septic tank • Pour-flush • Simple pit latrine • Ventilated improved pit-latrine	• Service or bucket latrines • Public latrines • Latrines with an open pit

Analysis of Interventions

Interventions: by the year 2015-

1: Halving the proportion of people without access to improved water sources

2: Halving the proportion of people without access to improved water sources and sanitation

3: Everyone has access to improved water and improved sanitation services

4: Intervention 3+ everyone has a minimum of water disinfected at the point of use

5: Everyone has access to a regulated piped water supply & sewage connection in their houses.

Table 8.3. Costs and benefits of improved water and sanitation under different scenarios.

Costs and Benefits	Intervention				
	1	**2**	**3**	**4**	**5**
Number of people receiving treatments in San Cristóbal	**12,806**	**32,015**	**40,659**	**170,000**	**170,000**
Annual number of diarrhea cases averted	3,400	10,200	17,000	88,400	119,000
Annual cost of interventions	**$51,000**	**$204,000**	**$408,000**	**$510,000**	**$3,774,000**
Annual cost per person receiving interventions	$3.40	$6.30	$10.00	$3.00	$22.20
Annual health sector treatment costs saved	$68,000	$205,700	$326,400	$1,657,500	$2,237,200
Annual patient treatment costs saved	$1,700	$5,100	$8,500	$45,900	$61,200
Productive days gained due to less diarrhea illness	14,407	43,540	69,153	351,525	474,463
Value of productive days gained due to less diarrhea illness	$7,043	$21,130	$32,976	$171,601	$232,109
School days gained due to less diarrhea illness	2,546	7,707	12,232	62,059	83,757
Baby days gained due to less diarrhea illness	7,043	21,770	34,256	174,162	234,991
Annual time gain (hours saved) due to more convenient water supply and sanitation facilities	540,414	2,857,024	8,154,237	8,154,237	18,359,040
Annual value of time savings	$357,608	$1,889,529	$5,077,269	$5,077,269	$11,841,412
Value of averted deaths (predicted future earnings)	$7,043	$21,450	$33,616	$175,763	$237,872
Total economic benefits of interventions	**$582,811**	**$2,575,019**	**$6,157,849**	**$10,602,547**	**$19,314,566**
Benefit-cost ratio (total benefits/total costs)	**11.43**	**12.62**	**15.09**	**20.79**	**5.12**
Benefits-Costs (TSC)	**$531,811**	**$2,371,019**	**$5,749,849**	**$10,092,547**	**$15,540,566**

8.4 Geographic Data Sources

The majority of the GIS layers utilized in our analysis were provided to us by our partners at the LAIGE (Laboratorio de Análisis de Información Geográfica y Estadística) laboratory at ECOSUR. All layers and the source of the layer are noted below:

Datum	Source
Chiapas state DEM	ECOSUR
City Neighboorhoods	ECOSUR
Geologic Units	ECOSUR
Rivers	ECOSUR
San Cristobal Roads	ECOSUR
Soil Types	ECOSUR
Wetland Areas	ECOSUR
Rainfall Data	ECOSUR - CLICOM
Watershed Delineation	Espiritu 1998
Mexico Municipal Areas	ESRI 2004
World Base Map	ESRI 2004
Well Locations	SAPAM
Land Use	Zermoglio 2005

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