INTEGRATED WATER MANAGEMENT PRACTICES IN MEXICO AND THEIR IMPACT ON LOCAL DRINKING WATER QUALITY: EFFICIENT ASSESSMENT METHODS

A Thesis

By

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2016

Major Subject: Water Management and Hydrological Science

ABSTRACT

While supplying safe drinking water is a critical issue in the development of nations worldwide it has not been formalized as a requirement by the United Nations (UN). As a result, efforts to bring modern water distribution to the citizens of developing countries have resulted in greater access to unsanitized water. As has been observed in Mexico, governmental centralization can leave municipal governments weak; lacking the essential resources and skills to manage water distribution systems. This study sought to examine the water distribution system San José de Gracia, Michoacán in Central Mexico using readily available water quality testing kits. A further objective of the study was to use EPANET models of the water distribution system to examine how chlorination and pumping regimes affect water quality in this town. Sampling sites and indicators were chosen using Rapid Drinking Water Quality methods promoted by the World Health Organization (WHO). Despite being classified as having “improved” potable water by the WHO, the water distributed in the town was not found to be safe for human consumption. Costly inefficiencies in the distribution system were found to be built in that make the chlorination system in use obsolete.

DEDICATION

To my sources of energy Maria de los Angeles Gonzalez Partida, Bruno, Marley, Edgar, Ethan, and Jimena. To my wife and our future together. Towards responsible resource development in the Anthropocene.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Jacqueline Aitkenhead-Peterson, and my committee members, Dr. Senseman and Dr. Kaiser, for their patience and guidance throughout the course of this research. The Municipality of Marcos Castellanos for their help collecting data and information on local water resources. The L.T. Jordan Institute, which provided me with enthusiasm and funding to complete my research trip abroad. Thanks also go to my friends and colleagues and the College of Geosciences for making my time at Texas A&M University a memorable and valuable experience. Also, thanks to Geneva Redmond for lending me her skills as an editor and reminding me that I can do anything I set my mind to. Finally, thanks to Spencer “Spok” Pokorski and Alan Lewis for their encouragement and support throughout.

NOMENCLATURE

IMF	International Monetary fund
IBRD	International Bank of Reconstruction and Development
UN	United Nations
MDG	Millennium Development Goal
GDP	Gross Domestic Product
GIS	Geographic Information Systems
IWRM	Integrated Water Resource Management
WHO	World Health Organization
DWQG	Drinking Water Quality Guidelines
pcpy	per capita per year
TAMU	Texas A&M University
RADWQ	Rapid Assessment of Drinking-water Quality
CONAGUA	Comisión Nacional del Agua
RBC	River Basin Councils
EC	electric conductivity
INEGI	Instituto Nacional de Estadística y Geografía
TMVB	Trans-Mexican Volcanic Belt
LDC	Least Developed Country

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1. INTRODUCTION

Water is an essential part of a country's wellbeing and stability as it touches all three essential components of sustainability: the economy, government, and environment. Historically, international development has been mostly synonymous with economic development. However, over the past several decades the term has regarded in a more holistic and multidisciplinary sense, encompassing human development and sustainability in addition to economic productivity (Todaro, 2011). Water quality can be used to assess whether national policies are being followed and how effectively management structures are adapting to regional and local conditions. The growth and development of a community, thus, can be measured in terms of water quality.

Mexico has identified water infrastructure to be a crucial component of its national development goals. Unfortunately, water management in Mexico has suffered from a long history of centralization and shortsighted planning (Sánchez et al., 2012; Scott et al., 2008; Tortajada et al., 2005). The absence of comprehensive planning for both water and land resources has created an inefficient water management system that widely lacks clear goals and objectives. Deficiencies in the Mexican federal government have adversely impacted the welfare of the Mexican people and complicate its relationship with other nations (McDonald et al., 2003; Wilder et al. 2006).

1.1 History of International Development Strategies

Water has been the subject of international development efforts since the first years of the United Nations because of its integral role in life and the economy. The United Nations

(UN) was chartered at the end of World War II with the principal aims of maintaining peace by establishing friendly relations between nations, promoting universal human rights, and improving the lives of the poor (Amrith et al., 2008). Values such as social equity and environmental justice have been slowly integrated into the UN's mission, including those that target long-term planning and management of water resources (Gleick, 1998). Assessing how well agreements are implemented in developing countries has recently become a focus in academic research and international development. To tackle poverty issues, including those related to water, the UN has asked for cooperation from its member nations in accomplishing development goals. The UN comprises six organizations that tackle these challenges by building human capital, enhancing the transfer of technology, and financing development. The UN first gave Technical Assistance to the Republic of Haiti in 1948 to assess the reasons for the nation's lack of economic growth (Amrith et al., 2008). This was the first attempt to define and identify development and the problems which needed to be addressed in future attempts to assist a nation.

In order to finance development and the reconstruction of countries after World War II, an agreement between 44 nations in 1944 formed the Economic and Social Council, one of the six organizations of the UN, to enhance development efforts through economic assistance by mobilizing capital. The International Monetary Fund (IMF) and the International Bank of Reconstruction and Development (IBRD, or World Bank) were created to finance, assist and regulate member nations of the larger UN assembly (Zanetta, 2004). The ideals of the neo-classical model that was being applied at the time were centered on supply-side economics. The neo-classical model was predicated on the theory that development could be generated by simply supplying infrastructure related to economic growth. The growth would in turn trickle down throughout society and stabilize national governments (Williamson, 2009).

In the late 1940s, the World Bank (WB) focused on increasing necessary infrastructure to promote economic growth through what were then thought to be the drivers of growth: energy, transportation and agriculture. Projects aimed at the modernization of agriculture, which first began making development loans in Latin America between 1948-1959, were the third largest funding target by the World Bank (Zanetta, 2004). From these loans, dams, power plants and transportation networks were built to drive output from markets and satisfy the economic ideals of Import Substitution Industrialization (ISI) (Weintraub, 2009). ISI increased GDP as governments borrowed money to develop infrastructure. However, this did not impact the inequality of income distribution because no investments were made into human capital (Weintraub, 2009).

Water management in the twentieth century was centered on resource exploitation to further economic and population growth. This led to large water development projects to increase the supply for uses deemed beneficial around the world (Hughes et al., 2013). However, little concern was given for environmental impacts, sustainability, equity or the role of community (Gleick, 1998). Although, the modernization of countries to meet development standards has long been incorporated into the process of globalization, social and ecological impacts were not seriously considered at the international level until the 1970s (Rahaman et al., 2005). Member nations of international institutions are subjected to non-binding agreements that define problems, outline solutions and promote international cooperation. The first major declaration of a need to act on the environment came from the 1972 Stockholm Conference on the Human Environment. International consensuses such as these provided catalysts for governments of developing nations to pursue Integrated Water Resource Management (IWRM).

Throughout the 1960s and 1970s, nations in Latin America took on greater debt in order to fund social programs targeting urban and, to a lesser extent, rural areas (Todaro, 2011). Since urban population growth was at the center of international development at the time, these social programs created further gaps in quality of life between urban and rural populations, especially in terms of access to water infrastructure and human capital in the form of education (Levy, 2010). The inefficiency of economic development programs led Latin America into a debt crisis during the 1980s, which worsened because of a national currency crash fueled by loans that were largely in foreign currency (Williamson, 2009).

The debt crisis of the 1980s changed the directive of the WB and IMF to promote structural financial reforms (Todaro, 2011). These took form in structural adjustment loans, which given with directives on structural economic and political changes to which borrowing nations must comply. These changes were centered on the ideas of market liberalization and fiscal discipline, often regarded as the “Washington consensus” (Williamson, 2009). This began to challenge national autonomy by giving international powers a means by which to dictate national policy. Liberalization strategies were encouraged, partly because much of the investment in international development prior to the 1980s was ultimately borrowed and used in the country to build self-sufficiency, instead of encouraging participation in the global economy. This type of capital flow minimized Foreign Direct Investment (FDI), which could have otherwise fueled development at no cost to nations (Cooper, 2009).

1.2 Modern Mechanisms for Water Development

During the 1990s and 2000s, the UN and its financing organization shifted focus to social protection and improving governance. Efforts by the UN have since delivered several publications meant to transfer technology in the form of development-oriented knowledge and procedures. Among these, the eight Millennium Development Goals (MDGs) established in 2000, and Drinking-water Quality Guidelines (DQG), first published in 1984, set measurable standards and specified indicators for nations to target. Other publications on IWRM and the Rapid Assessment of Drinking-water Quality (RADWQ) provided instructions on how to manage and evaluate water resources.

The modern framework for implementing integrated resource management places water at the center of development goals. The eight MDGs, established in 2000 had attainment targets set for 2015, encompassed: education, health, eradication of hunger, empowerment of women, and sustainability. Eight MDGs contained eighteen targets that outlined the parameters needed to be addressed for the goals to be achieved. The MDGs also identified forty-eight indicators to be used when evaluating the success or failure of development in a country (UN, 2010).

Although the MDGs promoted long-established universal human rights, they have been criticized because of their continuing approach to development schemes that apply a single set of methods across diverse development scenarios (Vandemoortele, 2009). The MDGs have also been criticized as idealistic because they outlined a desired state of development without describing precisely how the changes should be achieved. This ambiguity makes it possible for interest groups to use MDGs to push private agendas (i.e. foreign loans and policy recommendations) that are not necessarily in the best interest of the country or people (Vandemoortele, 2009). Furthermore, Vandermoortele (2009) explained that, because the MDGs used benchmarks based on data from development indicators from 1990, present efforts to apply them have failed to account for over ten years of changes in development conditions. While setting the benchmarks to 1990 levels allowed the UN to establish what originally seemed to be more obtainable targets, the magnitude of improvements will reflect progress in development conditions from 1990 and not 2000. The current parameters of several indicators collected and used by the UN through the World Bank and UN Development Program are illustrated (Table 1). The data is made available through the International Benchmarking Network for Water and Sanitation Utilities, a worldwide database for performance of water and sanitation utilities.

Table 1 Comparison of water indicators across multiple countries. N/A – data not available. Source: IBNET

Indicator	Ghana 2009	USA 2011	Mexico 2012	Brazil 2011
Water Coverage (%)	55	100	98	81
Sewerage Coverage (%)	N/A	46	89	47
Total Water Consumption (l/person/day)	46	610	228	174
Residential Consumption (l/person/day)	N/A	218	F	116
Non-Revenue Water (%)	52	13	24	39
Non-Revenue Water (m^3/km/day)	42.1	10	21.5	32.6
% Sold that is Metered (%)	N/A	100	75	N/A
Operational Cost W&WW (US$/$m^3$ water sold)	0.54	0.92	0.67	1.41
Staff W/1000 W pop served (W/1000 W pop served)	N/A	0.7	0.5	N/A
Average Revenue W&WW (US$/$m^3$ water sold)	0.63	1.36	1.05	2.03
Collection Period (Days)	372	415	397	138
Collection Ratio (%)	79	168	79	99
Operating Cost Coverage (ratio)	1.16	1.48	1.56	1.44

Additional criticisms came in 2012, when the United Nations (UN) and World Health Organization (WHO) reported achieving a 50% reduction in the population without access to improved drinking water sources (Clasen, 2012). The announcement meant that a MDG target had been reached three years ahead of schedule. Several authors have written on the systematic overestimation of the methods used to monitor the progress. One author estimated that a 25% of the world's population lacked access to improved water sources, rather than the 11% that was reported by UN and WHO (Onda et al., 2012; Zawahri et al., 2011). Other authors have remarked on the failure of the definitions to distinguish between "improved" and "unimproved" access to water. Suggesting that "improved" did not realistically reflect the safety of the water being provided or the level of sanitary risk (Bain et al. 2012; Gine-Garriga et al. 2011). The literature has also suggested that the MDGs did not require monitoring of location-specific indicators and they merely use monetary metrics that continue a tradition of donor-centric development (Bain et al., 2012; Saith, 2006; Vandemoortele, 2009).

1.3 Integrated Water Resource Management

Since the MDGs inherently required water resource management, IWRM has often been referred to as the most holistic and efficient approach for countries to protect their water resources (Giordano et al., 2014). IWRM is the accepted mechanism for improving the water sector worldwide (Richter et al., 2013). The ideals of IWRM were first embodied in the formation of the Tennessee Valley Authority in 1933, the first effort to regionalize water management (Ludwig et al., 2013). The first international agreement on IWRM followed many years later during the 1977 UN Conference on Water in Mar del Plata, Argentina, which emphasized regional, national, and international coordination between water sectors (Rahaman et al., 2005). Throughout water conferences that followed, the UN and participating nations agreed to incorporate equity, the environment, and most importantly, the economy, declaring water an economic good (Rahaman et al., 2005). The 2002 World Summit on Sustainable Development in Johannesburg, South Africa, defined IWRM as an economic and welfare-maximizing process that coordinated management and development of water, land, and related resources without compromising the environment (Rahaman et al., 2005).

Similar to the MDGs, IWRM has been criticized as simply presenting more goals and ideals than actual mechanisms for achieving an integrated regional water management. However, IWRM does promote efficiency through coordination to tackle multi-dimensional problems (Biswas et al., 2005; Stålnacke et al., 2010). In order to bring efficiency into the regulatory system, international organizations often recommend IWRM for its ability to promote coordinated management of land, water and other natural resources (Durán Juárez et al., 2006; Kalbus et al., 2012; Sánchez et al., 2012; Scott et al., 2008). This process of enabling individuals, organizations, and societies to obtain, strengthen, and maintain the capabilities to set and achieve their own development objectives over time is known as "capacity development" (UNDP, 2008). Capacity development has evolved from technical training and foreign expertise into a dynamic process for assisting national governments, civil society organizations, independent national and regional institutions and other stakeholders as they pursue their own development goals. International organizations working with IWRM are increasingly engaged in supporting capacity development of water managers through adequate venues for knowledge transfer that is tailored to regional conditions (Kalbus et al., 2012). Similarly, the UN plays an important role in capacity development around the world (Fukuda-Parr et al., 2013).

Promising advances have been made in the use of computer models to support IWRM decision-making. The goal of such models is to address spatial and temporal variability in water quality and quantity by incorporating the physical characteristics of a basin, anthropogenic water systems, and local stakeholders (Jamieson et al., 1996; Nikolic et al., 2013;). Such models however require a variety of physical data, which may not always available in developing nations. With climate change threats, implementation of IWRM will be crucial for all nations (Stålnacke et al., 2010). In theory, IWRM could provide developing regions with the necessary framework to make effective decisions and possibly mitigate climate change effects. This benefit can only be achieved if water management institutions are able to cope with the uncertainty that comes with climate change planning (Ludwig et al., 2013). IWRM presently focuses on current and historic issues in management, often using system models that require historical data on the hydrologic cycle. Managers must be able to incorporate long-term adaptation strategies that can address the unpredictability of climate change. The literature overwhelmingly suggests that IWRM has not been successful, mainly because authorities have not sufficiently incentivized the formation of strong regional authorities provided room for alternative pragmatic solutions in the global discourse (Biswas et al., 2005; Giordano et al., 2014;). Various methods for implementing IWRM have been applied around the world. Such efforts have been hampered though because two key components have been difficult to achieve in developing nations: good governance and reliable data mining (Stålnacke et al., 2010).

2. CAPACITY DEVELOPMENT IN WATER MANAGEMENT

Implementing IWRM internationally requires cooperation and coordination between many levels of governance. Having recognized this, international organizations have developed programs and procedures to work with countries towards this goal. Target 3 of Millennium Development Goal 7 (ensuring environmental sustainability), which seeks to halve the proportion of the world's population without sustainable access to safe drinking water and sanitation, is assessed by the Joint Monitoring Programme (JMP), run by the United Nation Children's Fund (UNICEF) and the WHO (Zawahri et al., 2011). The JMP uses household level surveys and assessment questionnaires to collect data on drinking water and sanitation services (Shordt et al., 2004). In 2004, the WHO and UNICEF began to use the RADWQ methods to assess the ability for JMP to monitor water safety in conjunction with water access by using physical indicators (Egbuna et al., 2013). The goal of the RADWQ handbook, which outlines methods and procedures to assess water quality management in a holistic fashion, is to define critical areas and identify entities that may require capacity development and a new regulatory framework (Howard et al., 2012).

The Millennium Development Goals (MDGs) set an arguably narrow definition of 'improved' water access, failing to account for the quality of water being delivered. The quality of drinking water will depend on the types of contaminants to which the source waters are exposed and the level of treatment the water receives before distribution. Increased water access increases the responsibility to provide safe potable water, thereby challenging the government's ability to protect and manage natural resources. Governments must take steps toward IWRM in order to efficiently protect water resources from contamination in the interest of protecting human health.

2.1 International Guidelines for Drinking-Water Quality

Not all efforts made by the UN and its associated bodies have lacked specificity. Many have formulated guidelines for developing nations to help them design effective water management and water-monitoring. The WHO produced the Drinking Water Quality Guidelines (DWQG), a Water Safety Plan Manual, and the Rapid Assessment of Drinking Water Quality (RADWQ) handbook, which dealt specifically with improving water management and quality (Howard et al., 2012). These tools account for the constraints on available resources for testing water quality, while providing instructions for assembling region-specific programs. Additional publications by the WHO have provided background into methods of treating and testing drinking water (Au, 2004; Howard et al., 2003). This has served as a form of technology transfer allowing developing countries access to scientific knowledge and management strategies.

The WHO guidelines for drinking water quality (DWQG) established environmental indicators and standards of quality, which developing countries often lack (Onda et al., 2012; Sánchez et al., 2012; Tortajada et al., 2005). Despite their non-binding nature, the DWQG transfers knowledge to underdeveloped regions that are considered essential toward removing barriers to progress (Wade-Miller, 2006). In DWQG publications since 2003, the WHO has emphasized a risk-based integrated approach to drinking water quality that considers protecting water from contaminants at all stages of domestic supply and delivery (Sobsey et al., 2002). The guidelines include chapters on topics ranging from disinfection to plumbing, surveillance, system assessment, indicator parameters, safety plans, and even guidelines for things like climate change, airports, and intense rainfall events (WHO, 2011).

The water quality indicators selected for publication in the DWQG include essential physiochemical properties of water, such as pH and electrical conductivity (EC), that give insight into the source of water and its aesthetics (WHO, 2011). Through DWQG, the WHO recommends that developing nations test their drinking water for indicator bacteria once per month (WHO, 2011). Their low- resolution recommendation considers the reality that many communities in developing nations may lack access to elementary monitoring equipment and management methods (Yang et al., 2013). Data with low temporal resolution can be used to test for localized hazards and more quickly identify the most pressing challenges, such as natural or human contaminants (Bain et al., 2012). Rapid assessment of water quality provides two key services: a quantitative measure of water quality and insight into local water management challenges and opportunities for improvement. In essence, rapid water quality analyses can provide a measure of the effectiveness of local water management strategies towards providing safe drinking-water.

2.1.1 Chlorine in water distribution systems

Water distribution systems (WDS) represent considerable investments for utilities and governments in developing countries. The main priority of a water utility is to reliably provide safe water. Maintaining the proper disinfection inputs for a WDS to provide safe water to citizens represents an ongoing investment. Chlorine is the most commonly used disinfectant used as a safeguard against pathogens because of its high reactivity with organic matter and relative safety (Hallam et al., 2003; LeChevallier et al., 1990; Ozdemir et al., 2002). Unfortunately, because of this high reactivity, chlorine concentrations are not constant throughout the distribution network, and furthermore cannot be guaranteed to eliminate all dangerous pathogens. LeChevallier (1990) recommended using a strong, highly reactive disinfectant such as free chlorine as a primary disinfectant and monochloramine as a secondary disinfectant in the distribution system because it showed promise in more effectively penetrating biofilm. There have been some health concerns regarding the use of monochloramines, although the EPA still permits their use in drinking water disinfection (WHO, 2011). Mexico has set permissible limits on free chlorine between 0.2-1.5 mg/L and may not exceed 3 mg/L (NOM-127-SSA1-1994) (Alcocer-Yamanaka et al., 2004). As a result of the various variables which affect chlorine concentrations throughout distribution systems as well as the creation of THM, multiple regression analysis is the most common approach to model water networks. Through a multiple regression method, the water quality parameters that impact the evolution of water in a system; such as, pH, temperature, organic matter content, initial chlorine dosage, and distance traveled can be taken into consideration (Ahn et al., 2012; Grayman et al., 1993).

Chlorine decay is often modeled as a time-varying, first-order decay factor because organic matter content is usually an unknown variable. Chlorine decay is divided into two parts, chlorine bulk decay from general consumption by organic matter in the water column, and wall decay from reaction with biofilm and pipe materials (Ahn et al., 2012). Modeling parameters of chlorine decay are also affected by conditions within the storage tanks, water itself and ambient temperature (Grayman et al., 1993; Rossman et al., 1995;). Additionally, models provide less accurate results in areas off the main water line and after storage. This is because water quality, chlorine concentrations, in areas off the main water line depends heavily on water consumption, and such data is difficult to obtain. Chlorine concentrations in water prior to entering a distribution network is a key factor in determining what concentrations will be throughout the system. Considering seasonal changes in water demand, water treatment plants need to be flexible in the volume of chlorine initially mixed into the water to maintain a minimum of 0.1 mg/L throughout the system (Ahn et al., 2012).

The most commonly used and accepted model for first order decay is Equation 1, in which the chlorine residual (C_t) is a function of the initial chlorine concentration (C_0) as affect by a decay coefficient ($-k$) (Ahn et al., 2012; Alcocer-Yamanaka et al., 2004; Clark et al., 1994; Georgescu et al., 2012; Grayman et al., 1993; Rossman et al., 1995; Vasconcelos, 1996). The decay coefficient (k) can be calibrated by incorporating parameters specific to the distribution system (Equation 2), which attributes decay to the sum of bulk water decay (K_b) and wall decay (K_w) (Powell et al., 2000). Bulk decay coefficients can vary greatly depending on the quality of water before chlorination, ranges have been reported anywhere from 0.02 - 0.74 h^{-1} (Hallam et al., 2003). The bulk decay coefficient has been further expanded (Equation 3), such as wall decay of chlorine (k_w), mass transfer coefficient between bulk flow and pipe wall (k_f), and the hydraulic radius of the pipeline (R_H) (Ahn et al., 2012). The decay coefficient can be further calibrated to the specific water system being modeled, in its simplest form, by calculating k_b and incorporating temperature (T) and Total Organic Carbon (TOC) (Equation 4). Serious limitations in accuracy can arise when there is a lack of design knowledge of the water distribution network (Ahn et al., 2012; Vasconcelos, 1996). This is especially important for obtaining accurate results when modeling storage tank chlorine dynamics, because flow rates in and out of the tanks as well as the ratio of active to emergency storage volume need to be known (Rossman et al., 1995).

$$C = C_0^{-kt} \qquad \text{(Eq.1)}$$

$$k = k_b + k_w \quad \text{(Eq.2)}$$

$$k = k_b + \frac{k_w k}{R_H(k_w + k_f)} \text{(Eq.3)}$$

$$k_b = 1.8 \times 10^6 TOCe^{\left[\frac{-6050}{T+273}\right]} \quad \text{(Eq.4)}$$

Dangerous by-products can be produced when chlorine reacts with organic matter as it decays, such as total trihalomethanes (TTHM) which are potentially carcinogenic (Ahn et al., 2012). Measuring organic content in the drinking water source is important for adding appropriate chlorination volumes and also to protect consumers and utility workers from these dangerous disinfectant by-products. EPANET is capable of modeling TTHM formation in a distribution system through a first order regression model. It does this by using a kinetic model developed using nonlinear least squares regression. Mexico does regulate THM, setting the maximum exposure limit at 0.2 mg/L.

2.1.1.1 Biofilms

Biofilm growth is influenced by many factors including; pipe material, disinfectant type used for water treatment, quality of source water, and physic-chemical parameters of water such as nutrient amounts and temperature (Srinivasan et al., 2008). Suppression of biofilm growth requires chlorine concentrations estimated at 1.8 mg/L but may differ depending on the pipe material and roughness (Block, 1992). In PVC and copper pipes, 1 mg/L of chlorine was able to remove viable biofilm up to 100-fold (LeChevallier et al., 1990). However, in iron pipes, whose rough surface harbors biofilm, concentration of free chlorine up 4 mg/L were ineffective at controlling biofilm (LeChevallier et al., 1990). In areas where coliform regrowth is a problem, utilities keep free chlorine residual concentration between 3-6 mg/L. Past research from as early as 1986 demonstrated that biofilm could be a source of coliform bacteria in drinking water (LeChevallier et al., 1990). It is important to maintain residual chlorine concentrations in distribution systems to maintain a low biofilm growth. However, high concentrations of chlorine residuals are usually not accepted by water utilities, as they can cause corrosion, excessive concentrations of trihalomethanes, and consumer complaints of aesthetics such as chorine taste and odor (Ahn et al., 2012; Ozdemir et al., 2002).

2.2 National Development Strategies

The Latin American average withdrawal per capita per year (pcpy) for domestic use is 98 m^3 (Castro et al., 2009). As is true in most of Latin America, Mexico's greatest obstacle in implementing IWRM come from rapid, unregulated urban expansion and destruction of natural land cover to expand the agricultural exploitation of land (Lorz et al., 2012). IWRM in Latin America has mainly focused on building the knowledge base for understanding the natural framework, sediment characteristics, drinking water supply systems, and wastewater treatment (Kalbus et al., 2012). However, coordination failure resulting from a lack of coordinated decision-making, at all levels of government has made it difficult to implement such management strategies (Tortajada et al., 2005).

2.2.1 **Development background of Mexico**

The World Bank classifies Mexico as an upper-middle income nation. Despite having a GPD of more than 1.5 trillion dollars a year and 287 billion dollars of external debt stock in 2011, Mexico's development is considerably limited for a country with such wealth (Bank, 2014; Castro et al., 2009), which may be in part due to its widespread range in climate and biomes. Mexico has favorable trade access through coastlines in both the Pacific Ocean and the Gulf of Mexico which it has tried to utilize through various free trade agreements.

Mexico has a wide range of climates and biomes; ranging from arid desert along the U.S.-Mexico border to alpine temperate in Central Mexico and tropical rainforests in the south (Figure 1). Such extensive natural diversity is in part due do to its active geologic history. Much of the country is mountainous and enriched with metals and minerals. It is currently a leading producer of petroleum, silver, copper, gold, lead, fluorspar, zinc, and natural gas (Perez, 2011). Taking into account the existence of extensive natural diversity in the country, the federal government has protected relatively small areas that fall into limited types of biomes. Figure 1 shows that large protected areas are limited to Warm sub humid and Very dry warm locations.

Today, approximately 59% percent of the land area in Mexico is owned by community-based land holdings called Ejidos, (communally owned land distributed after the revolution of 1917), which represent 66% of agricultural production units (Berkes et al., 2000). Almost 41% of land is owned by private individuals, but only represent 31% of agricultural production. While only 13% of land in Mexico is arable, just 3% of this arable land is used for irrigated agriculture (Figure 2). In spite of the low agricultural production in Mexico, 77% percent of withdrawn freshwater is used for agricultural purposes and only 23% of withdrawals are used for domestic or industrial purposes (CIA, 2013).

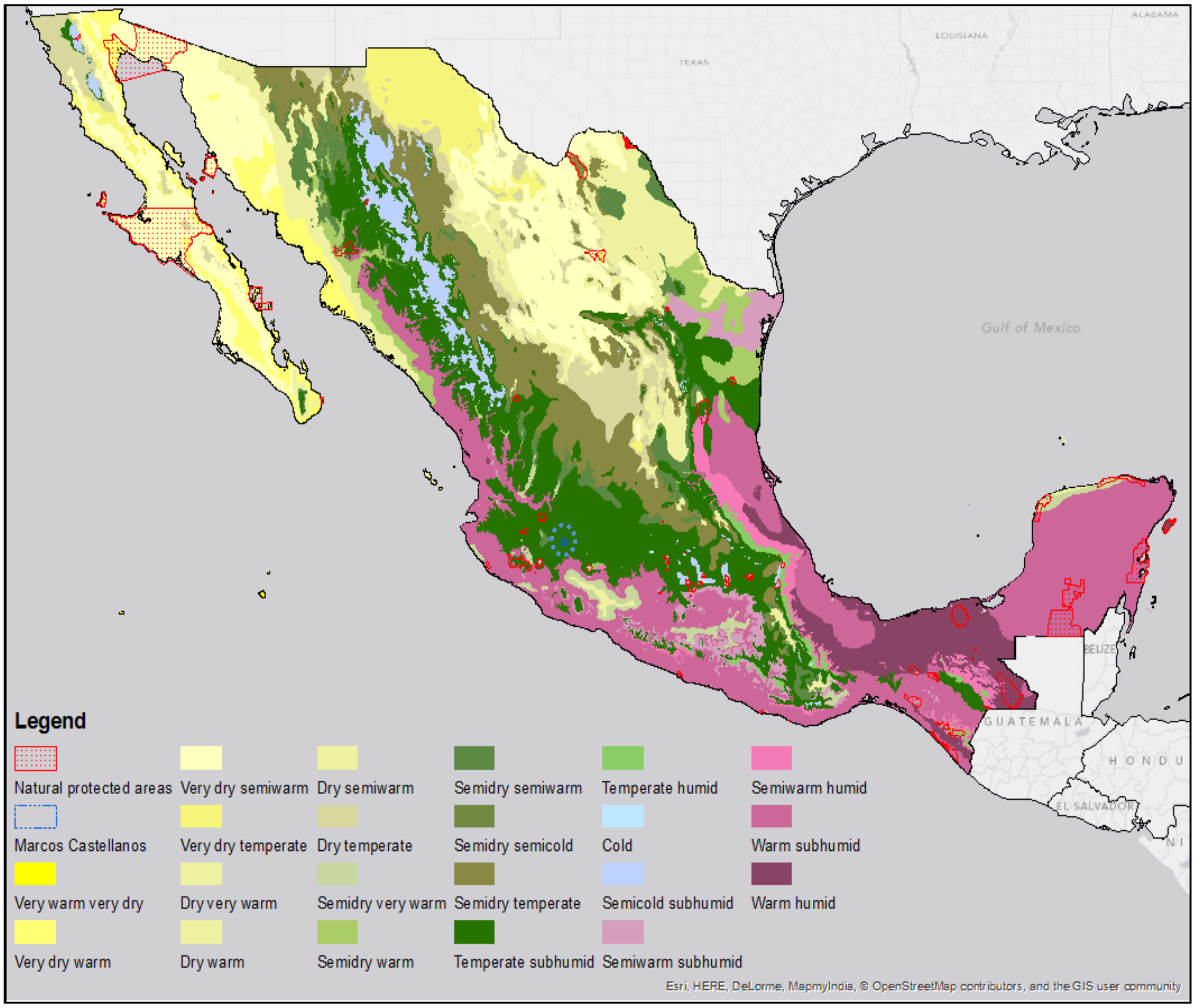

Figure 1 Climate regions and boundaries of federally protected areas. Data Source: INEGI.

The lack of access to safe drinking-water and sanitation facilities reflects much of the nation's high level of poverty and inequality (Armentia et al., 2009; Bank, 2003). In Mexico, only 13% of urban wastewater receives treatment before being discharged into streams (Bank, 2012). Raw sewage in combination with non-point sources of pollution has rendered most surface waters unsuitable for most uses. While the per capita water availability for Mexico is around 4,400 m^3 pcpy, northern states have only 2,044 m^3 pcpy. In spite of having less water resources, the northern states house a staggering 77% of the population and generate 86% of the national GDP (Castro et al., 2009).

Mexico is a youthful country, with almost half of its population below the age of 25 and a median age of 27. Dependency is primarily associated with minors and the elderly are less than 10% of the population (CIA, 2013). Widespread income and social inequality in Mexico have hindered national and local development. Nearly half of the country's population lives on an income of less than 2.5 USD per day, the majority of which are indigenous groups (Crandall et al., 2005). High levels of income inequality can be attributed to residual effects of colonization. In 1910, only 2.5% of the population owned land in Mexico, compared to 75% of the population in the United States (Haber et al., 2003). A lack of substantial growth in cities throughout the country, has created unsustainable populations in the country's major cities, and prevented growth in labor from rural migrants outside of the central region (Figure 3). Populations are greatest in the central region with pockets of development along border cities, tourist areas in the south and oil producing communities in the Gulf coast.

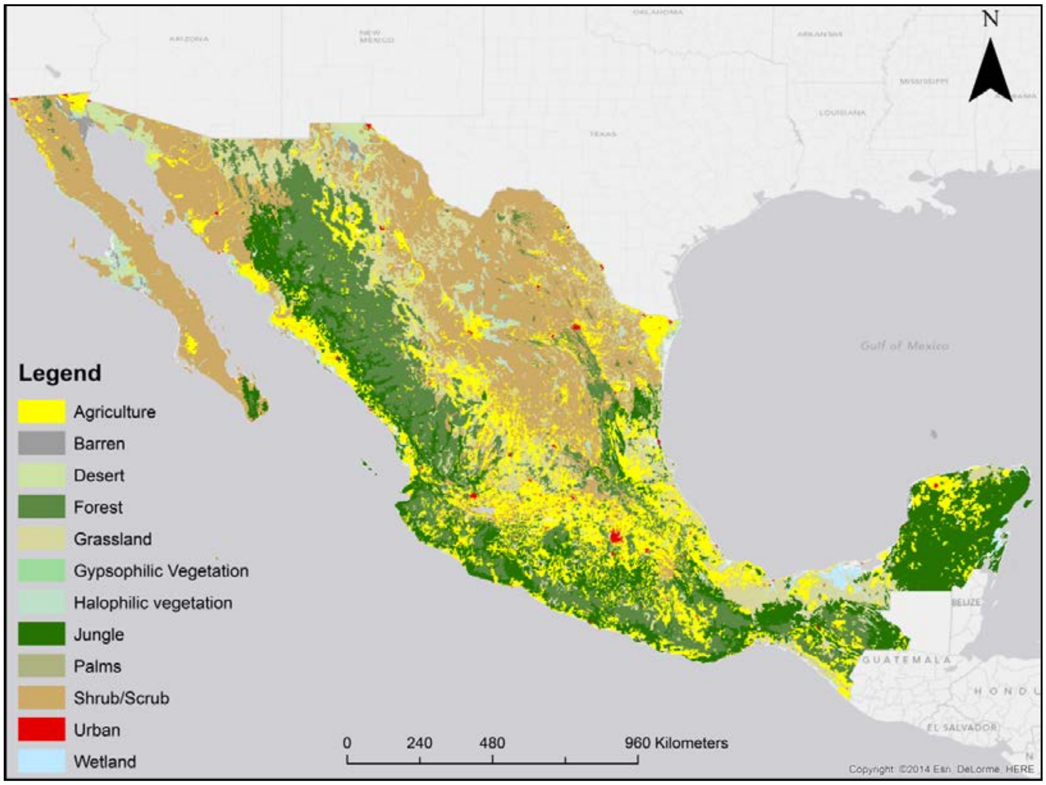

Figure 2 Land cover in Mexico. Data source: INEGI

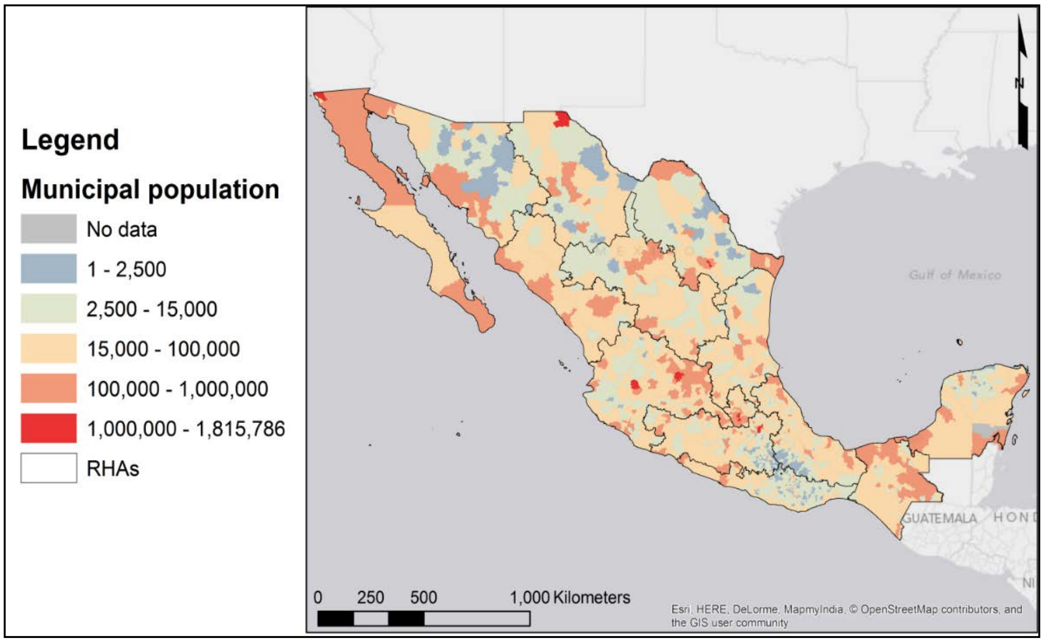

Figure 3 Populations by municipalities. Data source: INEGI

2.2.2 Water management in Mexico

The goal of providing safe drinking water challenges developing countries to update their water policy and execute infrastructure development projects that are within their means. In Mexico, expansion of hydraulic systems accounted for up to 14% of the federal budget between 1941 and 1955 (Aguilar, 2004). By the 1970s, it became apparent that urban population growth demanded more attention than rural agricultural needs and so financial investment began to shift to development of urban water systems (Ley et al., 2011; Soarez, 2007). Since then, efforts for economic development tied to water resources have continued but have focused on domestic uses of water. Unfortunately, Mexico’s water resources planning and management has often failed to guarantee that clean, safe water is delivered to users.

Mexico’s failures in improving water quality have long been attributed to a historically centralized government and a lack of comprehensive planning (Aguilar et al., 2011; Azuela, 1995; Tortajada et al., 2005; Viesca, 2003). Mexico is centralized not only in terms of population, but also in terms of government control. The federal government controls all natural resources including water and oil, the majority of social programs and access to funding from international lenders (Berkes et al., 2000). Federal taxes are at a high level and prohibit meaningful taxation at the state level. As a result states are unable to generate revenues from fees, taxes or resources extracted from within their own boundaries. In this manner, the federal government of Mexico has created a dependency for infrastructure investment and enforcement of legislation, constricting the role of state and local governments (Rich, 2003).

Lack of access to safe water continues to threaten the health of citizens, despite federal law, NOM-127-SSA1-1994, mandating potable water service (CONAGUA, 1994; Scott et al., 2008; Viesca, 2003). Research has long highlighted the importance of developing management practices that are specific to the characteristics of the watershed and/or aquifer that serves a population (Lloyd, 1999; Tortajada et al., 2005;). Key among these management practices is regular water quality monitoring, as it helps to establish a working relationship between human activity and water quality (Bartram, 2009; Ferrier et al., 2009; Howard et al., 2012; Lloyd, 1999; Sara, 2010). Once a relationship is established, authorities can take measures to ensure that land use and water delivery systems are regulated appropriately to protect water resources.

Unfortunately, for developing countries such as Mexico, the most accepted methods for testing water used in developed nations require expensive equipment and facilities that are generally unavailable to rural areas and even most urban areas (Giné-Garriga et al., 2011; Sutton, 2008). Frequent water testing provides data with higher temporal resolution, which can help to better explain the spatial-temporal variability of water quality in a community. However, this requires a detailed understanding of water quality that raises the cost of monitoring, making it impractical for most Mexican municipalities with the current structure of financing. Complicated systems of jurisdiction for different levels of government, has made reform in the water sector extremely difficult.

In 1992, Mexico adopted new water laws outlining the role of Federal, State and Local Governments in managing water resources. Although the federal government promised further decentralization of its water management, the National Water Commission (CONAGUA) is still the primary operator and regulator of the nation’s waters (Barkin et al., 2006; Hazin, 1997; Sánchez et al., 2012; Tortajada et al., 2007). Water quality regulations have been in place for several decades in Mexico although state and municipal governments have been largely unsuccessful in enforcing them (Durán Juárez et al., 2006). The formal River Basin Councils (RBC), established in 1989, have not been successful in applying an integrative approach and lack the power to develop and enforce policy (Barkin et al., 2006; Sánchez et al., 2012; Scott et al., 2008). Since the federal government controls the financing of infrastructure projects and allocation of water rights, RBCs have no way to incentivize sustainable practices (Tortajada et al., 2007).

Additional policy inconsistencies in land use management have further complicated attempts to implement integrated water management. Regulation and enforcement of land use falls under municipal control, however Ejidial land, falls under federal jurisdiction and not under the jurisdiction of RBCs or municipal governments, making it harder to develop and implement sustainable land use projects (Aguilar et al., 2011; Azuela, 1995; Tortajada et al., 2007;). Mexico's mountainous terrain further complicates attempts to regionalize water management. Mexico has 1,471 sub-basins, creating 722 hydrologic basins that the nation's water authority has grouped into 37 hydrologic regions (CONAGUA, 2012). Politically, Mexico's basins are subdivided into 13 Regiones Hidrológico-Administrativas (RHAs) or, Hydrologic-Administrative Regions. Within these, 26 River Basin Commissions, RBCs operate to manage surface water and often groundwater as well (Scott et al., 2008).

2.3 Research Objectives

The aim of this study was to use water quality as a measure of water management performance in Mexico at the local, regional, and federal levels. Low-cost, field water quality sampling methods were used to assess possible threats to safe drinking water in the town of San José de Gracia and the municipality of Marcos Castellanos. The town's water distribution system was modeled using EPANET to examine how local management regimes can affect the safety of drinking water. Federal government management regimes were assessed by comparing local and regional water quality to national and international standards.

This study is an exploratory overview of the successes and failures of water disinfection in the urban center of the town of San José de Gracia. The study will attempt to answer the following questions:

- What is the current state of municipal level IWRM in Mexico?
- Is the disinfection system of the local water utility adequate to handling the volumes of water demanded?
- Is the design of the water treatment and distribution system adequate for the population demands and financial constraints of local water utility?
- What is the adequate quantity of chlorine that should be applied once calibrated to meet the distribution system's needs?

These questions will be answered in part by conducting low-cost water quality tests that measure pH, electrical conductivity (EC), coliform bacteria and *E. coli* and total and free chlorine. Field test results, as well as results obtained from traditional analytical chemistry will be used to construct a model (EPANET) of the town's water distribution system (WDS). The model will be used to determine how areas of the town could be affected by insufficient free chlorine present in the system at the neighborhood block resolution.

2.4 Hypotheses

Objective 1: Assess whether federal potable water quality standards and international standards are being met in the town of San José de Gracia, Mexico.

Sub-objective 1: Determine whether chlorine concentration at water customer connections satisfy minimum safe concentration specified by the Mexican federal government, the WHO DWQG, and the U.S. EPA.

H_0: The mean of sampled chlorine concentration meets minimum safety standard of 0.2 mg/L.

H_1: The mean of sampled chlorine concentration is below the minimum safety standard of 0.2 mg/L.

Sub-objective 2: Determine whether coliform bacteria are present at water customer connections.

H_0: Coliform bacteria are not present in water delivered to customers.

H_1: Coliform bacteria are present in water delivered to customers.

Objective 2: Develop an EPANET model representing the town’s water distribution system to analyze the effectiveness of water management at the municipal level. This objective will be accomplished by determining if chlorination at the system’s water sources contributes to observed variability in the quality of drinking water from field studies.

Objective 3: Since the local aquifer is unconfined, land uses could affect water quality of the town’s groundwater supplies. By detecting herbicides in the town’s drinking water, there may be a possible threat from contamination.

H_0: If herbicides are not detected in any of the drinking water samples, then the town’s water supply may not be vulnerable to human activity.

H_1: If herbicides are detected in any of the drinking water samples, then the town’s water supply may be vulnerable to human activity.

3. MATERIALS AND METHODS

3.1 Site Description

This research takes place in RHA 8, the Lerma-Santiago-Pacífico Basin (Figures 4 and 5). Marcos Castellanos, the municipality, and the town of San José de Gracia, the areas studied are primarily in the Lerma basin. Hydrologic region 8 has a current population of more than twenty two million people, and falls within nine state boundaries (CONAGUA, 2012). The Lerma-Chapala Basin produces 11.5% of Mexico's GDP, more than 50% of Mexico's exported manufactured goods and 20% of the nation's service activity (UNESCO, 2012). Irrigated agriculture, which represents 78% of surface water abstractions, produces only five percent of GDP but employs 21% of the basin's population (Mestre, 2001; UNESCO, 2012).

3.1.1 **Characteristics of the Lerma-Chapala basin**

The Lerma-Chapala Basin, with an area of 54,421 km^2, is home to just over 11 million people. The basin supplies an additional 4 million people in the two most important cities in Mexico: Mexico City and Guadalajara (Juarez-Aguilar, 2010; Mestre, 2001;Wester et al., 2003). The headwaters of the 750-km long Lerma River, the basin's primary tributary, originate from the high mountains near the city of Toluca in the State of Mexico at more than 3,000 m MSL (Millington et al., 2006). The River empties an average of 1.5 billion m^3 per year into Lake Chapala, the largest natural lake in Mexico, located at an elevation of 1,510 m ASL. The basin receives an average of 755 mm of rain annually, primarily during the month of July (De Anda et al., 1998). Although studies have been performed on the hydrological balance of Lake Chapala, the Lerma River has been ignored in the research, its impact left out of the Lake Chapala basin models of hydrology and phosphorus loading (de Anda et al., 1998, 2000). Since the City of Mexico relies on inter-basin transfer of water from the Lerma River it is critical that models of the lake be updated to include flows from the Lerma River and possible impacts of flow based on what Mexico City extracts. Since basin management organizations do not include inter-basin users, the current management scenario is seriously lacking full stakeholder participation.

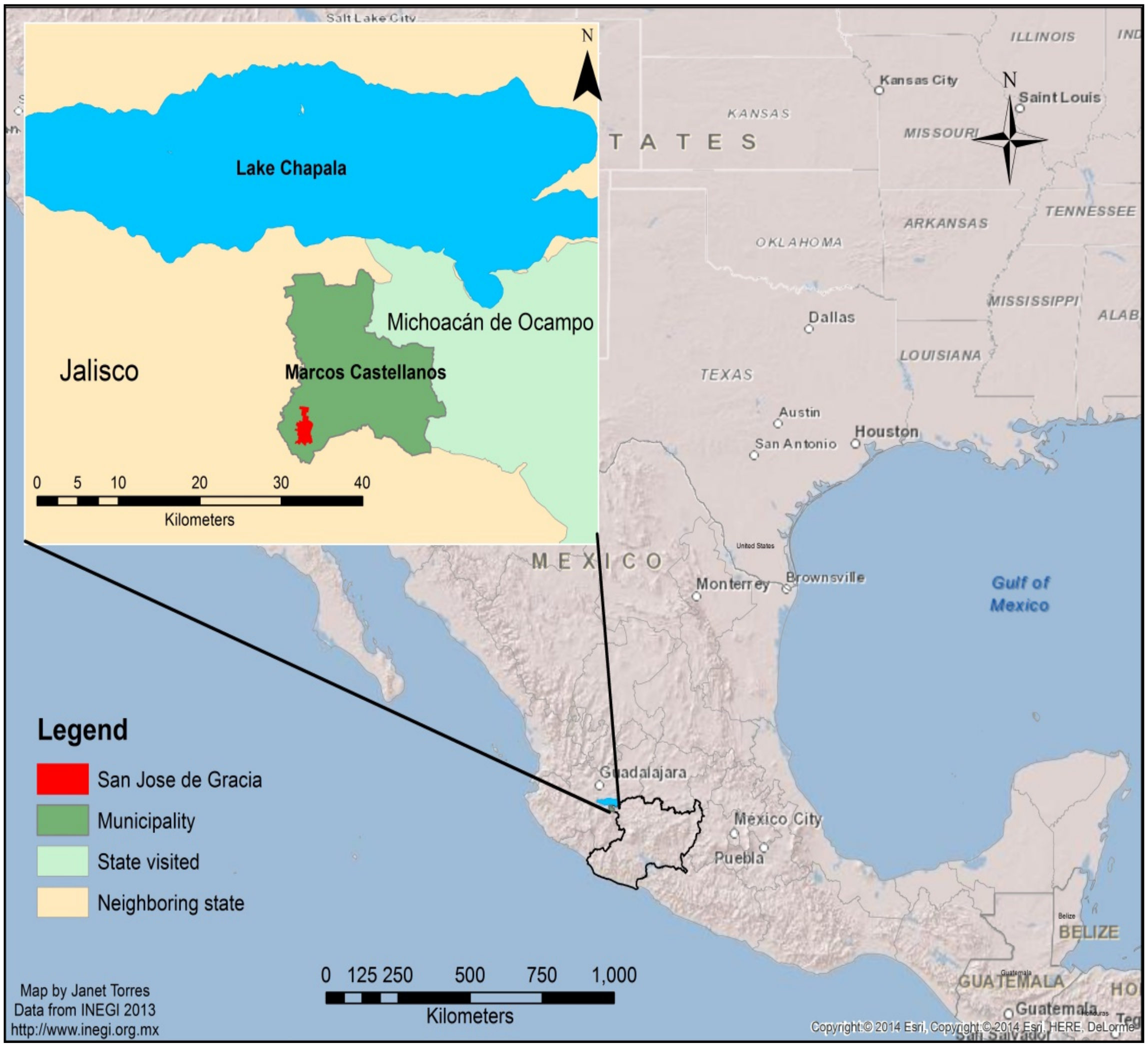

Figure 4 Location of Marcos Castellanos municipality. Source of data: INEGI

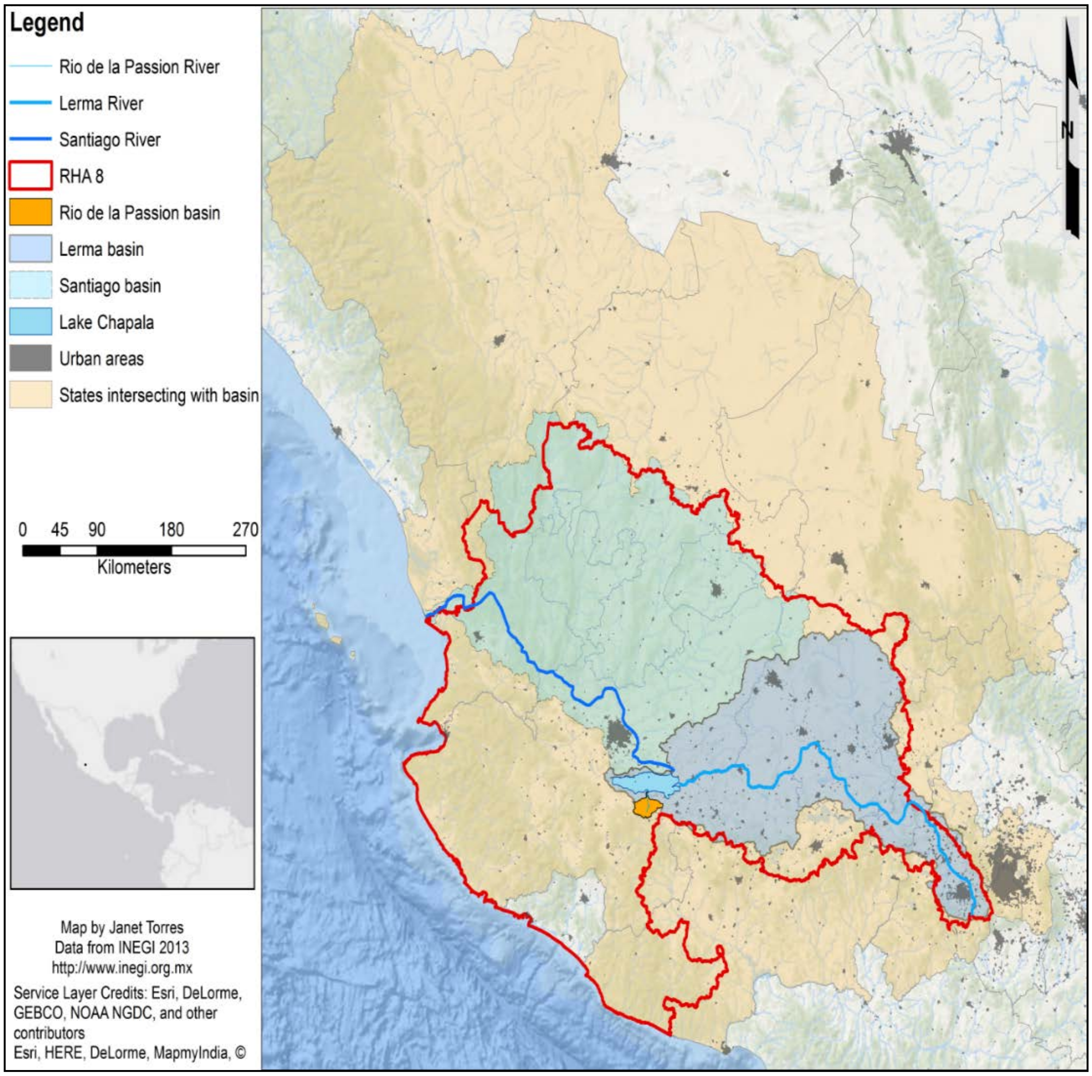

Figure 5 hydro-political sub-divisions of the study area. Source of Data: INEGI

3.1.1.1 Geology

The geology of the Lerma-Chapala Basin's is the primary factor determining how land use affects the quality of water available for human consumption. Managing threats to groundwater quality that can arise from geologic features, such as heavy metals, have been difficult because detailed geological maps exist for only about 20% of Mexico's land area (Perez, 2011). The Lerma-Chapala Basin contains 90% basaltic rock because of its location in the Trans-Mexican Volcanic Belt (TMVB) which was undergoing tectonic deformation and volcanism for the better part of the late Tertiary to Quaternary periods (Israde-Alcantara et al., 1999; UNESCO, 2012). As a result, a large portion of the aquifers are recharged through fractures and fissures, making water quality management a very difficult task (Lloyd, 1999). Lake Chapala lays on a graben (depressed landform or rift valley) controlled by three tectonic features, the Zacoalco, Colima and Citala Rift (Michaud et al., 2006). The graben is thought to have started its lacustrine phase in the Early Pliocene, originally draining in directly into the Pacific Ocean. Tectonic uplifting created a small mountain range to the west damming the river and producing the outflow through the Santiago River (Israde-Alcantara et al., 1999; Lind et al., 2002).

The basin is interlaced with basaltic fracture aquifers that are poorly understood because of lack of geological research in this area. There have been no studies to define the recharge area or size of the aquifer from which the Municipality of Marcos Castellanos draws its water (Figure 6).

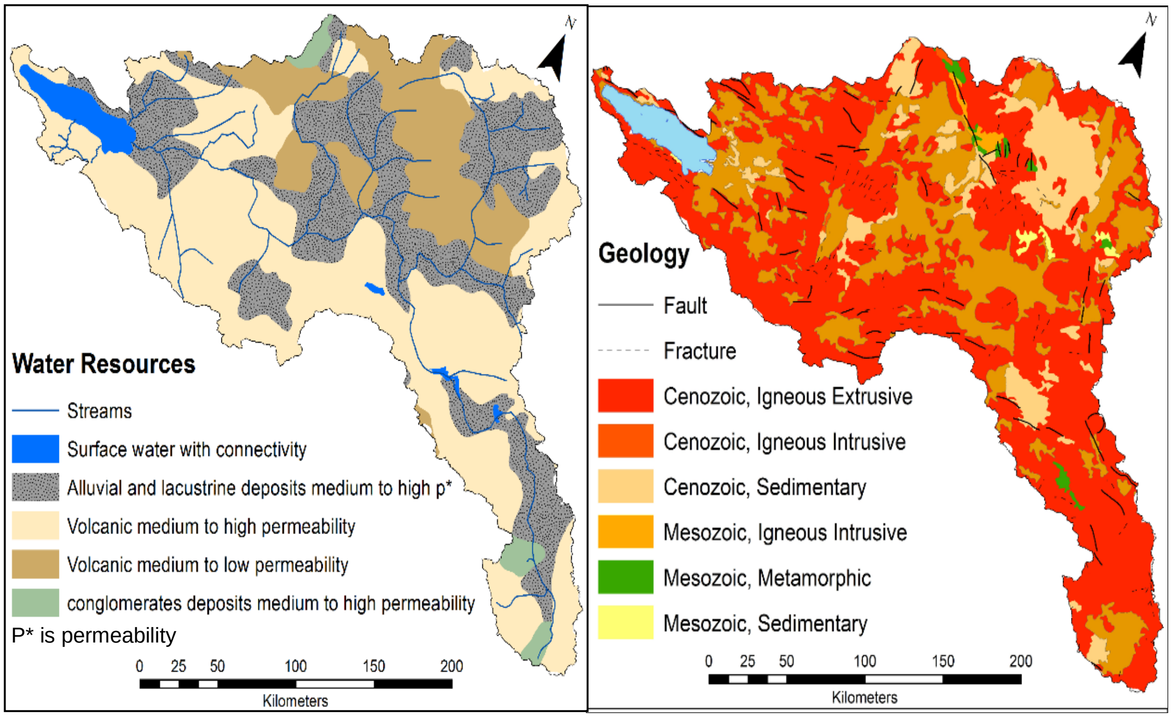

Figure 6 Rock types and the potential permeability of rocks in the Lerma-Chapala Basin

Heavy industrialization near the headwaters of the Lerma River, agricultural landscapes and a lack of a general understanding of the basin's recharge zones throughout the basin have left its population vulnerable to contaminated groundwater and unable to utilize surface water for municipal supplies. Where dynamic groundwater models cannot be used because of the lack of data, vulnerability can be classified using a geographical surface analysis (Al-Adamat et al., 2003). This is where the logic behind IWRM begins to play out in the development of datasets and strategies for developing nations.

3.1.1.2 Land use

The Lerma-Chapala basin is primarily agricultural, over 50%, with induced grasslands as the second largest use at 11% (Cotler et al., 2006). The Lerma-Chapala basin experiences degradation in about 36% of its soils, in part because of the reduction in conifer and hardwood forests cover that used to prevail in the basin (Cotler et al., 2006). Loss in agricultural production averages 22% and up to 60% in the Cienega de Chapala region, directly east of Lake Chapala (Silva-García et al., 2006; UNESCO, 2012).

3.1.2 **Local characteristics**

The municipality selected for this research, Marcos Castellanos, is located in an economically key area of Mexico; it has an area of 233 km^2 and a maximum elevation of 2,000 m ASL (Figure 7). Marcos Castellanos was described by the famous historian, Luis González as a place representative of the typical central Mexican town, found in a primarily agrarian municipality with no other urban centers (González and González, 1974). The municipality has a temperate climate with temperatures ranging from 10 to 21° C with an average annual rainfall of 1016 mm that falls primarily in the summer months of June-

August (SNIM, 2010). Its location, 21°13'56" N 86°43'54" W, in the Lerma-Chapala Basin near Lake Chapala has made it an ideal place for commerce since colonization. Marcos Castellanos lacks a manufacturing sector; the main industry is the production of dairy products and is therefore an agriculture based economy (McDonald, 2003, 2001). The municipality is located in the Rio de la Passion, (River of Passion) watershed (Figure 8). Agriculture and grassland are the primary land covers of the Rio de la Passion watershed. This land cover is used to sustain small herds of dairy cattle by growing corn and grazing grasses. There are small patches of forests with low densities of trees and larger areas with scrub and scrub cover.

One of the town's water supplies, the Ojo de Agua well, is located in the urban area and three (Milpillas and Jarero wells and Agua Caliente spring) are located in agricultural areas. When the Jarero well was visited it appeared to be surrounded by land in transition from agricultural to urban with some shrub/scrub. The spring and wells are considered "improved" sources of water because they are protected by a fence and receive dosages of chlorine. However, despite the fences used to protect the Agua Caliente Spring and Milpillas well they are exposed to runoff and the immediately surrounding land uses can also pose a threat to water quality (Figure 9).

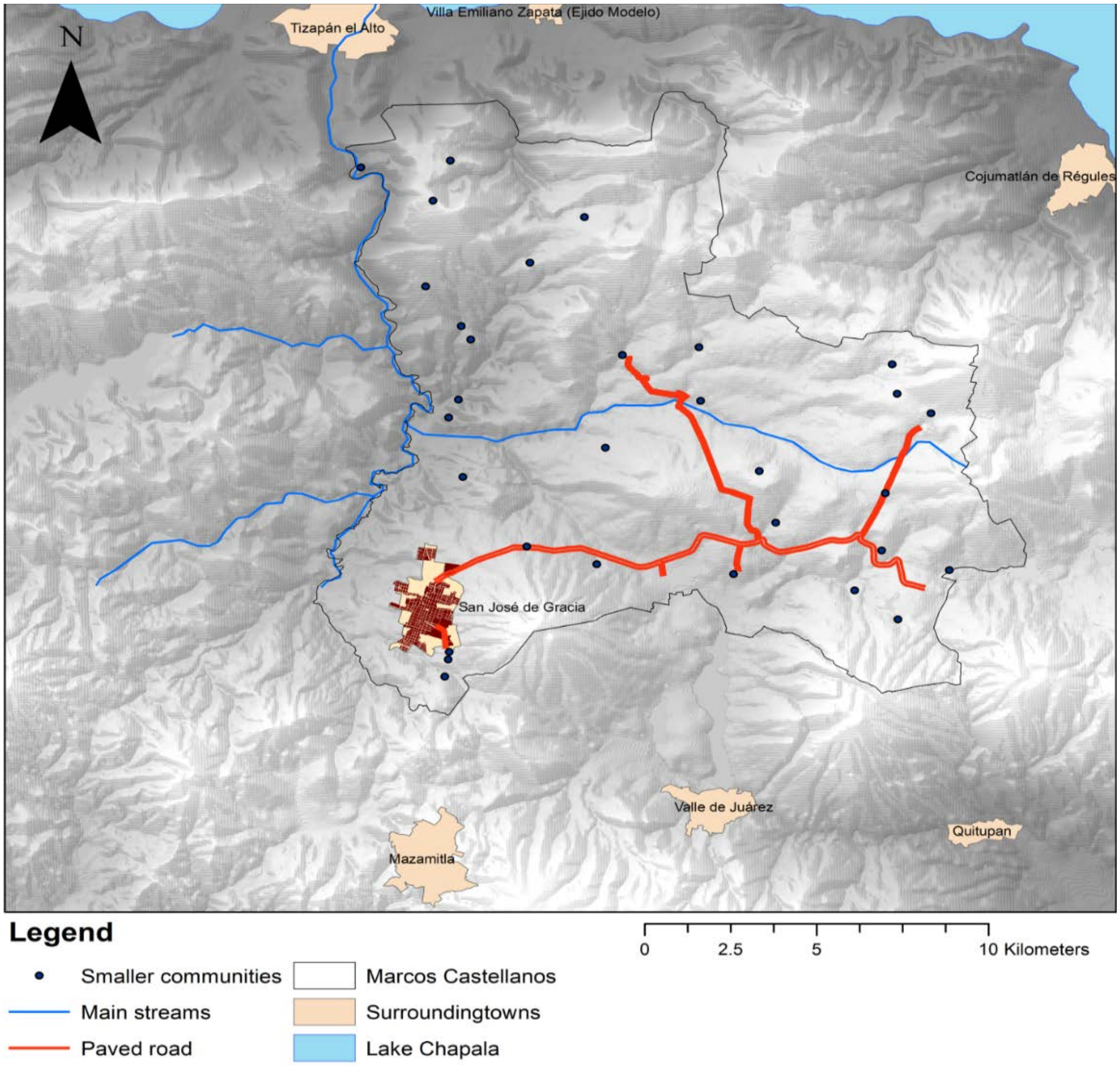

Figure 7 Marcos Castellanos and surrounding communities including San José de Gracia

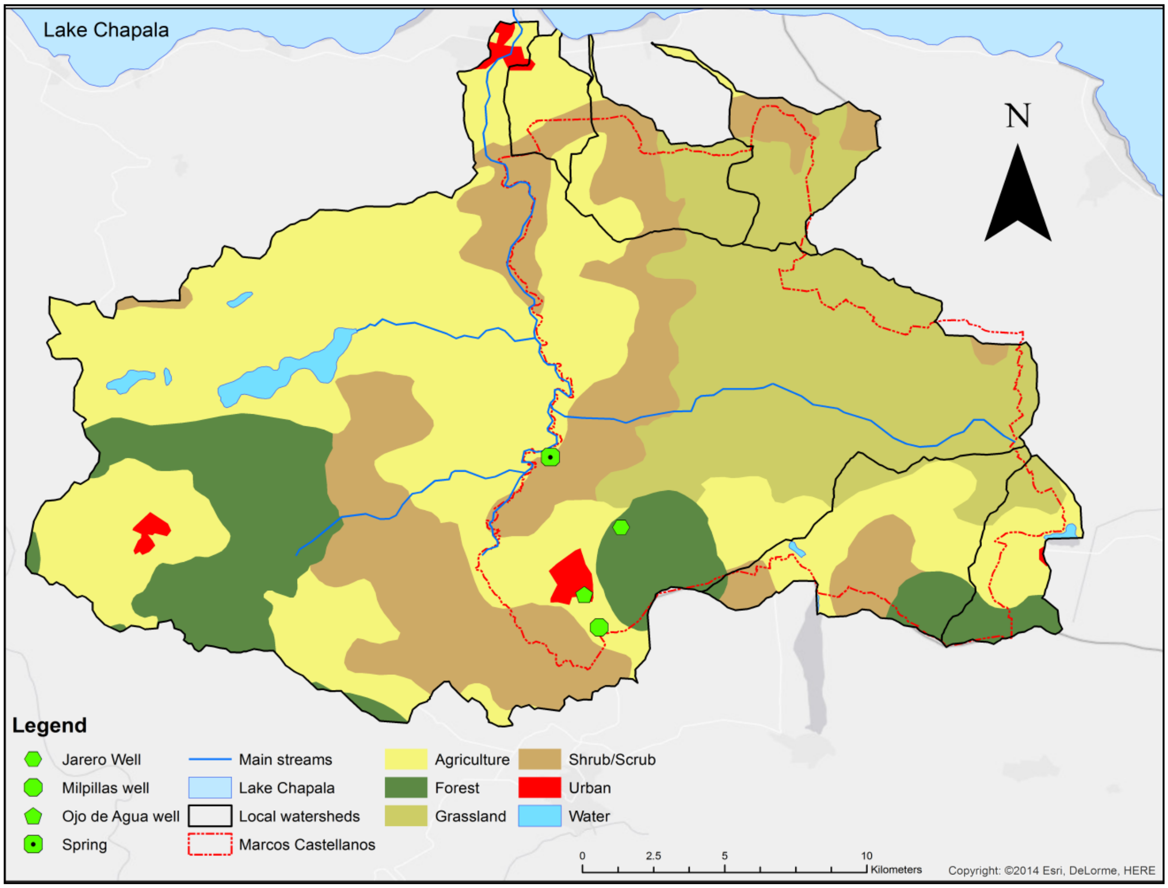

Figure 8 Land cover and supply wells in the municipality. Data source: own and INEGI

Figure 9 Water sources for the town of San José de Gracia

A. Aguacaliente spring

B. Jarero well

C. Milpillas well

D. Ojo de Agua well

Figure 9 Water sources for the town of San José de Gracia

The chlorination systems used in the municipality are rudimentary and receive little maintenance. Only 3 of the 4 storage water deposits were accessible (Figure 10). The fourth storage water deposit for Ojo de Agua well is not pictured because the chlorination system was not accessible as it was locked in a room that is also used to store herbicides, pesticides and fungicides used by the municipality for gardens throughout the town of San José de Gracia. During the visit to the storage water deposit for Milpillas well, the bucket used to feed the chlorine pump was empty suggesting that the water coming out of the well was not being chlorinated at the time. During one of the visits the chlorination system of the main supply line was off because of a lack of chlorine. The workers confirmed that even if they are out of the disinfectant they will run the pumps to supply the town. This brings up the issue of biofilm in the pipe network building up, creating issues with disinfection even when the managers have the appropriate supplies. It should be noted that workers are also being directly exposed to the disinfectant with no safety gear, no policy limiting exposure, and little training.

A. Agua caliente pump station and chlorination site part a.

B. Agua caliente pump station and chlorination site part b.

C. Jarrero well chlorination system part a.

E. Milpillas well chlorination

D. Jarrero well chlorination system part b.

Figure 10 Chlorination sites for water supplies in San Jose de Garcia

Although the municipality is primarily rural, INEGI categorizes Marcos Castellanos as semi-urban because of its 13,031 citizens, more than fifty percent of which are concentrated in one urban area (INEGI, 2010). The largest city in a municipality, San José de Gracia, with a population of 9,537, heads the municipality. The municipality is in the central western region of Mexico, which was a traditional source of Mexicans emigrating to the U.S. between the 1970s and 1990s (Riosmena et al., 2012). The most recent census, conducted by the Mexican authorities in 2010, showed the first increase, in the municipal population since 1995 (10%), presumably caused by the changes in immigration patterns. Although the indigenous speaking population is only 0.2%, the municipality has 8 Ejidial communities (INEGI, 2010). In 2012 INEGI reported that 94% and 98% of households in the municipality have improved sewage and water connections, respectively. In the town of San José de Gracia, water delivery service is limited to a 12-hr period daily, from 6:00 am to 6:00 pm, for most people in the center of the town. For residents in the Northern and Southern developments of the town water delivery is for twelve hour periods every other day.

Over the last decade, the municipality of Marcos Castellanos has experienced urban population growth (INEGI, 2010). While problems related to urban development and poor land management have increased the population potentially affected by water-borne diseases, the town’s water quality monitoring has not improved. There is currently no monitoring of water quality by the municipality. Current disinfection methods of the town’s three wells and a spring are in need of an assessment to determine drinking water quality and the nature of potential threats. Although the WDS is complex, a simplified model could be developed and used to aid municipal managers toward recognizing threats to the delivery of clean, safe potable water.

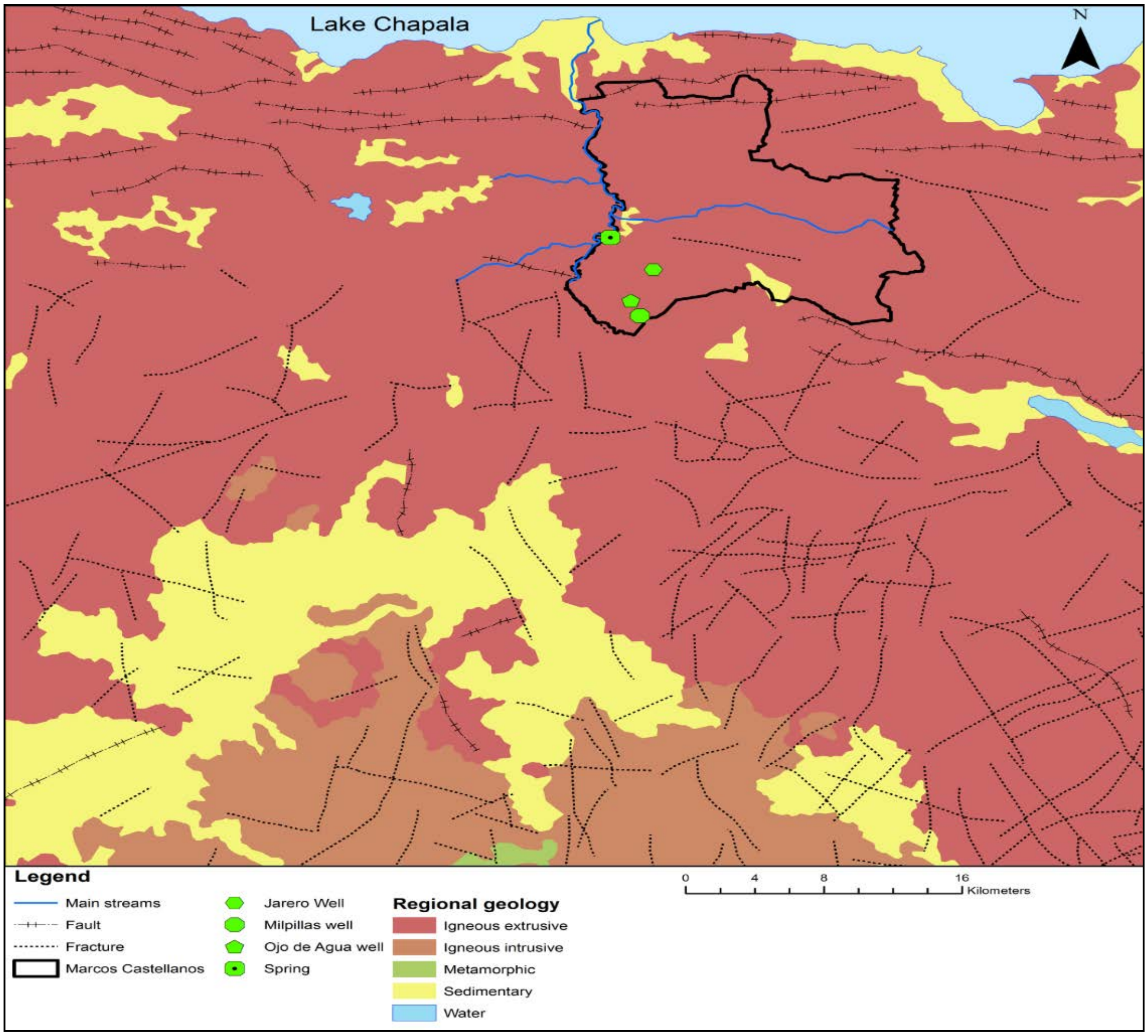

Figure 11 Geology, distribution of wells and spring studied. Data source: own and INEGI

The only geological data available for the municipality and town was very low resolution without much detail (Figure 11). The majority of the municipality comprises of extrusive igneous rocks with two patches of sedimentary rock (Figure 11). There is also a fracture line reported running along the base of an old volcano and some faults at the Northern extent of the municipality. More frequent fracturing can be observed at the south of the region (Figure 11) which is a possible location of a recharge zone for the local aquifers. Faulting can be seen along the edge of the Lake Chapala and some metamorphic rock can be seen on the far South edge, a possible source of natural contaminants to groundwater.

3.2 Modified RADWQ Procedure

In this study both RADWQ and EPANET were used to determine the chlorine concentrations required for the town's water system to provide safe drinking water at household nodes throughout the system. Coliform and chlorine tests were used to verify disinfection at various nodes in the actual system. The secondary objective of this study was to use RADWQ methods to select additional indicators of water quality that the municipality could be testing. Water testing kits were used to test for the indicators determined for recommendation by RADWQ methods.

Possible threats to drinking water quality were identified by using Geographical Information Systems (GIS) by conducting a surface analysis of land use, geology and hydrology. A RADWQ survey was conducted in the Municipality to assess the level of IWRM being implemented and the accuracy of development indicators for the region (Figure 12). The survey included the use of land cover, geological, hydrological, and infrastructure data while provided by the local government was mostly collected by the federal government.

Marcos Castellanos was visited on two occasions, once in 2012 and once in 2013. The first visit in 2012 was an opportunity to get an overview of the water management situation in the town of San José de Gracia and evaluate the general quality of water in the municipality. The second visit focused on taking samples of drinking water in the main town of San José de Gracia. Basic chemical parameters pH and EC were taken, as well as chlorine concentrations. Samples were also tested for total coliform bacteria and *E.coli* using a color changing medium that reacts to glucoronidase and galactosidase. These tests were completed as a way to check on the effectiveness of the water utility providers at maintaining a system compliant with federal law.

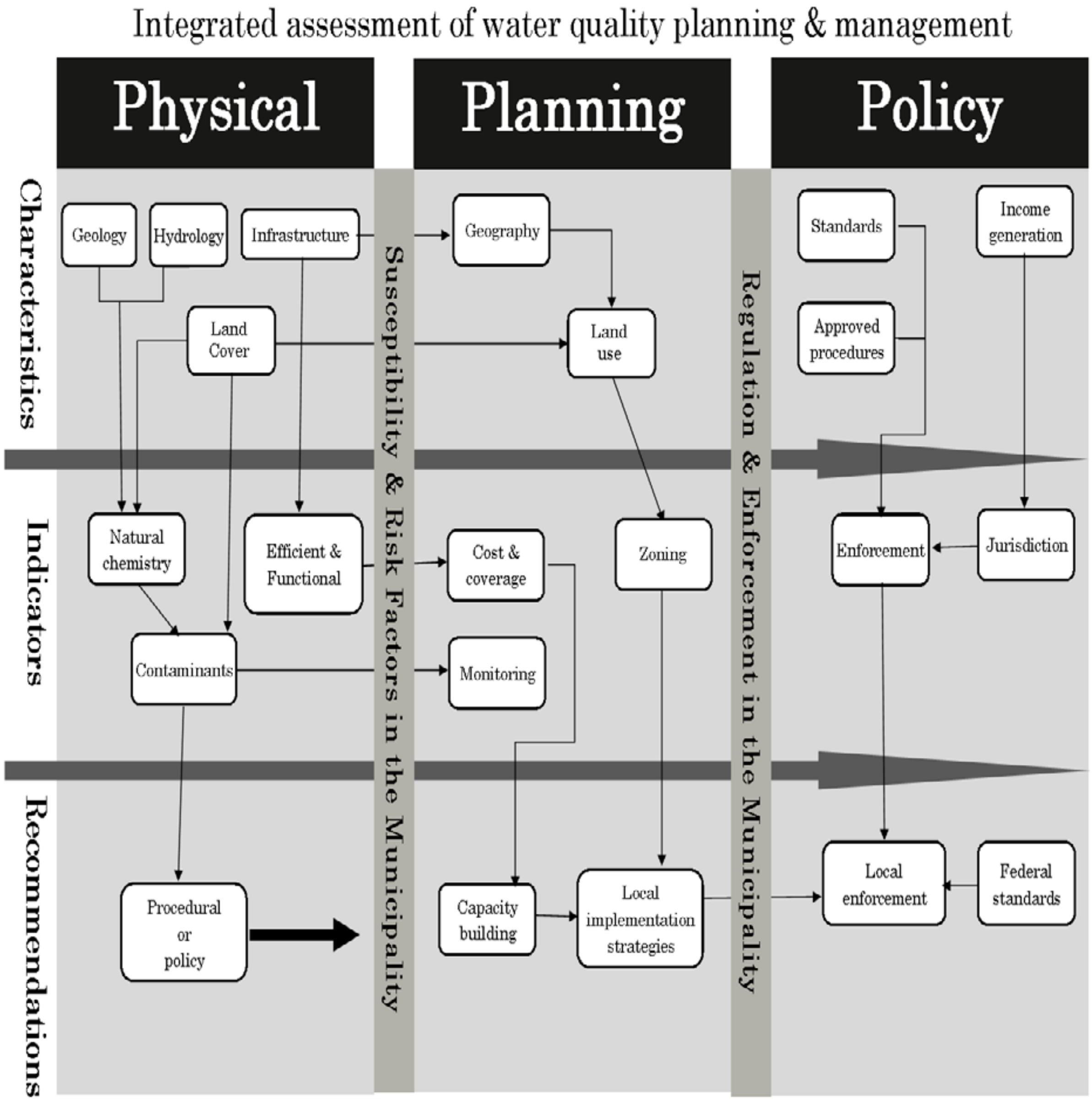

Figure 12 RADWQ procedure followed by this study. Figure adapted from Handbook of Catchment Management (Ferrier et al., 2009)

3.3 Sample Collection and Chemical and Biological Analyses

In 2012, the town's water sources were evaluated using the Watersafe® Well Water Testing Kit (Silver Lake Research Corporation, Monrovia, CA, USA). Using test strips the kits measured concentrations of nitrates/nitrites, hardness, chlorine, copper, iron and the pH of water. The kit also included present/absent tests for lead above 15 ugL^{-1}, trazine/simazine above 3 ugL^{-1} and fecal coliform. Although test strips are not as accurate as laboratory results, they provided an insight into the quality of water being served. As a backup, Sensafe™ heavy metals water testing kit (Sensafe, Rock Hill, SC, USA) was also used to compare with the Watersafe® results for metals. A stop watch was used to standardize strip exposure time.

A Coliscan® Easygel® kit (Micrology Laboratories, Goshen, IN, USA) was used to detect and measure *E.coli*, coliforms and total coliforms present in source water, storage and homeowner faucets. Coliscan kits have been utilized by other researchers and are proven to give reliable results when used properly (Bain et al., 2012; Stepenuck et al., 2011). Here 5 mL of spring water or well water samples or 1 to 5 mL of surface water was added to a Coliscan Easygel bottle and shaken prior to transfer to a petri dish for incubation. Volume of sample added was recorded. A chicken egg incubator (G.Q.F. Manufacturing Co., Savannah, GA, USA; Model: 1602N Thermal Air Hova-Bator) was used to incubate the petri dishes. The incubator was set at 35˚ C and plates were counted for colony forming units (CFU) after a 24 to 48-hr incubation period. The number of purple colonies was recorded as *E. coli*, pink colonies as coliforms and the number of pink plus purple colonies was recorded as total coliforms. To calculate the number of colony forming units per 100 mL, 100 mL was divided by the volume of water used and the resultant number was multiplied by the number of CFUs recorded for each petri dish. One sample was used for each petri dish and no sample replicates were used due to costs.

Twenty-five water samples were collected in 2012 (Figure 13). Overall four samples were taken from surface waters, nine from drinking water sources and storage water deposits and twelve from household faucets.

In 2013, only the drinking water for the town of San José de Gracia, was collected where 26 water samples were collected (Figure 14). Water testing in 2013 was limited to a meter to measure pH/Conductivity/TDS (Hanna Instruments, Woonsocket, RI, USA; Model HI 98129). Total/free chlorine was quantified using a test kit for Cl_2 (range between 0 and 3.4 mg/L) (Hach Company, Loveland, CO, USA; Model CN-70) Coliforms were quantified using Coliscan® Membrane Filter (MF) (Micrology Laboratories, Goshen, IN, USA). Here 100 mL of each water sample collected was vacuum filtered through a 47-mm diameter membrane filter. Two mL of Coliscan Plus solution was added to a sterile pad within a petri dish and the membrane filter was transferred from the filter tower using ascetic techniques (sterile forceps) and placed on the Coliscan Plus impregnated pad. No incubator was necessary for this method. The petri dishes were placed in a warm place and once CFU growth was noted on the membrane filters, a 24-hr period was needed before counting the colonies. Blue CFUs were counted as *E. coli* and red CFU's were counted as coliforms; the sum of the blue and red colonies was recorded as total coliforms. Because 100 mL of sample was used CFUs counted are per 100 mL no data transformation was necessary and concentrations were recorded as CFU/100 mL.

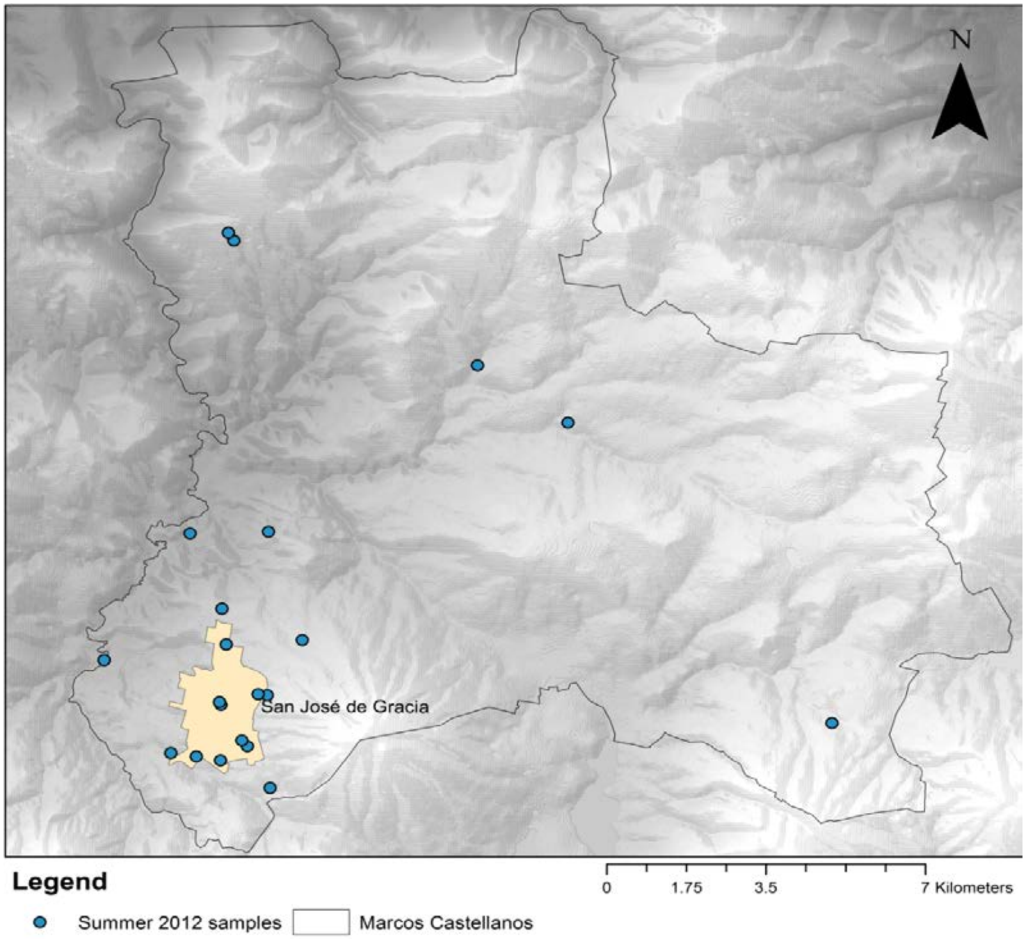

Figure 13 Spatial distribution of water samples collected in 2012

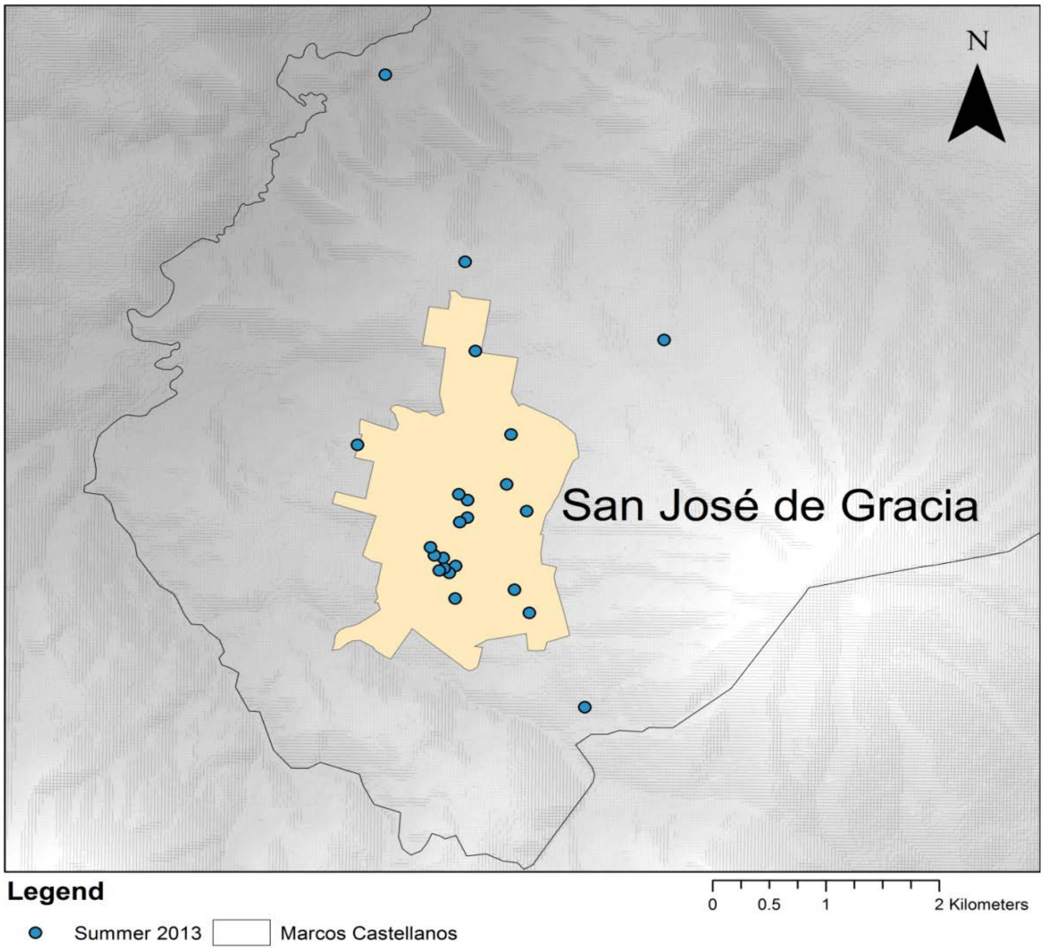

Figure 14 Sample sites in 2013

3.4 Analytical Chemistry

Water samples of 60 mL were collected, to be analyzed for cation (Na^+, K^+, Mg^{2+}, Ca^{2+}), dissolved organic carbon, NO_3-N, NH_4-N and PO_4-P concentrations. Sodium, potassium, magnesium and calcium were quantified by ion chromatography using an Ionpac CS16 analytical and Ionpac CG16 guard column for separation and 20 mM methanesulfonic acid as eluent at a flow rate of 1 mL min^{-1} and injection volume of 10 μL using a Dionex ICS 1000 (Dionex Corp. Sunnyvale, CA, USA). Dissolved organic carbon (DOC) was quantified using high-temperature Pt-catalyzed combustion with a Shimadzu TOC-VCSH (Shimadzu Corp Houston, TX, USA). Dissolved organic carbon was measured as non-purgeable carbon using USEPA method 415.1 which entails acidifying the sample and sparging for 4 min with C-free air. Ammonium-N was analyzed using the phenate hypochlorite method with sodium nitroprusside enhancement (USEPA method 350.1) and nitrate-N was analyzed using Cd–Cu reduction (USEPA method 353.3). Orthophosphate-P was quantified using the ammonium molybdate method. Colorimetric methods were performed with a Smartchem Discrete Analyzer (Model 200 Westco Scientific Instruments Inc., Brookfield, CT, USA). Sample replicates, blanks, NIST traceable and check standards were analyzed every 12th sample to monitor instrument precision.

3.5 EPANET Model

EPANET is a public-domain, water distribution system modeling software application developed by the Water Supply and Water Resources Division at the U.S. Environmental Protection Agency (EPA). EPANET can be used to simulate both water movement and quality behavior within pressurized pipe networks and is equipped to simultaneously model the decay of chlorine residual over time. The version used in this study, EPANET 2, is widely considered the industry standard because of its versatility as a standalone program and as an open-source toolkit. The software performs hydraulic simulation, given inputs of pipe diameter, pipe length, node elevation, constant or temporally varying water demand, constant or variable pump speeds, and head losses. Head losses are computed using the Hazen-Williams formula to account for changes in pressure throughout the system and coefficient values were entered based on parameters given for pipe diameter and material in the town public works department AutoCAD drawing.

The EPANET 2 program's water quality modeling functionality makes it the primary choice for analyzing the movement, spread, and decay of chlorine through the network over time. A global reaction rate coefficient was applied to the system since the precise conditions of each pipe are unknown. Storage tanks were modeled as complete mix reactors. Water-borne constituents were assumed to have no interactions. DOC is important for this model as it can help to calibrate the rate of disinfectant decay.

This study modeled chlorine concentrations in the water distribution system under current and alternative scenarios. In the current scenario, pumps were run on an operational schedule as indicated by the town engineer from 6:00 am to 6:00 pm using an assumed demand pattern (Figure 15). Chlorine concentrations in the model were based on sampled concentrations at sources or storage tank deposits immediately after chlorination. The chlorine concentrations used were; Agua Caliente Spring: 3 mg/L, Jarero well: 3 mg/L, Milpillas well: 2 mg/L and Ojo de Agua well: 2 mg/L. Additional scenarios were run with all initial chlorine concentrations at 3.5 mg/L which is the national maximum concentration of chlorine allowed in Mexico. Three scenarios were chosen, 1) partial supply as is currently pumped, 2) continuous supply, which would be the ideal development concentration and 3) continuous supply with no demand pattern which functions as the control. For each of these pumping scenarios chlorine concentrations in the model were recorded at 6:00 am, 12:00 noon and 5:00 pm using a contour map function in EPANET (see Appendices). Each scenario was then tested under different possible chlorination schedules. Each pumping scenario was run once with measured chlorine concentrations at the point of chlorination with concentrations of 3.5 mg/L and then with a failure to chlorinate at each source and at multiple sources (Table 2). The scenario's run can indicate the vulnerability of the water quality under partial and continuous supply and the impact of having multiple sources of chlorination.

Table 2 Codes for model runs in EPANET. AC=Agua Caliente spring, JR=Jarero well, MP=Milpillas well and ODA=Ojo de Agua well

Symbol	Definition
P	Partial Supply
C	Continuous Supply
N	Continuous Supply, No Demand Pattern (control)
0	Model based on sampled source chlorination: AC-3 mg/L, JR-3 mg/L, MP-2 mg/L, ODA-2 mg/L
1	All sources chlorinated at 3.5 mg/L
2	AC not chlorinated
3	JR not chlorinated
4	ODA not chlorinated
5	MP not chlorinated
6	Only AC, JR chlorinated at 3.5 mg/L; ODA, MP not chlorinated
7	Only JR chlorinated at 3.5 mg/L; AC, ODA, MP not chlorinated
8	Only AC chlorinated at 3.5 mg/L; JR, ODA, MP not chlorinated

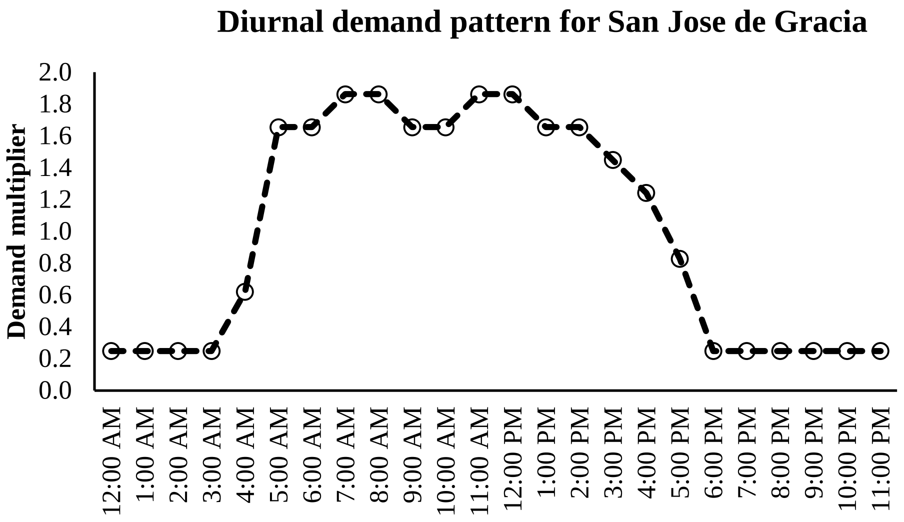

Figure 15 the assumed water demand pattern used in EPANET model

3.5.1 Calculating demand for EPANET model

The architecture of EPANET allows for a pipe network to be modeled at any level network detail, known as skeletonization. The water use data provided by the municipal government was not at the individual user level, because not all users are metered, so demand was calculated by town block (Table 2 and Figure 16). Most of the users were domestic (93%), but not metered (69%). Therefore, the model could not be designed at the individual user level. As a result, the distribution system model did not include pipes sizes smaller than 6.4 cm (Figure 17). In the model, nodes represent junctions in the system that can represent any number of users, their demand, and the elevation of the point. The elevation of the nodes was calculated using a function in ArcMap to extract the elevation value from a digital elevation model (DEM) and add it to a point file. Daily water demand was calculated using the average yearly demand for metered users with twelve months of consumption data. In 2012 there were 1,247 metered users, of those only 882 had all twelve months of water use data recorded (Table 3). The median volume of water consumed by these users was 195 m^3 /yr. Assuming that all water users (4,665; Table 3) had an annual median water use of 195 m^3 the total water use for 2012 was calculated as 909,675 m^3.

Table 3 Classes of water users in San José de Gracia. Data source: town records

Type	Number of contracts	Percent of all users (%)
Metered non-domestic	129	2.8
Metered domestic	1,118	24
Non-metered domestic	3,220	69
Non-metered non-domestic	103	2
Public	95	2
Total 2012 users	4,665	

Table 4 Median water use in m^3 per year from contracts with 12 months of data in 2012

Type of use	Metered with 12 months data in 2012		
	Number of contracts	2012 median	Daily median
Domestic	816	184	0.5
Non-domestic	66	611.5	1.7
Total	882	195	0.5

Town blocks with one lot were assumed to be non-domestic and assigned the median daily commercial consumption of 1.68 m^3 /day (Table 4). This resulted in 62 non-domestic town blocks, leaving 326 city blocks; the remaining town blocks were assigned the median daily water consumption of 0.53 m^3 per lot, the combined median (Table 4). It was decided to use 0.53 m^3, the median for all metered users with 12 months of data, because doing a weighted distribution (Equation 10) proved to be unnecessary, as the total number of non-domestic users was very low and would have produced an average median consumption per block close to 0.53 m^3 anyway if all non-domestic users were evenly distributed among all town blocks. If town blocks with more than one lot were assigned a weighted consumption value it would be calculated as shown in Equation 9 and 10.

$$\overline{ND} = \frac{ND}{NB} \qquad \text{Eq.9}$$

$$\widetilde{x_{lot}} = \frac{(N_{lots} - \overline{ND}) * \widetilde{x_d} + \overline{ND} * \widetilde{x_{nd}}}{N_{lots}} \text{ Eq.10}$$

Where $\overline{ND}$ is the average number of non-domestic user per block, ND is number of non-domestic users, NB is number of blocks, N_{lots} represents the number of lots, $\widetilde{x_d}$ is the median domestic consumption, and $\widetilde{x_{nd}}$ is median non-domestic consumption. The water consumption by town block was generated from using the number of lots in the block as a multiplier for the daily demand median of all users (Figure 16).

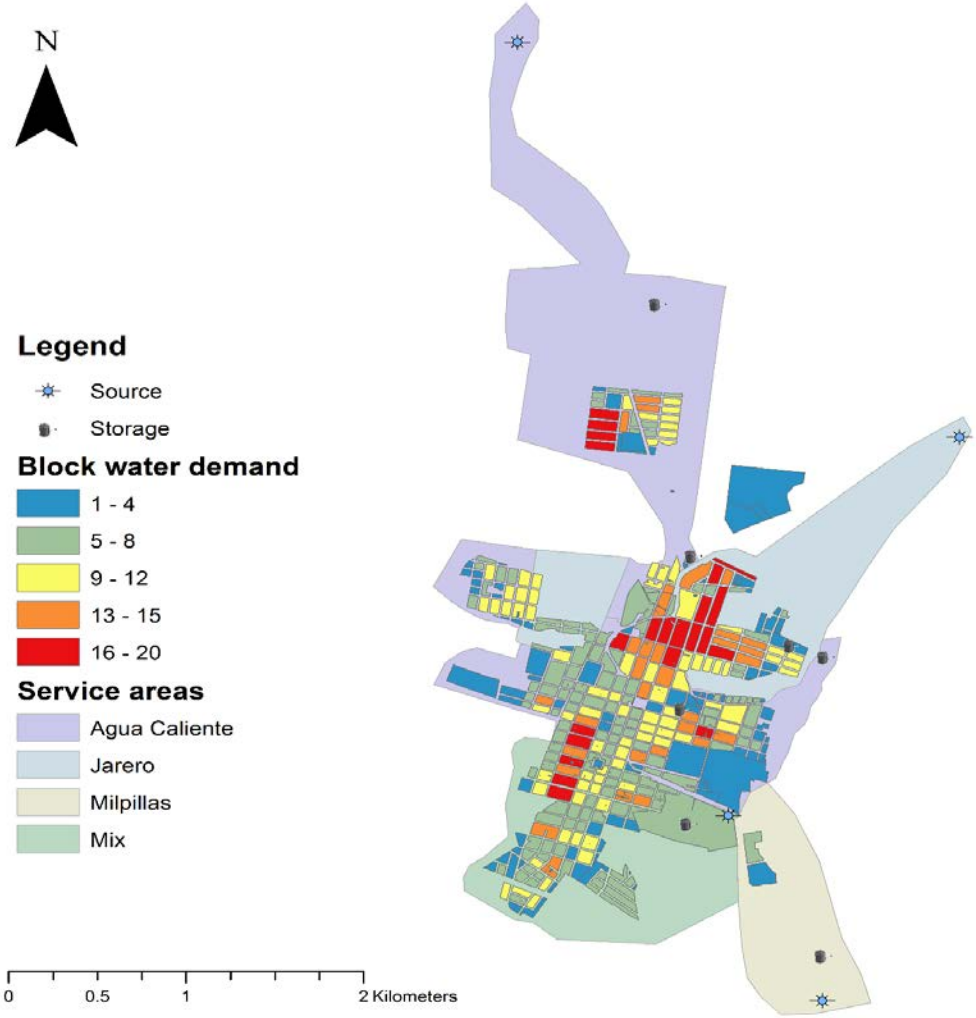

Figure 16 Estimated block demand used in EPANET model for San José de Gracia

3.5.2 Chlorine decay

The median concentration of DOC in the water samples taken in 2013 was 17.9 mg/L with a range of 14.6 to 20.0 mg/L (Figure 17). DOC was used to calculate decay instead of the TOC value required by EPANET because it was highly unlikely that particulate organic carbon (POC) was present in the source water samples taken from groundwater sources. The chlorine decay in the system was calculated for each source of water (Equation 4; Ahn 2012). In this equation C_0 is the initial chlorine concentration, and K_b (day^{-1}) is the decay rate. A decay rate for each of the water sources was calculated (Table 5). The Milpillas well and Agua Caliente spring had the highest decay rates. This was expected because the spring is effectively a surface water source complete with various aquatic fauna living in it and the area around the well is used for dairy farming. It should be noted that the water managers do not currently consider this when attempting to disinfect the water.

Table 5 Bulk decay rates used in EPANET model for each of the sources

Source	C_0 mg/L	TOC	T (°C)	K_b (day^{-1})
Spring	3.5	18.5	21.7	1.0
Jarerro	3	14.6	24.7	0.9
Milpillas	2	18.7	24.8	1.2
Ojo de Agua	2	15.1	24.5	1.0
Median	2.5	17.9	24.6	1.1

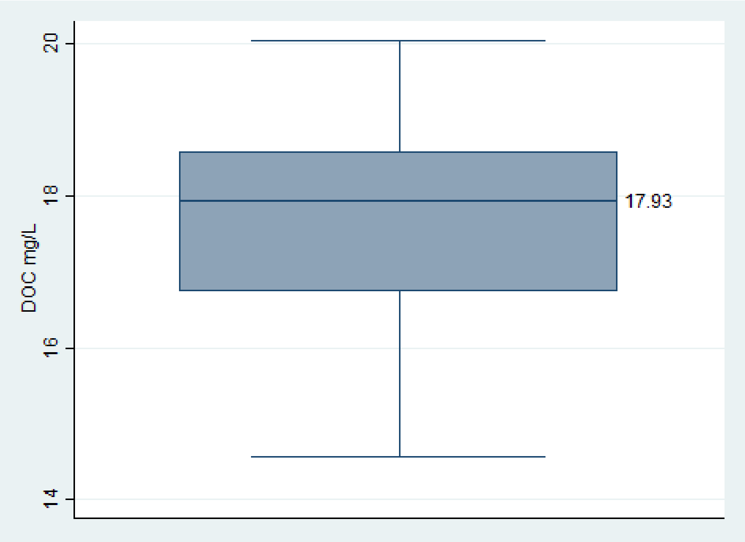

Figure 17 Box and whisker plot of DOC N=25

3.6 Statistical Analyses

This study was designed to provide a preliminary description of the water system in a small Mexican town. The level of IWRM implemented in the municipality was observed and qualitatively measured through RADWQ methods. Quantitative measurements of IWRM are in the form of water quality analysis. The funding was not available for enough testing to delve deeply into an inferential analysis. The majority of the data was used to describe water quality parameters that can give the municipality a basic idea of the main threats to water quality. Inferences were made about the potential source of groundwater based on geologic maps and water chemistry. Regression analysis was completed to determine the ability of free chlorine to predict the presence of coliform bacteria in the town of San José de Gracia.

For this study the population was defined as the number of contracts the water utility has (4,665 registered users). The target population for sampling was broken down into service areas. These areas were defined by the water distribution system. The town has four distinct drinking water sources, which are distributed to three individual delivery areas and one mixed zone. Non-probability samples were taken from each of the four water supply service areas. The samples were purposefully selected based on accessibility, and location within each of the four water supply service areas. Although this is not the ideal method of sampling, as sampling biases may occur, this was a preliminary study to determine the implications of water quality data for development in Mexico. In addition to descriptive statistics to get an idea of the variance generated by the methods and the quality of water, some inferential statistics, regression models, ANOVA, and one-tailed T-tests were conducted. Regression analyses were conducted for chlorine and coliform, as well as coliform and location of the sample within the distribution system. The location of the sample within the distribution systems is a choice of 1) source (well or spring), 2) deposit (water storage) or 3) household faucet. Two-sample 2-tailed t-tests were conducted on the results from EPANET to test if the operational and chlorination scenarios resulted in a significantly different number of nodes having safe levels of chlorine.

4. RESULTS

4.1 RADWQ Evaluation

The town of San José de Gracia utilizes surface water derived from a nearby spring in combination with three wells. Groundwater is the major source for drinking water at this location. While there has been no formal evaluation of the town's groundwater source, I concluded that based on water chemistry and its location in the middle of the Trans-Mexican Volcanic Belt (TMVB) and known basaltic deposits in the region, that the groundwater sources are likely a basaltic aquifer. Further support of a basaltic aquifer can be inferred from the shallow nature of the town's wells, averaging 130 m, since the average thickness of basalt deposits in the region are far greater, although the possibility of a shallow deposit of alluvial material below a thin section of basalt sourcing the water is still plausible. A sample of what appeared to be scoria was collected from a location near the Agua Caliente spring (Figure 18). The spring was at a low elevation and is near a stream that could have eroded the land near the scoria deposit, exposing the porous rock which can be a groundwater reservoir. The designation by INEGI of the region as having high to medium porosity is plausible considering the scoria deposits and lava flows which can have high degrees of fracturing that allow for infiltration. Although fractures were not specifically identified for this research, lava flows were observed (Figure 19) and INEGI geological data shows a fracture cutting through the municipality (Figure 11). Since the geological data from INEGI is very low resolution, more fractures could be present but not identified.

Only one well was found in relatively natural land cover. None of the water sources had a perimeter that is protected, as is recommended by the US EPA. None of the obvious, known, recharge areas, fractures or faults are protected with land use policies that could mitigate contamination of the aquifer. Most of the watershed studied was in use for agricultural purposes (Figure 20) such as growing crops for human or animal consumption, grazing of cattle, or urban development. Furthermore, the watershed had a long history of deforestation. Exposed soil profiles were also observed, leading to assumed problems of erosion and poor crop yields. Additionally, none of the towns or communities in the area treated their waste water to any degree. When asked, none of the workers in the water company knew the name of the aquifer, or had knowledge about where the water was coming from.

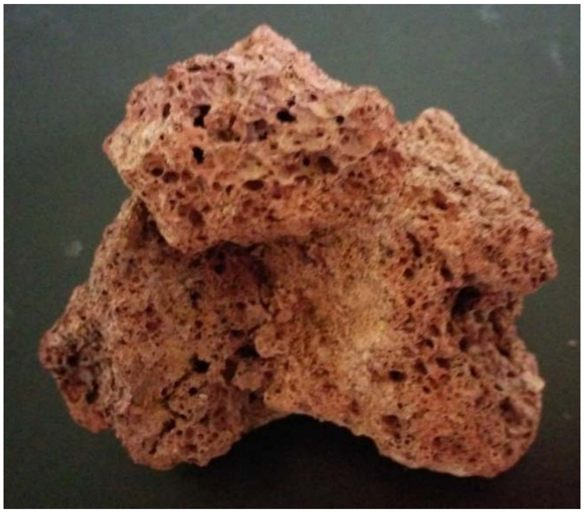

Figure 18 Sample of collected scoria

Figure 19 Exposed lava flows in the municipality

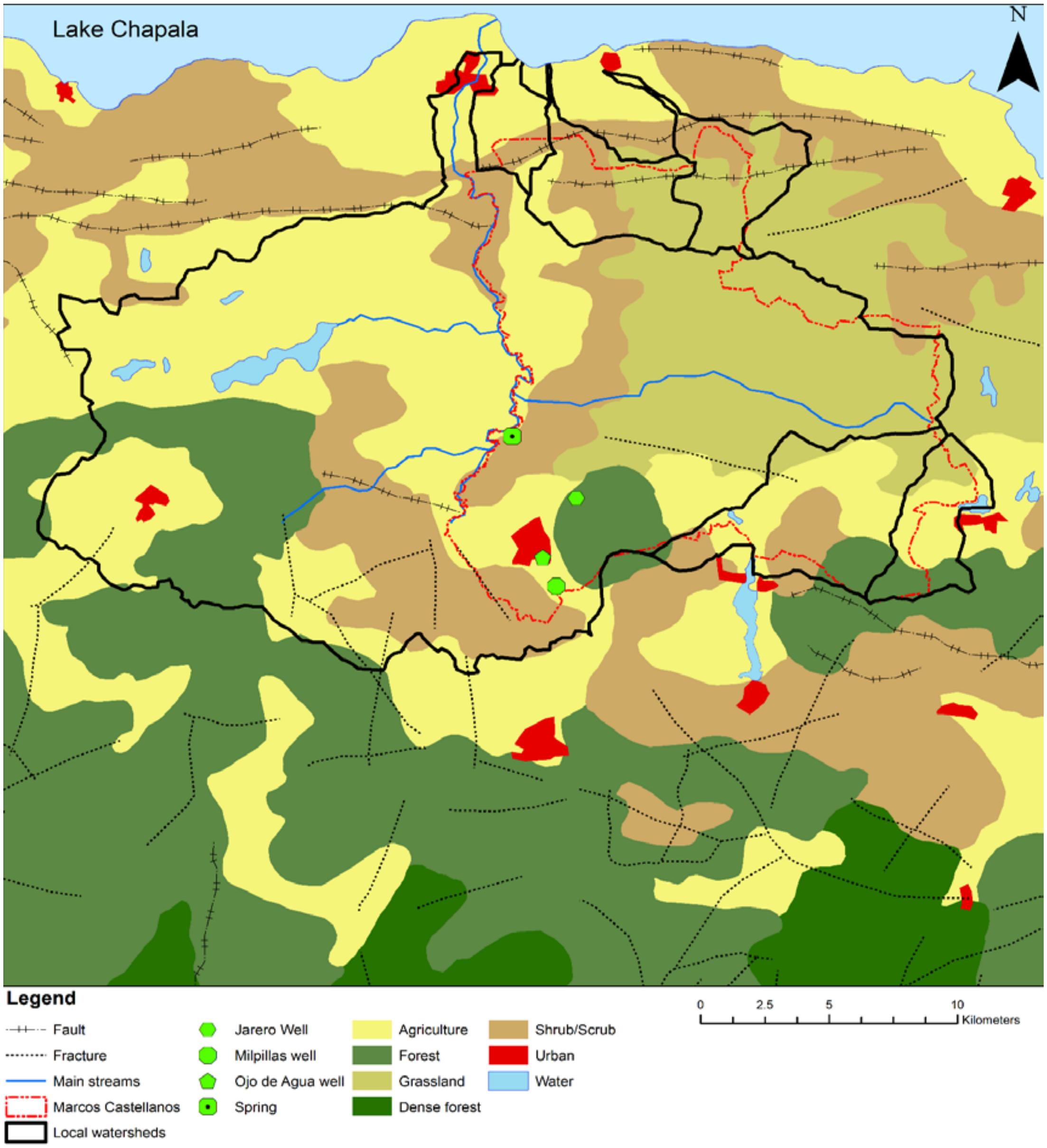

Figure 20 Land use and geological features around the Rio de la Passion watershed

4.2 Water Quality Results from Test Kits

Test kit results were recorded at source water, storage deposits and household faucets (Tables 6 and 7).

4.2.1 **pH and electrical conductivity**

The pH and conductivity of the samples were found to be within normal parameters (Table 6), and consistent with a basaltic aquifer (Table 7). The median pH was 8.2 with a standard deviation of 0.3 (Table 6). pH tended to increase from the water source to the storage deposits and household faucets and the pH of water in household faucets had a larger range (Figure 21). There appeared to be no distinct pattern of high or low pH in the town (Figure 22). Electrical conductivity had a median of 221 µS/cm and a standard deviation of 11.1 µS/cm (Table 6). EC concentrations were less variable in the water sources compared to the storage deposits or household faucets (Figure 23).

Table 6 Summary of water quality indicators. †Test kits used

Variable	n	Mean	Std. Dev.	Minimum	1st Quartile	Median	3rd Quartile	Maximum
†pH	38	8.14	0.29	7.25	8.01	8.2	8.33	8.63
†Temperature (F°)	38	71.57	4.37	67.50	69.00	69.35	71.90	83.40
†EC (µS/cm)	26	220.65	11.08	207.00	213.00	219.00	224.00	251.00
†TDS (mg/L)	26	110.12	5.61	102.88	105.88	108.88	112.87	124.86
Na$^+$ (mg/L)	6	18.66	2.81	16.02	17.63	17.90	18.34	24.15
K$^+$ (mg/L)	6	5.54	1.43	3.76	4.42	5.58	6.71	7.21
Mg^{2+} (mg/L)	6	8.18	1.72	6.31	6.67	7.97	9.21	10.94
Ca^{2+} (mg/L)	6	5.07	1.22	3.54	4.34	4.85	5.82	7.03
Cations (meq/L)	6	0.39	0.15	0.28	0.29	0.32	0.55	0.61
NO_3-N (mg/L)	6	0.39	0.15	0.28	0.29	0.32	0.55	0.61
DOC (mg/L)	25	17.58	1.49	14.56	16.73	17.93	18.57	20.04
NH_4-N (mg/L)	25	0.43	0.43	0.17	0.21	0.24	0.58	2.26
†Total coliform (CFU/100 mL)	37	46.57	101.64	0	0	1	33.33	466.62
†*E. coli* (CFU/100 mL)	37	8.89	24.58	0	0	0	1.00	112.00
†Other coliform (CFU/100 mL)	37	37.67	87.99	0	0	1	8.00	433.29
†Total Cl_2	37	0.65	0.97	0	0	0	1.000	3.40
†Free Cl_2	25	0.37	0.72	0	0	0	0.4	3.20

Table 7 Analysis of water chemistry as it relates to sources of groundwater

Reliability check	Formula	Agua Caliente	Jarero	Milpillas	Ojo de Agua	Confirm
TDS mg/L (actual)	<500 Silicate weathering	108	103	117	106	Yes
Conductivity (µS/cm) (actual)		216	207	233	212	
TDS is Approximate	Conductivity * 0.66	143	137	154	140	No
EC is Approximate	∑ cations (meq/L) * 100	161	196	219	194	Yes
TDS & conductivity	TDS/conductivity = Approx. 0.55-0.76	0.5	0.5	0.5	0.5	Yes
Cations and conductivity	conductivity/∑ meq cations = Approx. 100	134	105	106	109	Yes
Source water: Silicate weathering: >0.5 = Ferromagnesian minerals <5 = Granitic weathering	$Mg^{2+}Ca^{2+}Mg^{2+}$	0.76	0.70	0.64	0.78	Yes

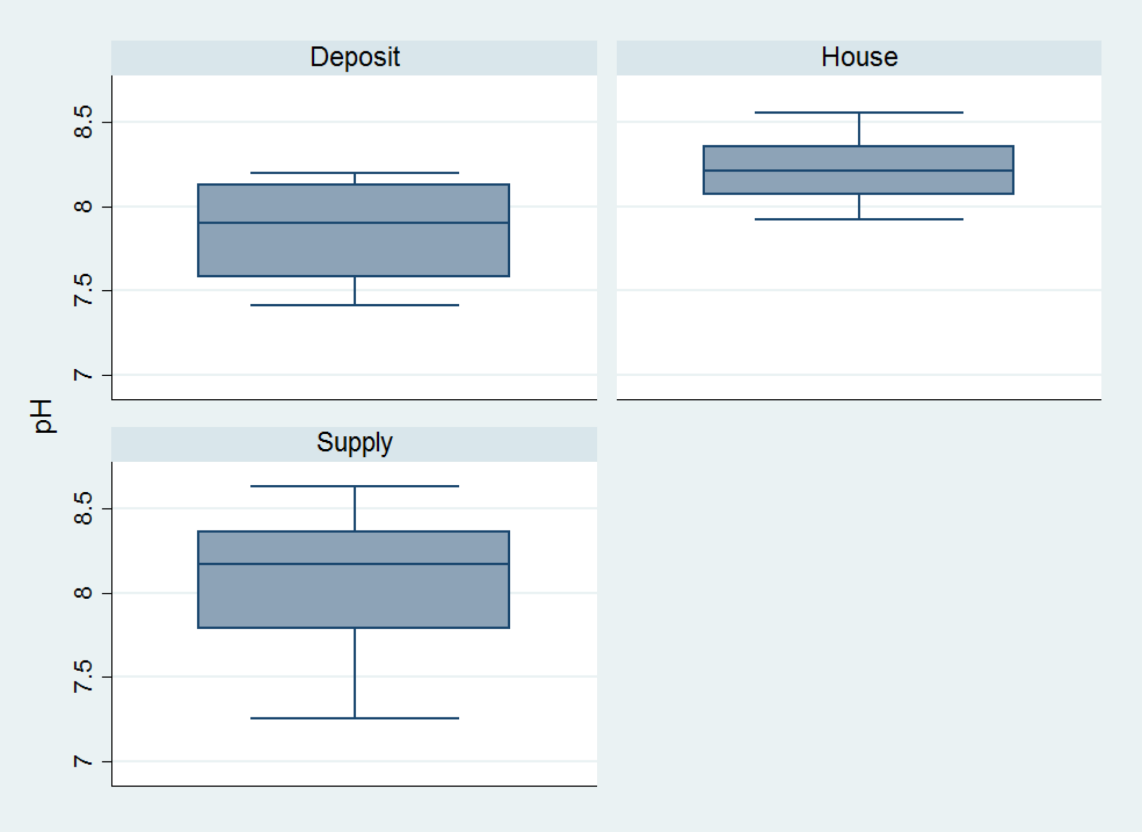

Figure 21 Box and whisker plots of pH in water samples. N=38

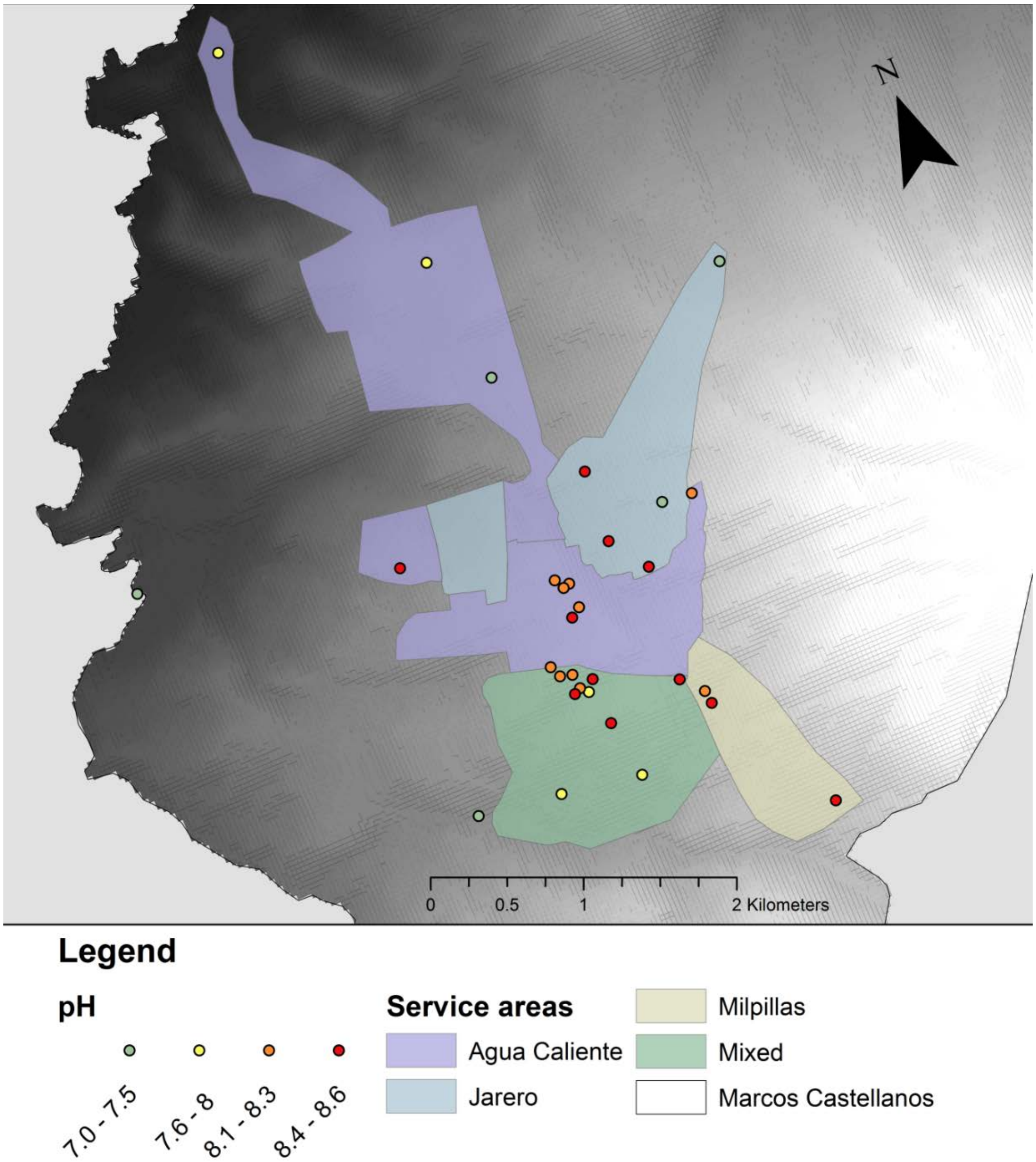

Figure 22. Spatial distribution of pH in water samples

Figure 22 Box and whisker plots of electrical conductivity (EC) in water samples. N=26

4.2.2 Total dissolved solids

Total dissolved solids (TDS) were measured using the Hanna meter. The median TDS measured was 108.88 mg/L with a standard deviation of 5.61 mg/L. The results were consistent with a hard rock aquifer (Table 7).

4.2.3 Pesticides

There were 18 samples tested for pesticides using the Watersafe® Well Water Testing Kit in 2012. Of those all but two tested positive for atrazine/triazines above EPA determined MCL of 3 ppb (Figure 23). Problems with bringing samples of a large prevented inclusion of laboratory results on exact concentrations of atrazine. Local authorities are aware however, that such pesticides are in use in the municipality. Since the recharge zone for the local aquifer may be at a distance there was no way of knowing if pesticides are being directly applied on recharge zones.

4.2.4 Metals

None of the samples collected tested positive for heavy metals, including lead, copper or iron.

4.2.5 Total coliform, *E. coli* and other coliform

Average total coliforms were 46.57±101.64 cfu/100 mL. Average E. coli was 8.9±24.6 cfu/100 mL (Table 6). A sample of results collected can be seen in Figure 24. Coliform and chlorine varied greatly between sample sites, indicative of a chlorination system that is not stable (Figure 25). Of the 37 samples tested over the two visits 60% of them failed to meet drinking water standards of 0 CFU/100 mL for total coliform. Almost 30% of the samples collected were found to contain *E.coli*. Only one sample, taken from the Milpillas well, tested positive for Pseudonomas spp. Some of colony forming units were so high that enumeration in the field was difficult when recommended sample volumes were used (Figure 26). These samples had to be diluted and reincubated so that a count could be made with confidence.

The highest coliform count in the town came from a house serviced by the Agua caliente spring, but overall results were very mixed (Figures 27, 28, and 29). Areas closest to the chlorination sites tended to have lower counts of coliforms and areas that are known to have mixed sources of water had both low and high counts at close proximities indicative of a very heterogeneous system. Overall areas sourced by water from the Jarero well, the best protected source, had the lowest coliform counts. Water sources had the highest median number of coliform colonies followed by storage deposits while samples from household faucets had the lowest median number of coliform colonies; but also had several outliers of very high counts (Figures 28 and 29). The results of coliform counts supported the notion that drinking water is being treated, as colonies decreased as they approached consumers, although it is not being treated to the extent that the water is safe. All of the storage tanks tested negative for coliform (Figure 28), with the exception of a pre-chlorination sample from a storage tank holding water from the Agua Caliente spring.

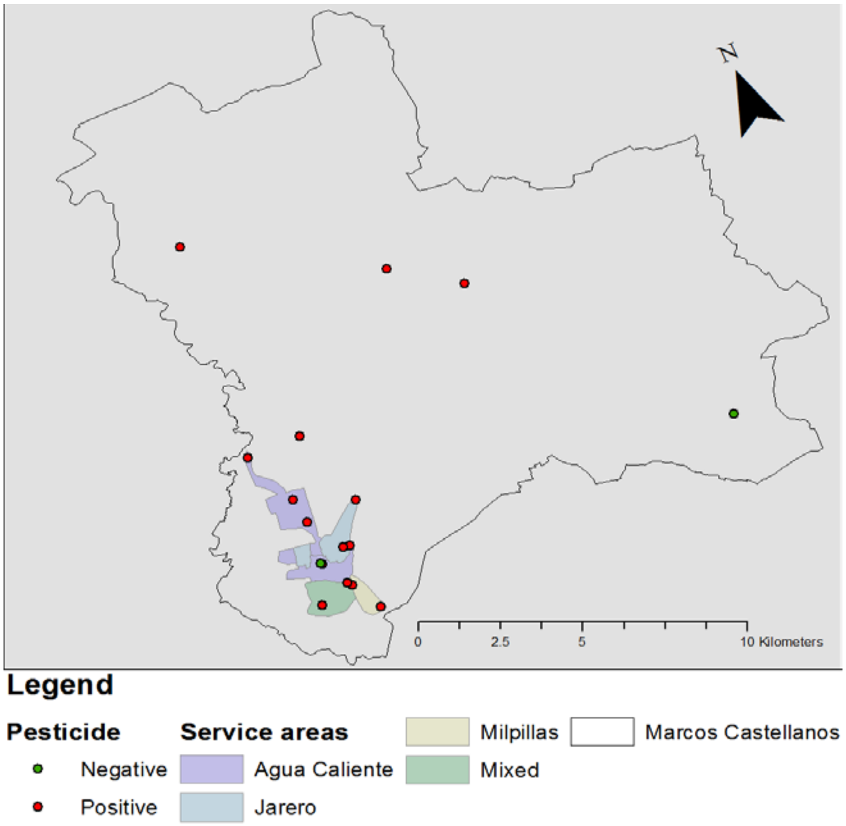

Figure 23 Spatial Distribution of pesticides tested

Figure 24 Sample of coliform tests on samples and control.

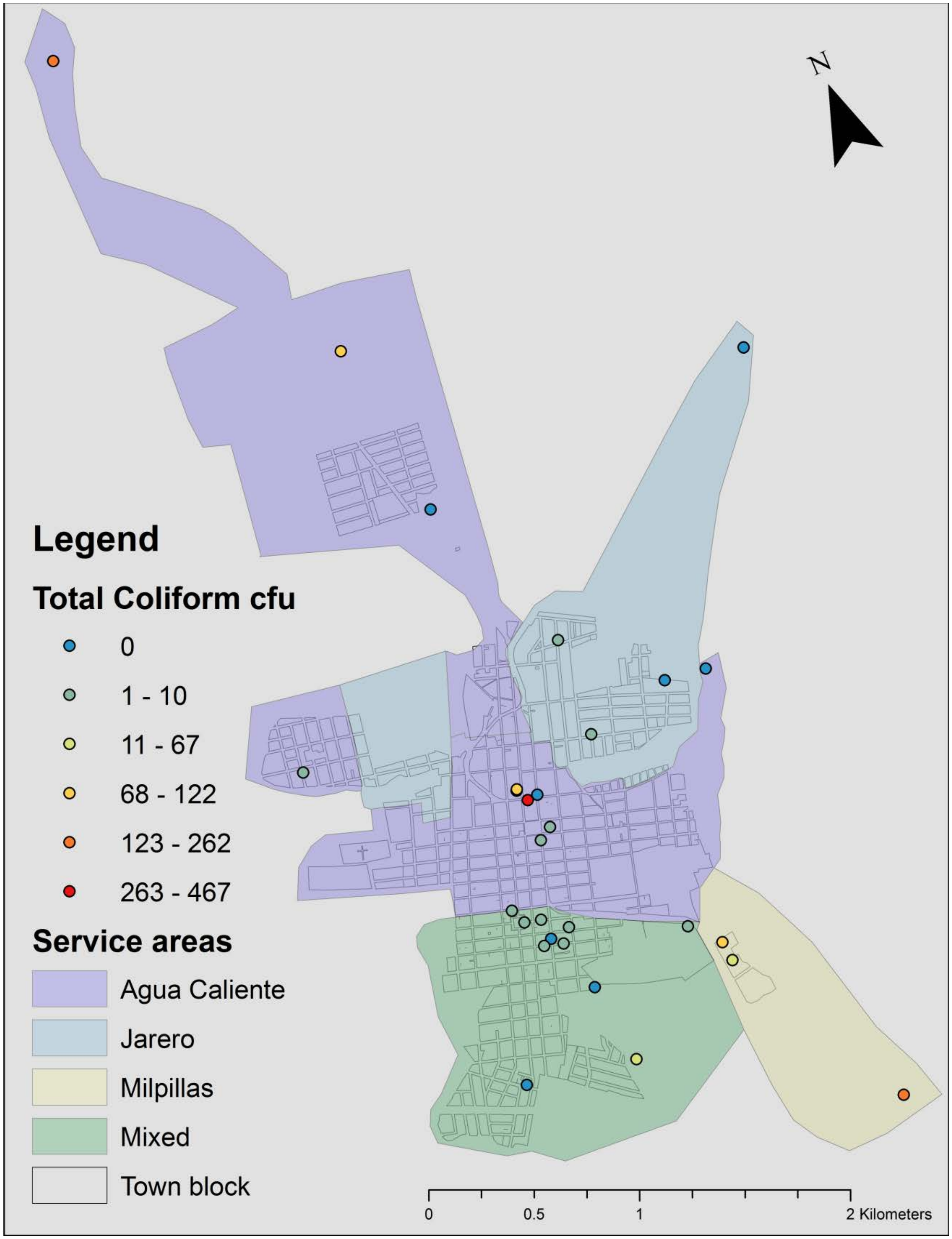

Figure 25 Spatial distribution of coliform in drinking water samples

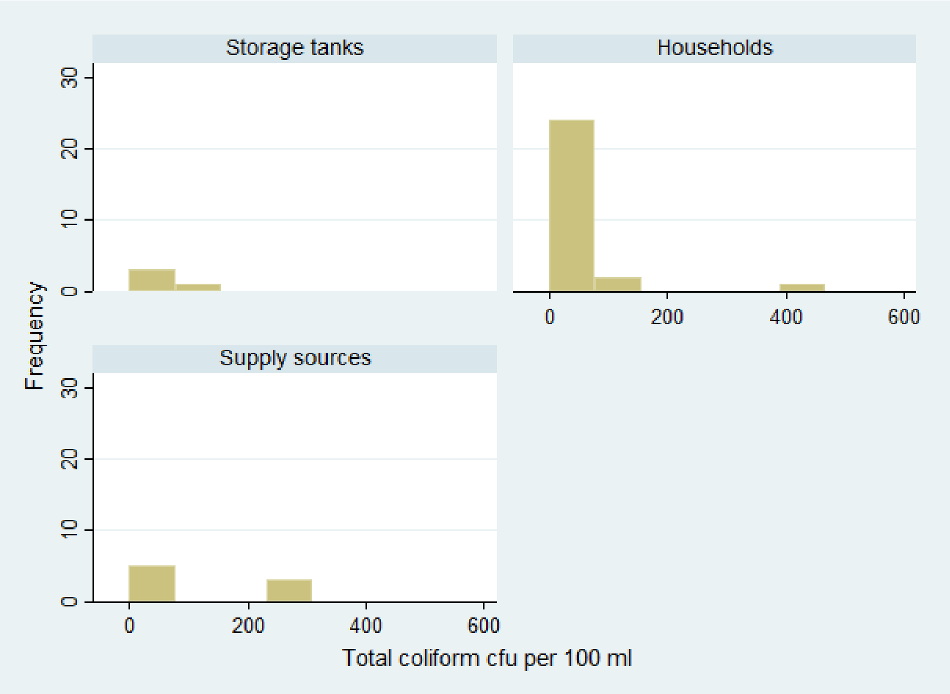

Figure 26 Histogram of coliform counts by sample type. N=37

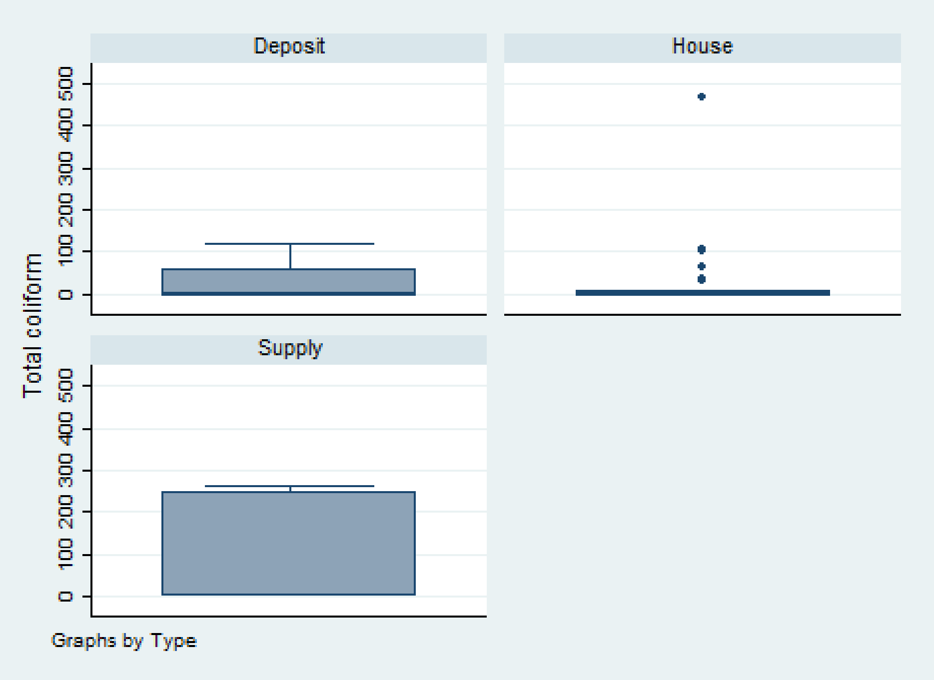

Figure 27 Box and whisker plots of coliforms in water samples. N=37

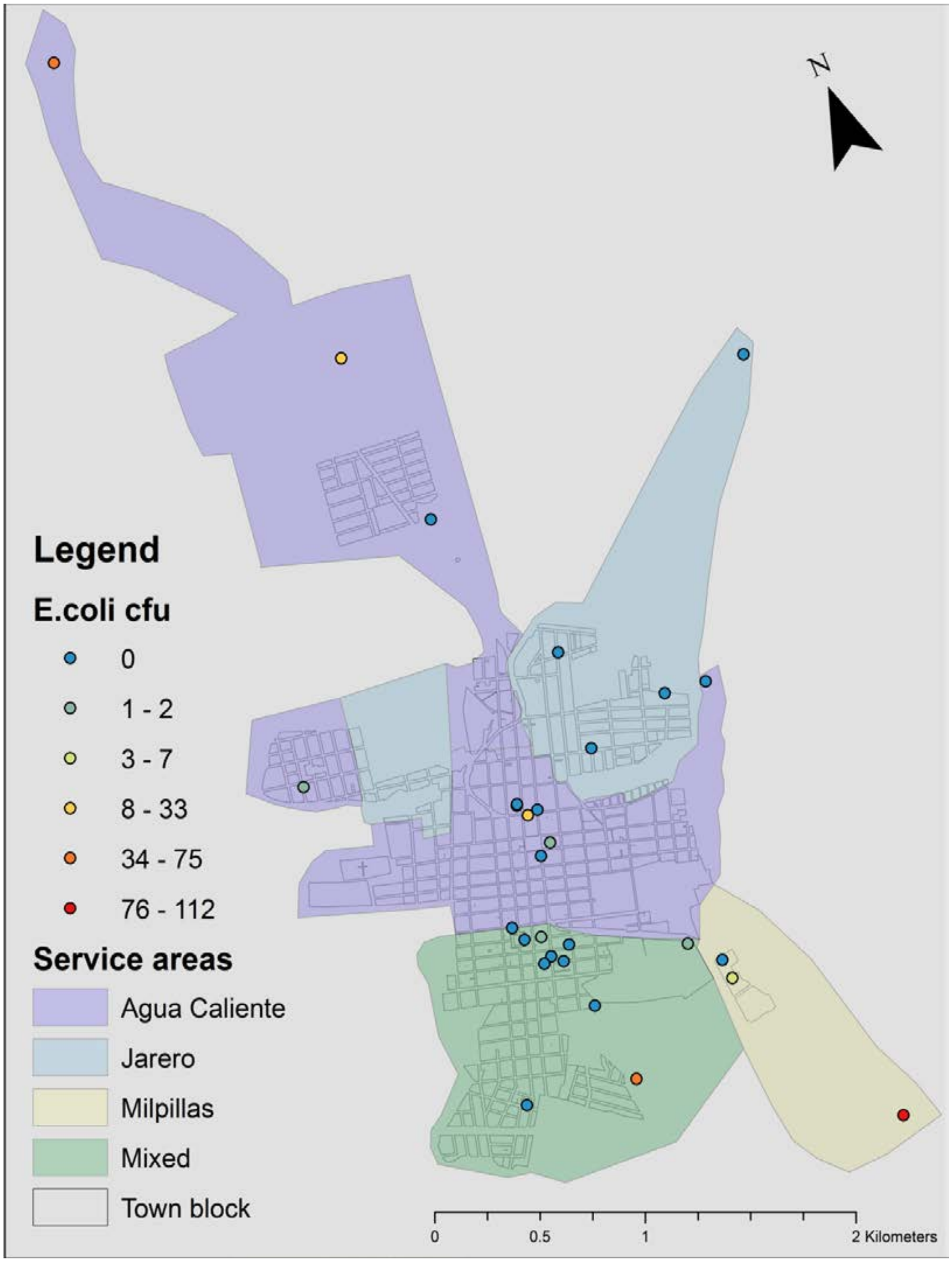

Figure 28 Spatial distribution of *E.coli* detected in samples

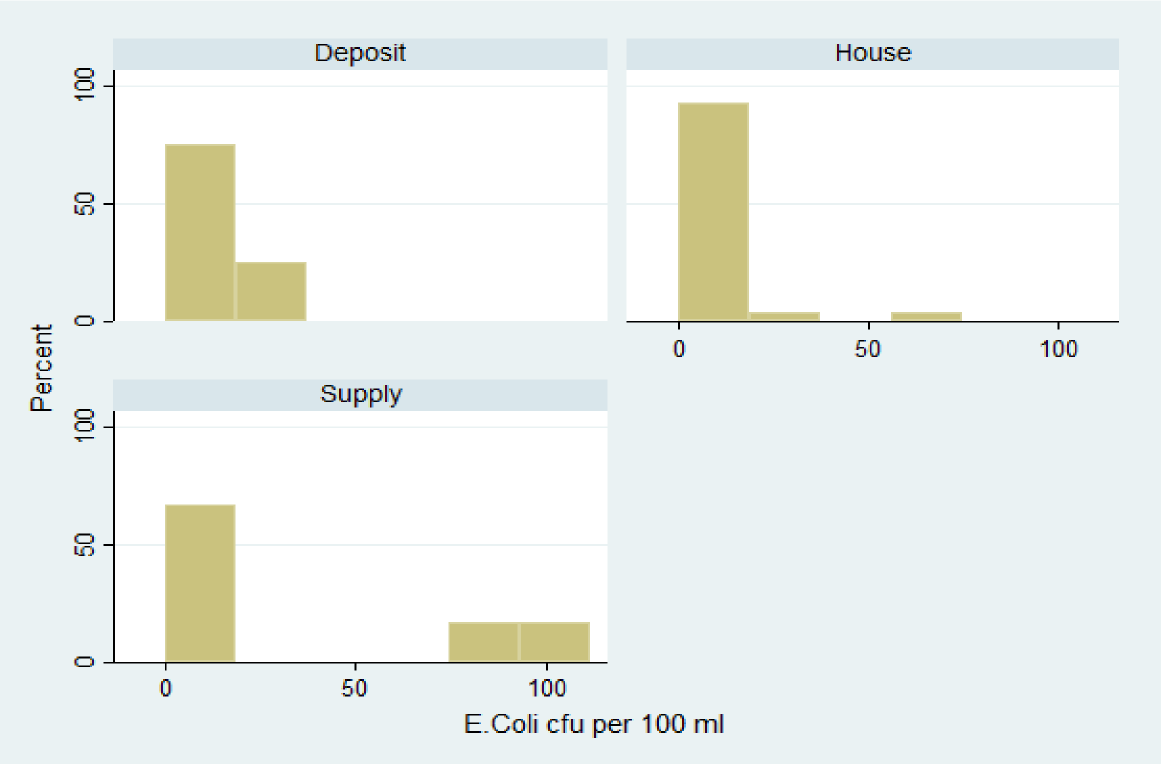

Figure 29 Frequency of *E.coli* by sample source N=37

A similar pattern to that of coliforms was observed with *E.coli*. None of the samples coming from the area supplied by the Jarero well had evidence of *E.coli*, but the Agua Caliente spring, Milpillas well and the mixed zone all high *E.coli* counts of between 76 and 112 CFU/100 mL (Figure 30). It should be noted that samples from storage deposits were primarily taken from the deposits holding water from Agua Caliente spring. Out of the four storage deposits visited three samples were from the spring and one from the Jarero well. Overall the presence of chlorine was a good predictor against the presence of coliform bacteria (Figure 31). All of the storage deposits tested negative for *E.coli,* with the exception of one pre-chlorination sample from a deposit holding water from the Agua Caliente spring. In the household faucet samples 22% had *E.coli*, compared to 50% of samples from source waters indicative that water may be re-contaminated in the distribution system (Figure 33). When there is free chlorine in the system the presence of coliform bacteria is zero and although the relationship shows an exponential decay function the relationship was not significant.

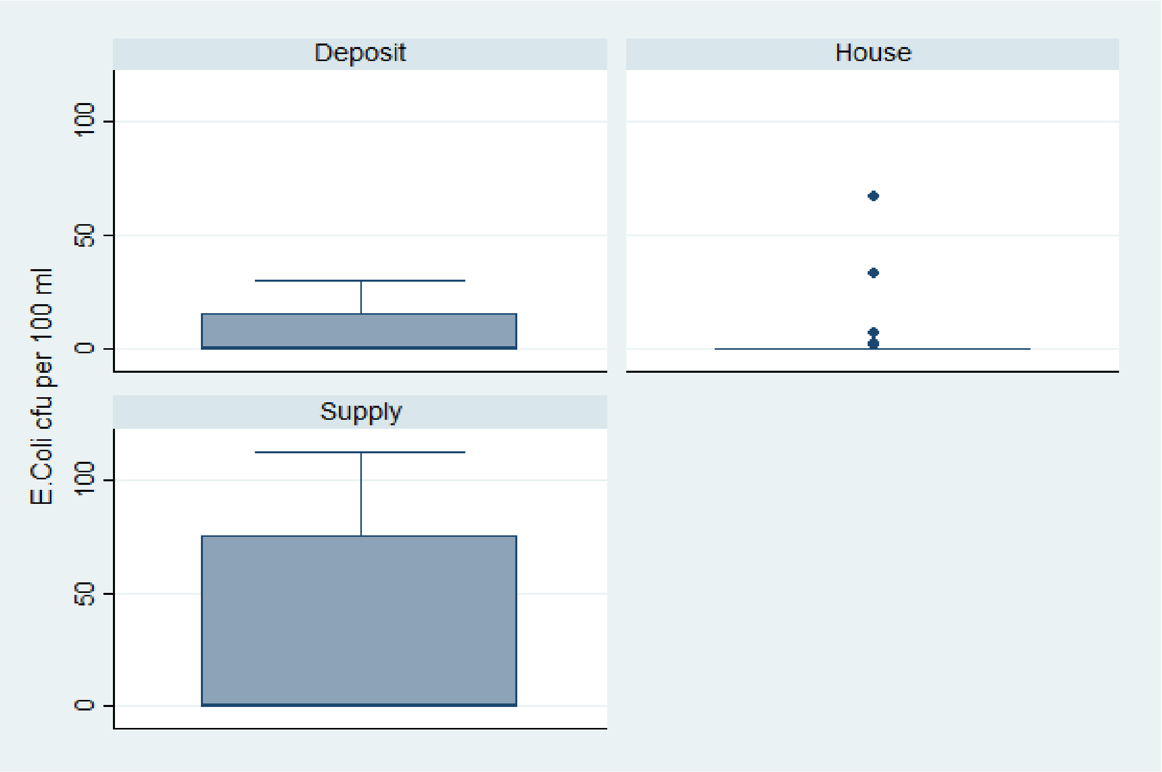

Figure 30 Box and whisker plots of E. coli in water samples. N=38

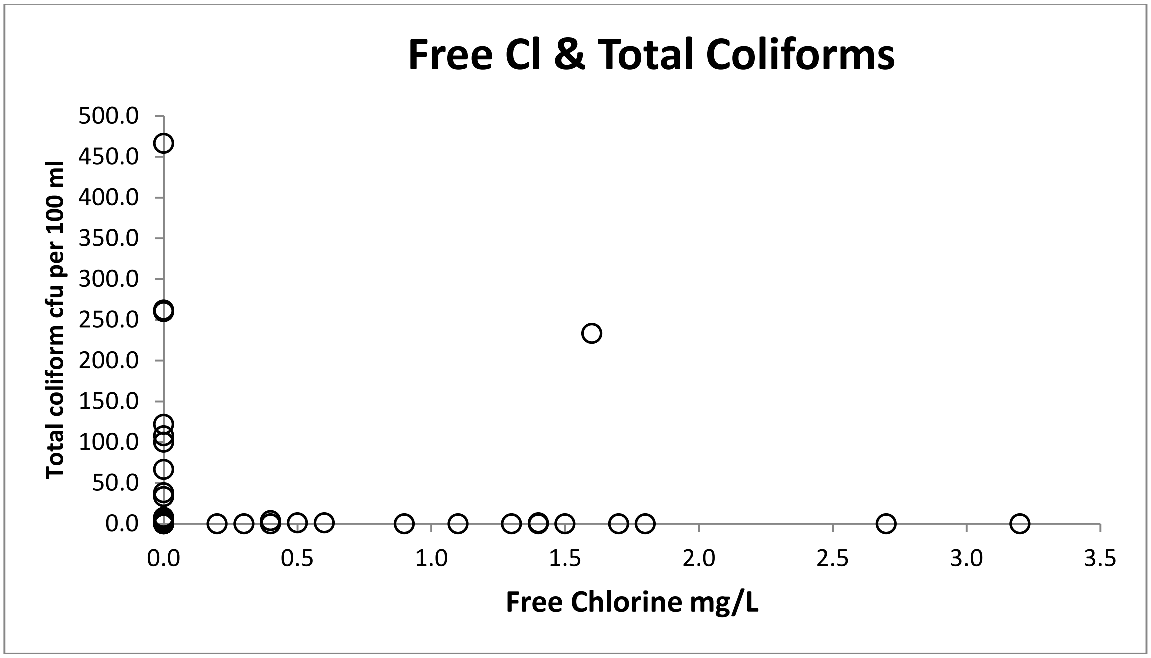

Figure 31 Scatter plot relating chlorine and total coliforms in water samples

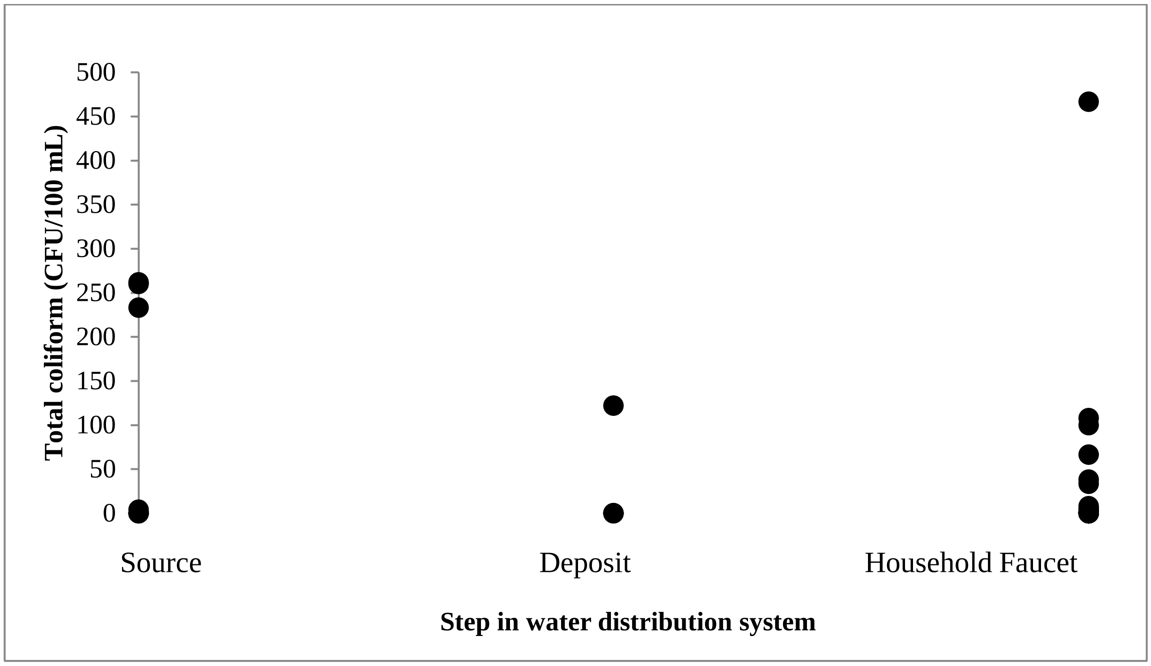

Figure 32 Total coliforms throughout the drinking water delivery system

4.2.6 **Chlorine**

Mean total chlorine was 0.7±1.0 mg/L and free chlorine was 0.4±0.7 mg/L (Table 6). During the second visit in 2013 there was a higher percentage of recorded zero concentrations of chlorine in the samples taken (Figure 33). Sixty percent of all samples taken from both years had no detectable concentrations of free chlorine, and 57% had no detectable concentrations of total chlorine. The spatial distribution of total and free chlorine was very irregular (Figures 34 and 35). Samples were collected in the afternoons, as it is at this time of day that chlorination should be highest because sources would have been receiving chlorine for a longer period of time. The highest concentrations of chlorine were closest to the chlorination sites. The lack of chlorine in water samples was also reflected in the number of samples that had coliform bacteria, nearly 62% in 2013 but only 45% in 2012.

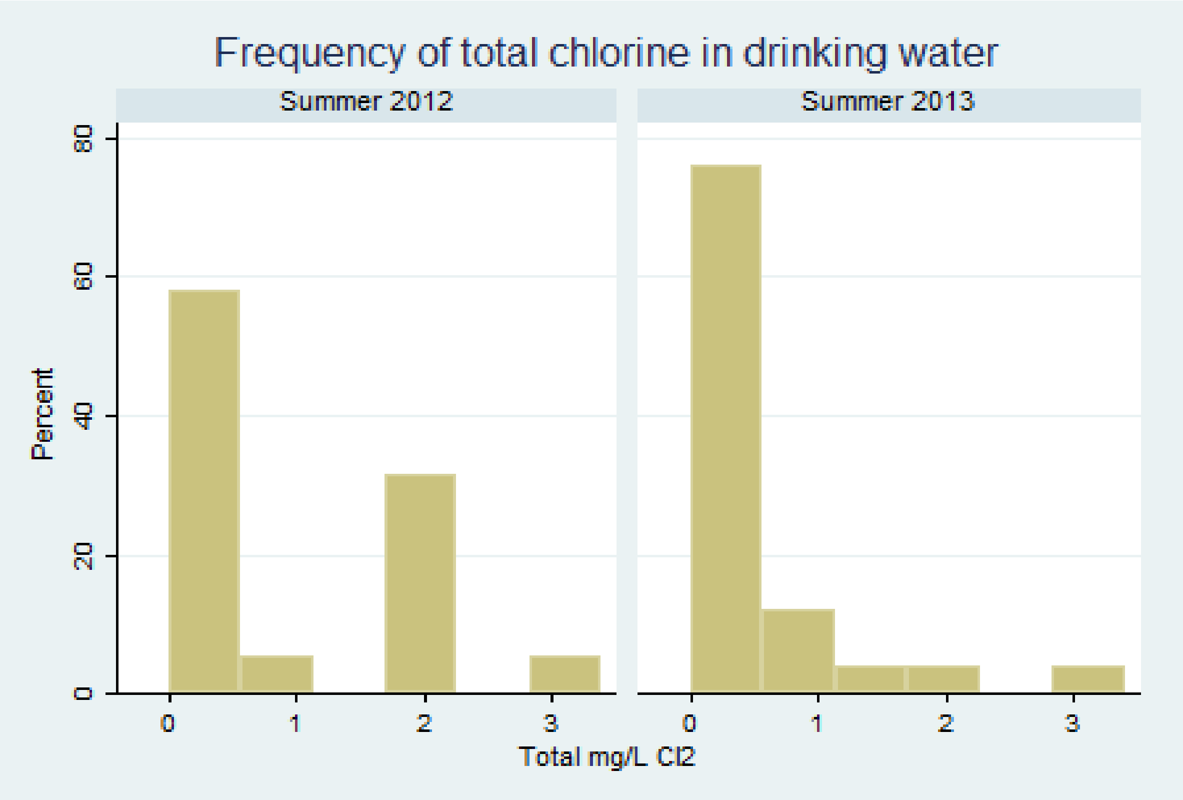

Figure 33 Frequency of Cl concentrations in drinking water by year N=37

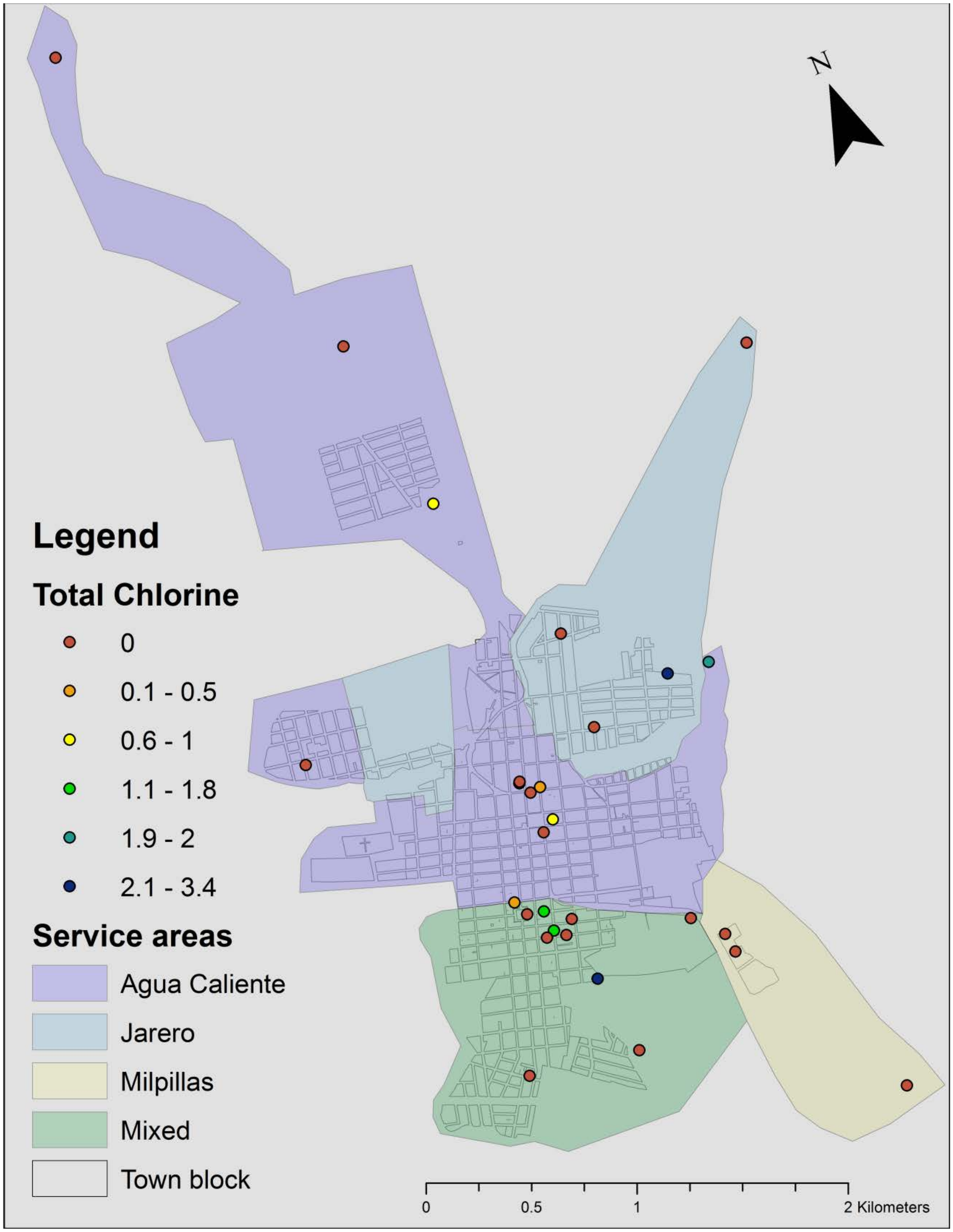

Figure 34 Spatial distribution of total chlorine

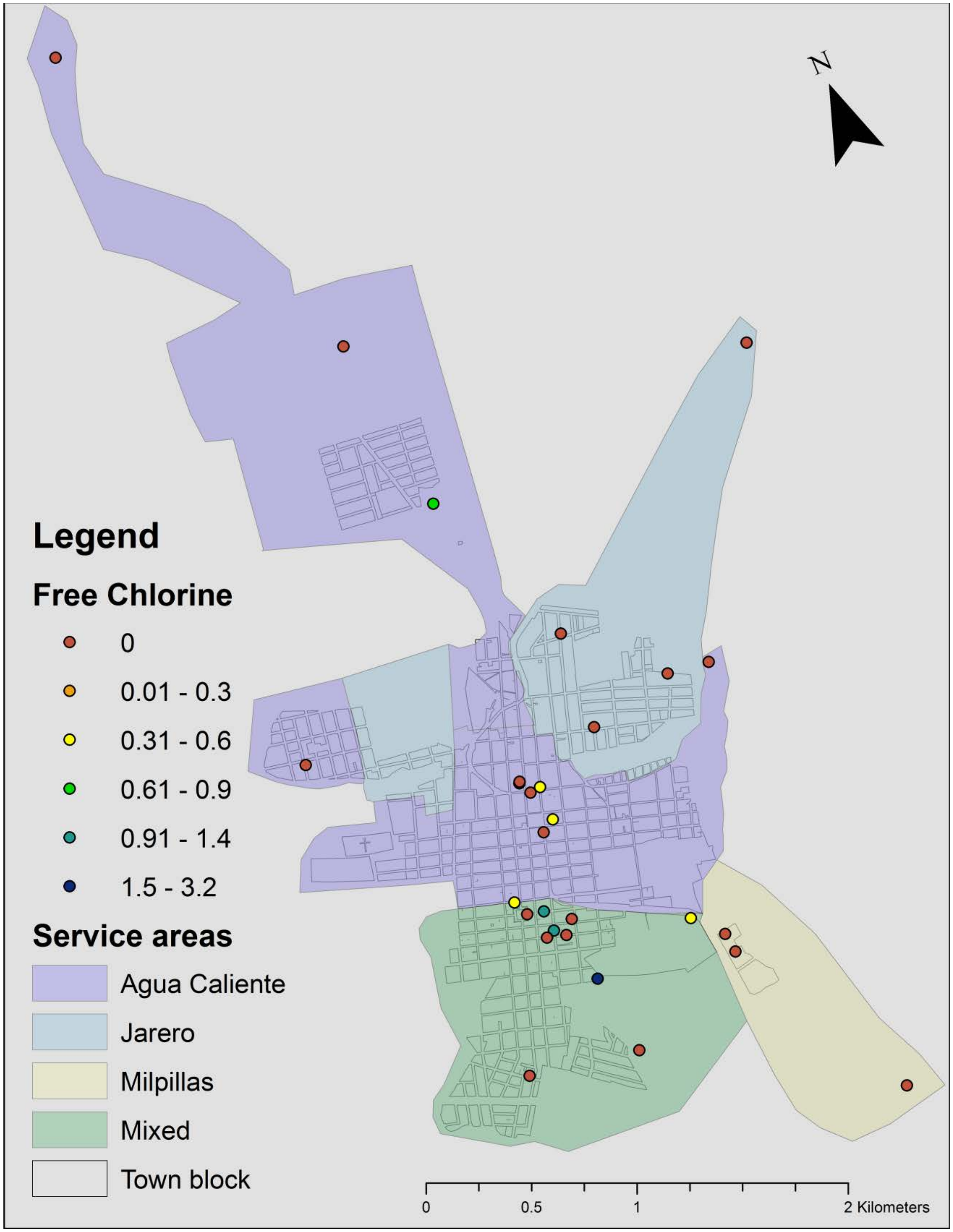

Figure 35 Spatial distribution of free chlorine

4.3 Analytical Chemistry

Below are the results of chemical analyses performed on water samples.

4.3.1 **Dissolved organic carbon**

Dissolved organic carbon concentrations ranged from 14.6 to 20.0 mg/L (Tables 6 and 8). Sample supply was short and so the surface waters Rio de la Passion and Southern creek did not have DOC analysis (Table 8). The spatial distribution of measured DOC can be found on Figure 36.

4.3.2 **Nitrate-N**

Nitrate-N concentrations ranged from 0.3 to 0.6 mg/L with a mean concentration of 0.4±0.2 (Table 6). Highest concentrations were observed in the water sources and by the time water reached storage concentrations tended to be around 0.3 mg/L with little variability (Figure 37 and 38). Nitrate-N concentrations were highest in the surface water collections 1.7 and 4.6 mg/L for the Rio de Passion and Southern Creek, respectively (Table 8).

4.3.3 **Ammonium-N**

Ammonium-N concentrations ranged from 0.17 to 2.26 mg/L with a mean sand standard deviation of 0.43±0.43 mg/L (Table 6). One sample taken from a household faucet had a concentration of 2.3 mg/L (Figure 39). Ammonium-N concentrations were highest in a surface water sample collected from the Southern Creek which was 7.2 mg/L (Table 8) indicative of raw sewage. Figure 40 shows the spatial distribution of Ammonium-N concentrations.

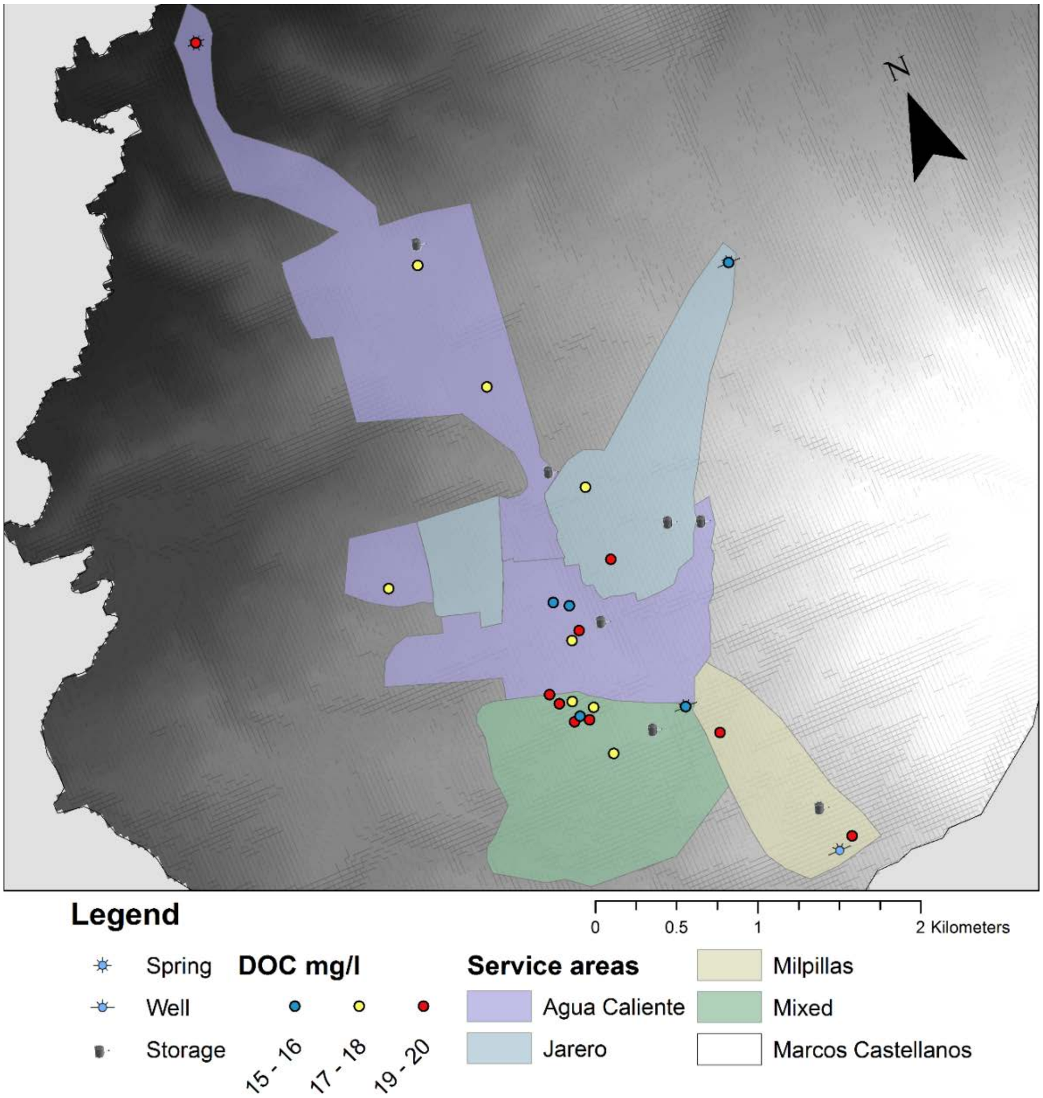

Figure 36 Spatial distribution of DOC N = 25

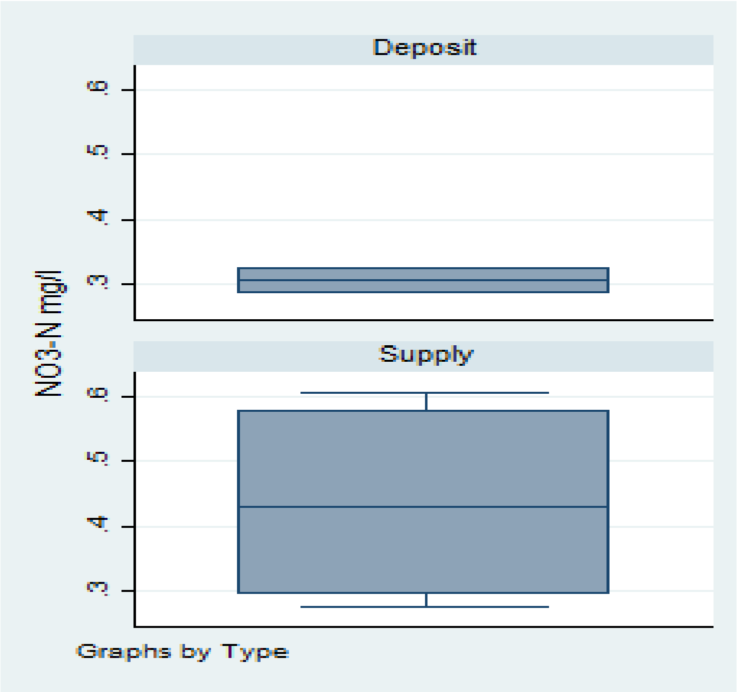

Figure 37 Box and whisker plots of nitrate-N in water sources and storage (deposit). N=12

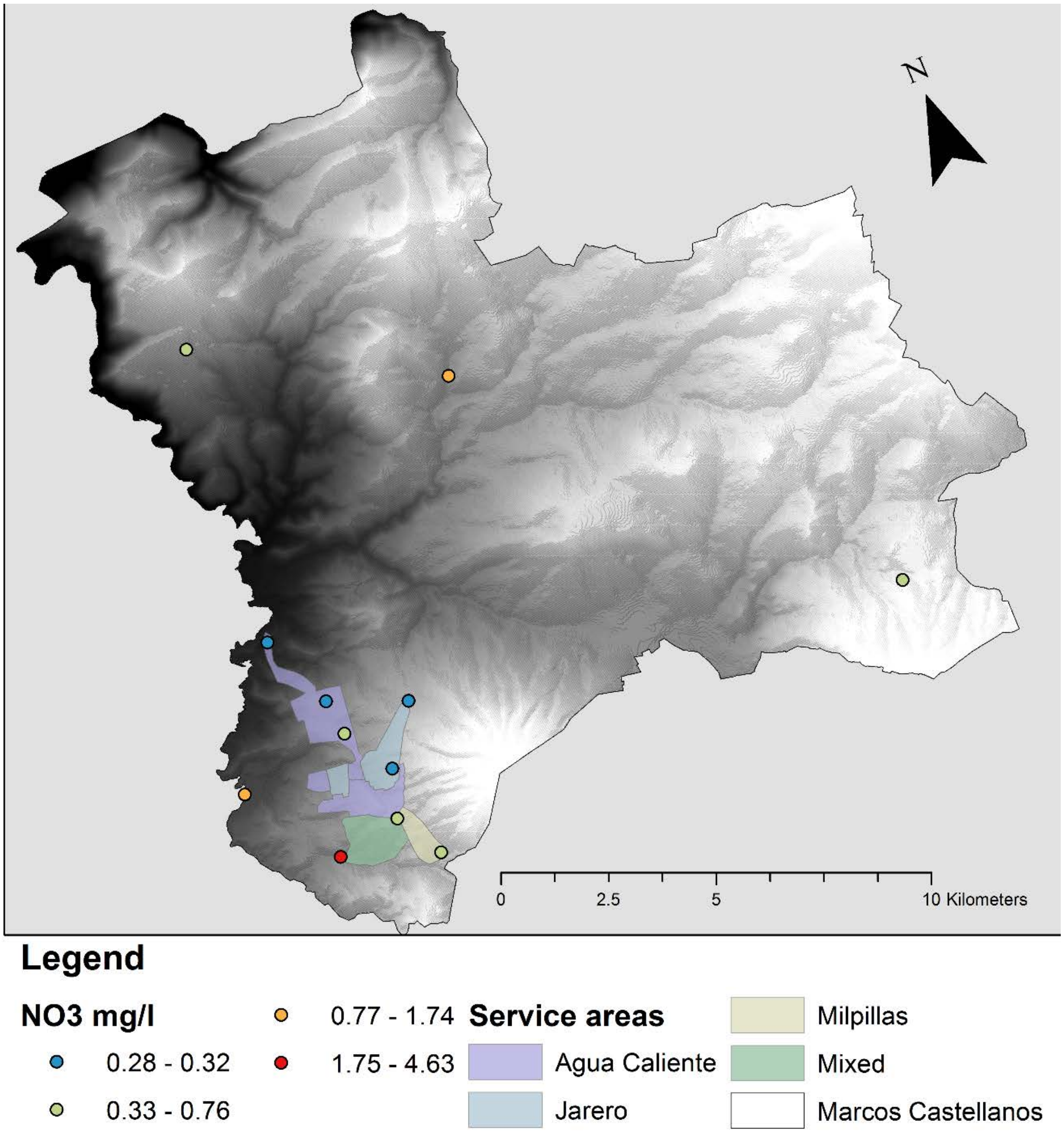

Figure 38 Spatial distribution of NO_3 measured in samples N = 12

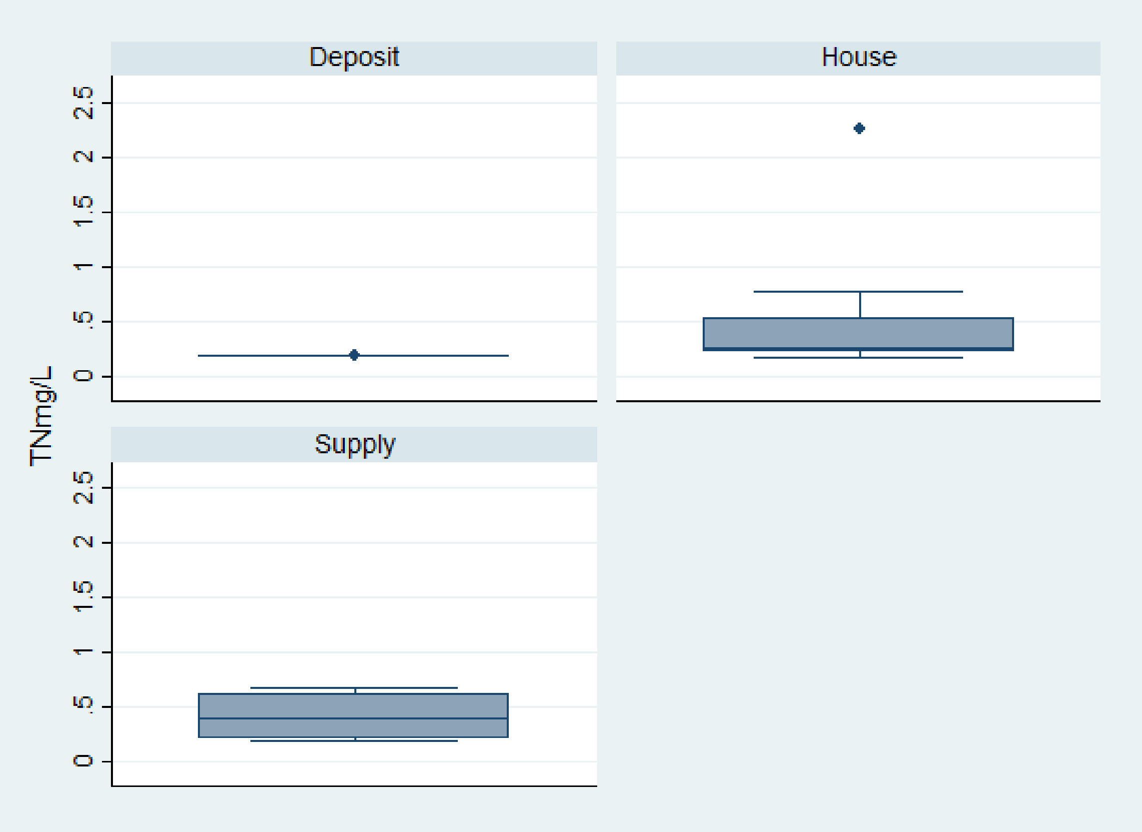

Figure 39 Box and whisker plots of NH_4-N in water samples. N = 25

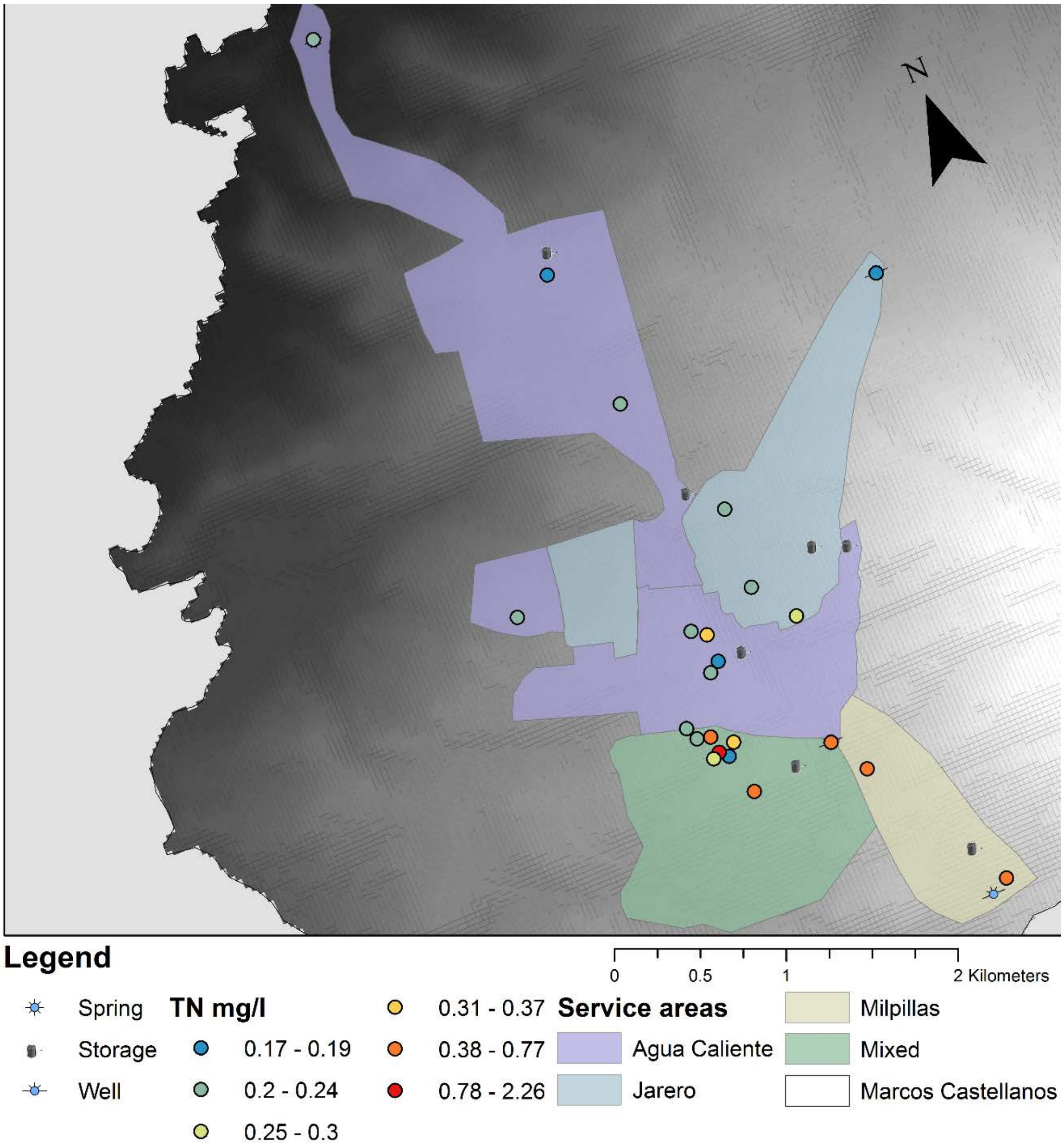

Figure 40 Spatial distribution of NH_4-N measured in samples N = 25

4.3.4 Phosphate-P

PO_4^{3-} concentrations in samples taken from sources and deposits of water are all fairly low, and ranged from 0.01 mg/L to 0.03 mg/L (Table 8). Drinking water samples derived from the Agua Caliente spring had the highest concentration of PO_4-P. Surface water samples taken from the southern creek had the highest concentration of phosphate-P at 2.8 mg/L (Table 8).

4.3.5 Cations: Sodium, Potassium. Magnesium and Calcium

Sodium concentrations ranged from 0.7 meq/L in the Ojo de Agua well water supply to 5.1 meq/L in the Southern creek (Table 8). Potassium concentrations ranged from 0.10 meq/L in the Ojo de Agua well water supply to 0.5 meq/L in the Southern creek (Table 8). Magnesium concentrations ranged from 0.5 meq/L in the Agua Caliente storage deposit to 2.2 meq/L in the Southern creek water (Table 8). Calcium concentrations ranged from 0.2 meq/L in the Agua Caliente spring water supply to 1.8 meq/L in the Southern creek (Table 8). Source water cations were > 0.5 indicative of the weathering of ferromagnesian minerals (Table 7). Figure 41 shows the spatial distribution of these results.

Surface waters were only tested on two occasions for safety because they were known to be contaminated with raw sewage. Both the Rio de la Passion, and a small creek that drains the southern portion of the municipality had elevated cations (Table 8). Surface water samples had much higher cation content than groundwater samples from water sources and their storage deposits.

Table 8 Laboratory tested water chemistry of drinking water sources, storage and surface waters. ND = no data because of short sample volume N = 6

Type	Description	Na^+ meq/L	K^+ meq/L	Mg^{2+} meq/L	Ca^{2+} meq/L	NO_3-N mg/L	NH_4-N mg/L	PO_4-P mg/L	DOC mg/L	TDN mg/L
Supply	Jarero well	0.8	0.2	0.7	0.3	0.3	0.2	0.01	14.6	0.2
Supply	Milpillas Well	1.1	0.2	0.6	0.3	0.3	0.2	0.01	18.7	0.6
Supply	Agua Caliente Spring	0.8	0.1	0.6	0.2	0.6	0.3	0.03	18.5	0.2
Supply	Ojo de Agua Well	0.7	0.1	0.9	0.3	0.3	0.2	0.01	15.1	0.7
Storage	Jarero deposit	0.8	0.2	0.8	0.2	0.3	0.2	0.01	ND	ND
Storage	Agua Caliente deposit	0.8	0.1	0.5	0.2	0.6	0.3	0.01	18.0	0.2
Surface	Rio de la Passion	0.7	0.5	0.6	0.7	1.7	0.5	0.8	ND	ND
Surface	Southern creek	5.1	0.5	2.2	1.8	4.6	7.2	2.8	ND	ND

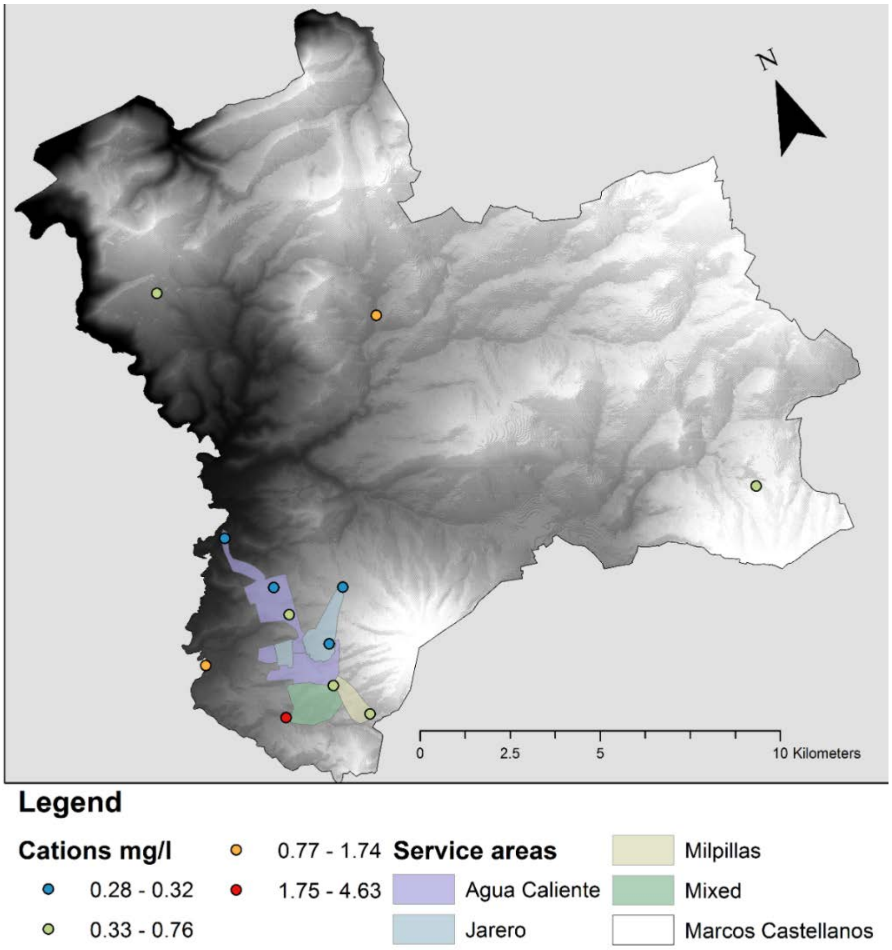

Figure 41 Spatial distribution of cations (meq/L)

4.4 EPANET Model

The scenarios chosen for modeling in EPANET reflect possible pumping and chlorination schedules. The two pumping schedules, partial and continuous, reflected certain levels of development. The ideal would be a continuous pumping schedule that would allow water to be delivered to household 24 hours a day. The partial pumping schedule, which is the current regime in the town, reflects the low availability of funds to pay for pumping costs and perhaps water availability. Most of the scenarios produced significantly different results in chlorine concentrations throughout the distribution system (Tables 9 and 10). Difficulties were encountered when designing the EPANET system using my sample concentrations and in maintaining homogeneous concentrations of chlorine. This may have been because the system has 4 different source points of water, in terms of both DOC content and in their location. Surprisingly, the highest decay rate was from the Milpillas well, where one would assume that the Agua Caliente Spring would have the highest decay rate since it is technically surface water. More samples and DOC analysis should be done in the future to address this anomaly. There were both spatial and temporal variations to chlorine concentrations in the system. For the most part chlorine concentrations were very low in the morning, reached their peak in the early afternoon, and begin to decline again before 5:00 pm when some well pumps and chlorination systems go offline (Figure 44 through 46). An ideal system would have low percentages of nodes below 2.0 mg/L of free chlorine, producing a somewhat concave line that increases slowly from left to right. Under current management conditions the model suggests that it is impossible to reach the minimum safety value of 2.0 mg/L in all of the nodes.

Table 8 One tailed T-tests on number of nodes below 2.0 mg/L of free chlorine. P = Partial supply (current regime in town), C = Continuous supply and N = Continuous supply with no demand pattern. Numbers following letters indicate the number of scenario run

Scenario	***P1***	***P2***	***P3***	***P4***	***P5***	***P6***	***P7***	***P8***
P0	0.298	0.001	*<0.001*	0.326	0.070	0.140	*<0.001*	*<0.001*
	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
C0	0.078	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
	N1	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**
N0	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

Table 9 One tailed T-tests on chlorine concentrations between pumping scenarios

Scenario pairing								
P0-C0	**P1-C1**	**P2-C2**	**P3-C3**	**P4-C4**	**P5-C5**	**P6-C6**	**P7-C7**	**P8-C8**
<0.001	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
P0-N0	**P1-N1**	**P2-N2**	**P3-N3**	**P4-N4**	**P5-N5**	**P6-N6**	**P7-N7**	**P8-N8**
<0.001	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
C0-N0	**C1-N1**	**C2-N2**	**C3-N3**	**C4-N4**	**C5-N5**	**C6-N6**	**C7-N7**	**C8-N8**
<0.001	*<0.001*	*<0.001*	*<0.001*	*<0.001*	0.001	*<0.001*	*<0.001*	0.076

The continuous model with a demand pattern performed the best, where only 3% of nodes had less than 2.0 mg/L of free chlorine when all sources are being chlorinated at the 3.5 mg/L maximum. The worst scenarios under this pumping schedule were scenarios number 7 and 8 at 6:00 am, 8 and 3 at 12:00 noon, and 3 and 8 at 5:00 pm (Figures 42, 43, and 44). Since EPANET incorporates demand when calculating the concentration of chlorine in the system, the importance of Jarero Well water receiving disinfection could be caused by the high demand from the North of the town that receives water from the Jarero Well. The system also performed poorly when only the Agua Caliente Well received chlorination. This could be because the water has to travel far from the chlorination site before reaching most of the users, allowing the chlorine to be mostly inactivated in the process of being distributed. The partial supply pumping scenario was able to reach a level of 95% of nodes with greater than 2.0 mg/L of free chlorine at 12:00 noon if all sources were chlorinated at 3.5 mg/L. The worst scenarios under this pumping schedule were scenarios number 8 and 7 at 6:00 am, which never reached levels lower than 60% of nodes with less than 2.0 mg/L. Chlorine concentrations at 12:00 noon were the worst under scenarios 8 and 3, the same scenarios were also the worst at 5:00 pm. Under the control scenario (N), which used continues supply but with no demand schedule, chlorination scenarios 2 and 7 had the most impact where nodes with lower than 2.0 mg/L never got below 10%. This supports the idea that Agua Caliente water has to travel further than the chlorine can stay active.

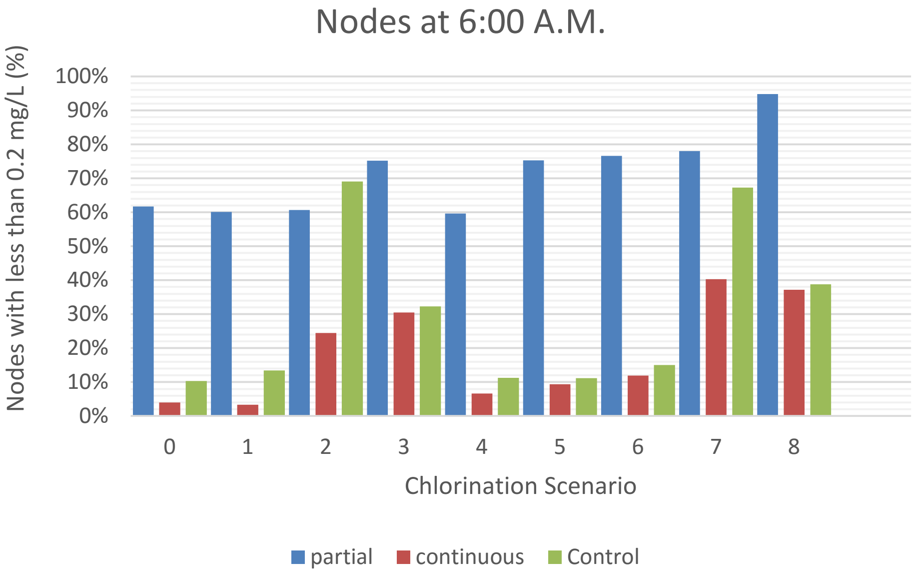

Figure 42 Concentration of Chlorine at nodes in all scenarios at 6:00 am

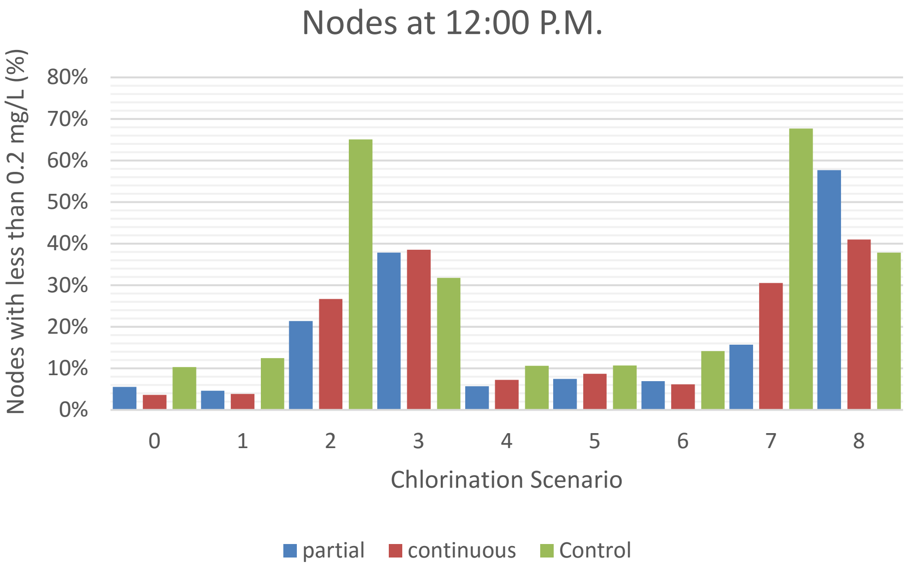

Figure 43 Concentration of Chlorine at nodes in all scenarios at 12:00 pm

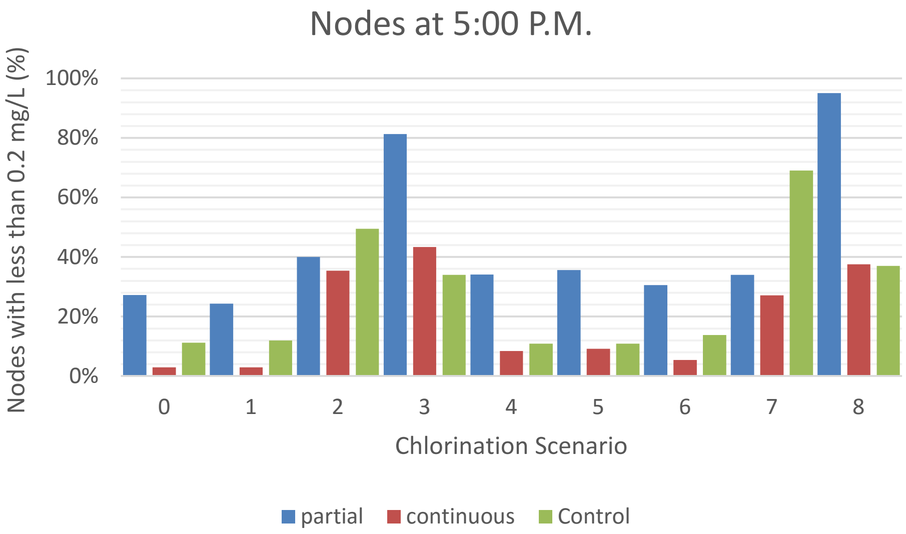

Figure 44 Concentration of Chlorine at nodes in all scenarios at 5:00 pm

The spatial variability of chlorine in the system mirrors the results from samples taken in the town. Areas closest to chlorination sites have the highest concentrations of chlorine, and the system itself is highly heterogeneous depending on the chlorination schedule. Overall the southern portion of the city is the most at risk of having low concentrations of chlorine and coliform bacteria present. The center of the town had the highest variability from block to block, while the northern part of the town had the most consistently acceptable levels. The continuous supply regime produced the greatest amount of spatial homogeneity of chlorine, although there were still areas receiving unacceptable concentrations. This was probably influenced by the differences in water quality between supply sources.

5. DISCUSSION

5.1 Lerma-Chapala Basin

Water abstractions in the Lerma-Chapala Basin are occurring at unsustainable volumes; in fact 70% of the groundwater wells in the basin are over utilized (Rodriguez 1997). Agriculture accounts for 68% of total water use in the basin. Combined with industrial and human needs, the basin is experiencing an annual deficit, of both ground and surface water, of more than 900 million m^3 (Wester et al., 2003). The basin's water crisis is exacerbated by pollution, as more than 90% of surface waters are deemed to be highly contaminated with industrial discharges and raw sewage (Millington et al., 2006). Indication of raw sewage in terms of high ammonium-N concentrations in surface waters was also observed in my study. Groundwater mining has also become an issue as municipalities have to turn to groundwater as a source of drinking water; aquifers in the basin are experiencing declines of 1.0 to 2.6 m/yr as abstractions from both agricultural and municipal exceed sustainable levels.

The UN and related international groups have used the Lerma Basin as an example of successful IWRM in a developing country (Casillas and González, 2007; Mestre, 2001; Millington et al., 2006). Much like UN's claim to reaching MDGs, this seems to be premature and loosely based. The decentralization efforts in the 1990's placed the building of waste water treatment facilities on the shoulders of municipal governments. Many of the local governments at the municipal and state level have very little ingress to work with. This is partially a result of Mexico's federally driven taxation system and high levels of poverty. As a result wastewater treatment systems are not common in Mexico. Incorporation of International drinking water standards are also weak in this regard. Waste water treatment is not required by these standards. As long as households have hygienically separated human waste from human contact and facilities and are not publically shared they are considered to be ‘improved’. While this standard may help Least Developed Countries (LDCs) take the small steps into modernization that they can afford, middle income countries such as Mexico are able to artificially shine with accomplishment.

5.2 Marcos Castellanos Municipality and Town of San José de Gracia

The level of integrated water management in Marcos Castellanos is low. Although the town of San José de Gracia does keep a simple record of payments and meter readings they do not use the data for any analysis. This record was useful for my research for estimating water use by homeowners and commercial entities. The water managers of the town are unaware of the total volume of water being extracted, lost in the system or ultimately used by consumers. While CONAGUA requires that groundwater users have a permit stating the volume of water being abstracted, the municipality has only one registered well. Additionally, no one in the municipal government of utilities is aware which aquifer their water is pumped from, the size of their pumps, or the areas of recharge. There are currently no land use regulations being implemented in the municipality or participation in regional basin management groups.

The town of San José de Gracia does not treat sewage or regulate effluent discharge by major dairy product manufacturers located in the town. Surface water samples from the Southern Creek were a magnitude higher in sodium, magnesium and calcium concentrations than water from other parts of the municipality, such as well and spring water sources, water storage deposits and household faucets. This may indicate significant illegal dumping of saline waters that are produced as waste by the industry. The Southern Creek when sampled had a white, grey appearance with no noticeable aquatic life forms. There are currently no programs run by the municipality to incentivize or educate farmers about buffer zones or riparian zone restoration near streams. Besides human fecal matter, some smaller creeks had noticeable accumulation of what appears to be bovine waste. It should also be noted that the local slaughterhouse also disposes of their waste, including blood and other biological materials, straight into the Northern Creek. Decomposition products from dead mammals in the form of DOC, nitrate-N, ammonium-N and phosphate-P and cations are reportedly extremely high (Aitkenhead-Peterson et al. 2012; Carter et al. 2007) and can be expected to have a negative effect on surface waters.

5.3 Indicators and Testing

Poor drinking water quality impacts the economy by increasing the cost of health care and reducing worker productivity by spreading illness (Hutton et al., 2004). Ironically, economic growth can prevent governments from making key investments that help to secure the quality of water being served. It is now generally accepted that improved access to water does not necessarily mean that water is free from chemical or microbial constituents or that the quality satisfies World Health Organization (WHO) and national safety standards (Yang et al., 2013). While efforts to improve access to water have increased welfare, they have lacked both treatment and monitoring. For example, drinking water sources for the town of San José de Gracia had above *E. coli* counts which ranged from 0 to 112 cfu/100 mL illustrating this problem. While high concentrations of *E. coli* were observed in water sources, their concentrations dropped in storage deposits and increased again in household faucets indicating potential regrowth within the system. Failing to monitor water quality has diminished the potential benefits from international and national investments. Water quality testing plays an important role in solving public health problems that can pose a significant financial burden to developing countries. Achieving the targets of MDG 7 to decrease the population without access to safe water will require regular monitoring of water quality.

When selecting indicators to test drinking water quality, it is important to consider the spatial and political context of the basin and efficiently select the most relevant variables for each distribution system (Abdul et al., 2012; Ferrier et al., 2009; Stedmon et al., 2011; Stepenuck et al., 2011). Utilizing systemic planning and understanding of local geography, RADWQ helps to maximize the utility of data that can be acquired with a low budget. With a basic understanding of the regional geography, low-cost tests can be used as affordable assessment tools to establish baseline information (Bain et al., 2012; Howard et al., 2012). Since a watershed's physical and anthropogenic characteristics, such as its, climate, geology, land use, and land management strategies are the overarching factors that determine local water quality, the RADWQ is a strategic move toward implementing IWRM into the development scheme more efficiently.

Physio-chemical properties of water, such as pH and conductivity, and water quality indicators, such coliform bacteria, are among the most common parameters chosen for initial evaluations in developing countries (Abdul et al., 2012; Bain et al., 2012; Giné-Garriga et al., 2013; Nnane et al., 2011; Stepenuck et al., 2011). Where local conditions create vulnerability for contamination from other contaminants, often heavy metals or pesticides, further testing can be done. Costs for testing for *E. coli* and coliforms were less than $2.50 for each for the Coliscan Easygel test and less than $5.00 each for membrane filtration. This is quite a reasonable cost per test but often E. coli growth can be too high to confidently count the number of colony forming units; meaning that 2 to 3 tests are needed for each site which will increase the per site sample cost. To ensure the safety and sustainability of water, governments must develop monitoring schemes that collect critical information needed to manage food and water safety (Farahi et al., 2012). Establishing comprehensive datasets in developing nations requires two essential elements; training personnel and inexpensive testing equipment (Mabey et al., 2004). The WHO has established seven criteria for scientists to develop Point of Care (POC) diagnostics; affordability, sensitivity, specificity, ease of use, rapid and robust, equipment free, and easily delivered to those in need. Research has already begun to quantify the reliability of commercial water testing kits for contaminants such as arsenic (Van Geen et al., 2005). Products using immunoassay-based kits for pesticide detection that allow for simple methods to be implemented have already been developed (Gabaldón et al., 1999). Although much research is needed to further develop simple but reliable testing kits for many other contaminants, research on efficacy of volunteers also provides resources for creating training manuals that can help build human capacity.

Low cost testing methods include the use of kits of varying costs, which give varying levels of accuracy from which to assess water management strategies being implemented. Low income test settings most commonly use fecal coliform tests, surveys, and the basic water quality parameters that can be measured with relatively inexpensive and re-usable meters (Abdul et al., 2012; Bain et al., 2012; Giné-Garriga et al., 2013; Nnane et al., 2011; Stepenuck et al., 2011). To assess the level of integrated management being used by water managers, RADWQ recommends obtaining information about the political and social atmosphere of the study region.

5.4 Disinfection of Drinking Water Systems

Water quality can be seriously degraded in storage tanks if it has a long residence time and poor mixing (Grayman et al., 1993). Additionally, water in the periphery of system will have less residual disinfectant than water for users closer to the disinfection site. Factors that decay chlorine range for system design, operational variables, and the physio-chemical properties of the water being used (Ahn et al., 2012; Clark et al., 1994, 2005; Hallam et al., 2003). Managing the concentration of chlorine in a distribution system is usually limited to controlling the amount of chlorine added at the water treatment plant. Water utility operators need to be knowledgeable of the water system they operate in order to adjust chlorination rates to their particular system.

Since chlorine reacts with organic matter throughout time; the age of water is an important factor in determining the quality of drinking water. The longer the residence time of the water in a distribution system the more time the chlorine has had to react with organic matter, decreasing chlorine residuals and increasing the concentration of disinfection by-products (Georgescu et al., 2012; Grayman et al., 1993; Powell et al., 2000). When water initially enters a distribution system after being taken from the source and treated, water age is modeled as being zero. Storage tanks (deposits) built into the distribution system can have a significant effect on water age. If the level of water in the tank is allowed to vary greatly, newer water can come in and replace old water decreasing the average age. If the tank is not allowed to vary greatly, that is when the tank is refilled after only a short decrease in the water level, the average age of water in the tank increases. One study found that a 9 foot variation in water level produced an average water age of 7 days; however a 1 foot variation increased average age to almost 20 days (Grayman et al., 1993).

Direct pumping from water sources to consumers is rare today even though it would shorten water age because storage tanks provide a controlled demand on sources and disinfection facilities. As a result the distribution system is more stable in terms of flows and pressure as well as in terms of equalizing service for all users. Storage tanks also add a factor of safety because they can reserve supplies for fire emergencies or power outages. In the United States it is estimated that less than 25% of water in a storage tank is actively used throughout the day, the rest remaining in reserve for fire storage (Grayman et al., 1993; Rossman et al., 1995). Storage tank location, distance from initial disinfection, and operating policies are very important in determining water age and quality. Modeling tank storage is a difficult and recent undertaking because of the considerable variability in the behavior of water within a tank. One of the phenomena that can take place is short circuiting, where the inflow of water into a tank has a direct flow path to the outflow of the tank. The result is dead zones, where mixing of water is limited, and water that most recently entered the tank is also the first to exit the tank (Grayman et al., 1993).

Chlorination systems at all of the sources in my study were somewhat passive, as there were no obvious design features of the systems that ensured a full mixing of the disinfectant. The distribution system for the Agua Caliente Spring lacked a filtration system to rid the water of suspended solids that are present in the water. This is a serious design flaw that contributes to elevated bulk decay rates and raises the concentration needed for chlorine to be an effective disinfectant. Overall it seemed chlorination was irregular and ineffective overall in the town of San José de Gracia. Irregularity of chlorination can contribute significantly to biofilm growth within the system and raises concerns over the health risks citizens are exposed to.

The results from EPANET indicated that under current operational schedules the maximum allowed concentration of 3.5 mg/L at the point of chlorination would provide enough disinfection for the whole system. The EPANET model also illustrated that having partial service as oppose to continuous service throughout the day can contribute to higher chlorine decay rates. The EPANET model results also suggested that chlorine is least present in the Southern and Western developments in the town which are furthest from the chlorination sites. Although water quality tests for chlorine and coliform bacteria showed some spatial patterns, there were not clear enough to make confident inferences. At the time the samples were collected chlorination was not regular, therefore results had added variance related to the lack of steady disinfection.

The water distribution model of the town did not include cisterns which are used in most homes. These water storage tanks are used to alleviate water scarcity caused by the fact that water is only delivered for 6 hours of the day, and for some locations only every other day. The presence of these storage tanks would contribute to chlorine decay prior to use by the household. The added variability to the distribution system of on and off chlorination, multiple sources, partial supply, and cisterns all contribute to variability in the number of coliforms and *E. coli* observed in samples from household faucets.

An assessment of 319 studies containing more than 96,000 samples found that more than a third of samples from improved sources still contained fecal contamination (Bain et al., 2014). The author of the study pointed out that this might even be an overestimation of safety because the studies routinely lacked a robust random sample. Studies often lacked samples that reflected the quality of water after storage. Bain (2014) also suggested that the priority should be to improve the international monitoring strategy and include the measuring of water quality with physical indicators.

There are several different steps the municipality could take to solve their ineffective chlorination system. The utility group could install additional chlorination stations within the city. Determining the location of these would require a diurnal study of coliforms and chlorine concentrations throughout the system. This measure however, would not be able to take into account the cisterns which are currently in use. The cisterns are currently essential to water users, and it would require a change to continuous supply to change the trend. Under the current system design with four separate water sources, the largest of which requires water to be pumped up more than 300 m, the municipality cannot afford to provide continuous water supply. They would have to perform a geological analysis of the area in hopes of finding a location at a higher elevation than the town that could provide enough water to supply the population to decrease pumping costs and perhaps be able to provide water throughout the day.

5.5 Water Costs

The cost of water to the citizens of the town of San Jose de Garcia was comparable to the cost of water in Glasgow, UK and close to being as high as water costs in Santa Fe, NM (Figure 45 and Table 11). Surface water from Loch Katrine is the primary source water for Glasgow’s potable water. The United Kingdom protects its surface waters allocated for drinking water by reducing development in the watershed and having strong regulations of types of recreation allowed (i.e. no motor boats only row boats). This is done to reduce treatment costs and ensuring water supplies are as uncontaminated as possible. Potable water for Santa Fe is derived from both surface and groundwater sources 1) Santa Fe River (stored in the McClure and Nichols Reservoirs), 2) well fields within the city and near the Rio Grande River. In the town of San José de Gracia, despite having a highly subsidized utility, irregular service, inadequate quality and no security, the citizens of the town are paying a highly inflated price for their water. Users are not only paying more for lower quality water and no waste water treatment, they are also charged at a declining block rate. Industrial users pay the lowest fee for a flat volumetric rate, while the rest of tariffs are on a declining block rate.

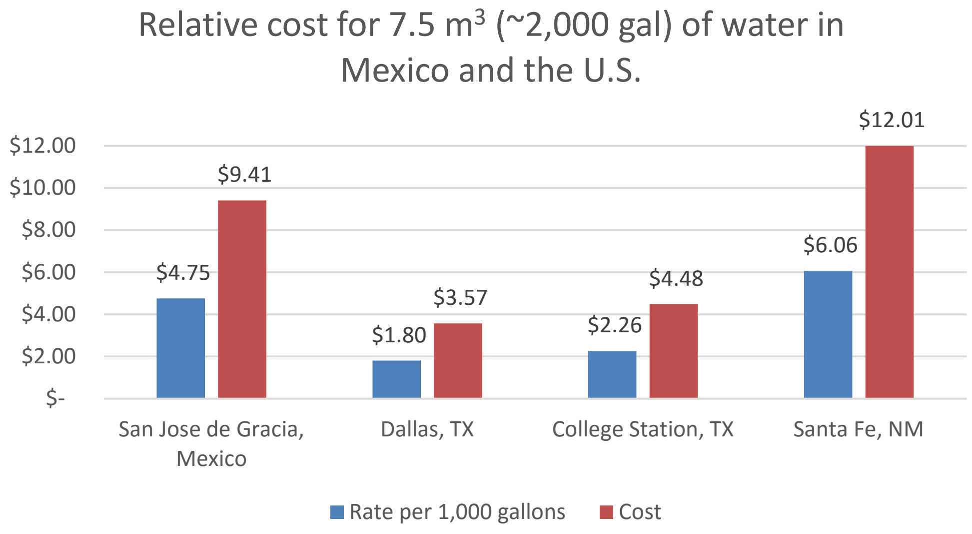

Figure 45 Comparison of water cost in San José de Gracia to U.S. cities

System requirements for providing safe water under the current design would be very expensive and complicated. Water disinfection could be improved through additional chlorination points and treatment before being distributed. Currently the spring water used is not being filtered to have suspended solids removed. This can significantly contribute to bulk decay rates of chlorine and poses a serious threat to the health of water consumers. Additionally well sites are not given a protective radius to limit the possibility of surface contaminants infiltrating the aquifer and causing negative health impacts. The town is also not protected against fire, not only are there no fire hydrants, but storage tanks operated by the town do not maintain a minimum level of water for use in cases of emergencies. Water security is a huge problem in the municipality, if there is a power outage the distribution system will not be functional as it has no backup generators and surface water is too far contaminated to be used in case of emergencies. The town’s water utility is not able to provide an efficient system and despite serving expensive water, they are not able to utilize the money in ways that improve the situation.

Table 10 Comparison of WB indicators of water costs using IBNET and collected data

Tariff report for domestic users	**UK**	**U.S.**	**U.S.**	**Brazil**	**Mexico**	**Mexico**	**Mexico**
City	Glasgow	El Paso	Houston	Sao Paulo	Mexico city	Monterrey	San José de Gracia
Utility	Scottish Water	El Paso Water Utilities	Dept. of public works and engineering	SABESP	SACM	SADM	Sistema de Agua Potable
Service	Water and waste water	Water and waste water	Water and waste water	Water and waste water	Water and waste water	Water only	Water only
Tariff type	Incline Block Tariffs	Incline Block Tariffs	Incline Block Tariffs	Incline Block Tariffs	Incline Block Tariffs	Volumetric flat	Decline Block Tariffs
Water (local currency/ m3)	2.9	1.0	2.9	1.7	34.5	6.6	57.0
Water (US$/m3)	4.7	1.0	2.9	1.0	3.0	0.6	4.8
Wastewater (local currency)	3.5	1.3	3.5	N/A	3	N/A	N/A
US$/m3	5.7	1.3	3.5	N/A	0.3	N/A	N/A
Total tariff (Local currency/ m3)	6.5	2.3	6.4	1.7	37.5	6.6	170.5
Total tariff (US$/m3)	10.4	2.3	6.4	1.0	3.2	0.6	14.2

Tariff per m3 = [connection fee +volumetric charge per 15 m3 per month +taxes and other fees]/15.
The exchange rate to the $US is as of April 30, 2011.

5.6 Limitations of Study

There were several limitations of this study which can be comparable to limitations faced by non-profit and international organizations working in developing countries. Limitations included 1) accuracy of testing kits is variable, 2) very low materials and transportation budget, and 3) lack of base knowledge and data from the local government to act as background to this study. These all posed serious barriers to understanding the water system in a small town of a developing nation. However, since water quality directly affects the quality of life and health of citizens it is important to evaluate the effectiveness of high level decisions taken to build water infrastructure with borrowed money.

6. CONCLUSION AND RECOMMENDATIONS

Water quality regulations serve not only to improve public health but also to raise living standards. The rate of a country's development is highly dependent on the efficacy of local governments to implement national standards. Federal and state laws regarding water resources should provide the framework for watershed management at the local level. Those laws are expected to provide sufficient guidance for municipal governments to achieve uniform national standards, while providing enough freedom for implementation strategies to be tailored to local needs. The highly centralized structure of the federal government has left local institutions financially and technically unable to meet water quality criteria. Centralization also weakened attempts at regional management through lack of continuity in funding and projects. Furthermore, testing frequencies recommended by international organizations do not reflect the amount of testing that needs to be done to confidently assure the public that safe water is being distributed for human consumption.

Inadequate local planning has contributed to a lack of uniform water quality that fails to meet national standards. Arguably, water related infrastructure and planning shows the government's ability to translate values and desired outcomes into policy that is effective at the micro and macro scale. The ground truth at the local level displays heterogeneous, geographically variable responses to homogeneous national policy. In general, the MDGs highlight the bearing that improved access to drinking water and sanitation services has for a nation's welfare (Kalbus et al., 2012). These goals called for active intervention by governments through the construction of water supply, distribution, and sanitation systems to improve health and environmental sustainability as an integral part of meeting poverty reduction goals (Zawahri et al., 2011). This ultimately promotes developing countries to take additional loans to build more infrastructure in order to meet development indexes set by non-binding agreements. These loans come with binding agreements to make changes to the nation's market systems, which are supposed to act in coordination with poverty reducing programs and new infrastructure to eliminate poverty. This much more inclusive and holistic development scheme is the result of failed attempts which did not incorporate all of these elements. However, much work to make global initiatives translatable to local terms is still needed. The definitions of improved water and sanitary services used by the UN have in a way helped stall progress in Mexico and perhaps other middle income countries as well. While critics point to the unfairness of MDGs to LDCs in Africa, for they have much more work to do, less stability and fewer funding opportunities, they are too relaxed to really put pressure on middle income countries like Mexico to improve conditions.

A common theme across the literature is the lack of data. Although the UN, and its associated organizations, requires some indicators be recorded, they are primarily development indicators. While publications from the UN highlight the importance of capacity development, they have overlooked baseline physical data collection, a crucial factor of resource management. Procedures in RADWQ and initiatives promoted by IWRM require high resolution physical data, such as geologic and soil maps. However, besides the recent interest by the World Bank to map Africa's geology there has been little effort in mobilizing global partnerships to help developing countries enrich their databases. Establishing a database with baseline indicators provides information that can be used to define hazards in need of safeguarding and identify where investments are needed for capacity building of water managers. Water quality assessment programs are an important step towards reducing the costs of water governance and increase the efficacy of policy. Ultimately, I have found through this research that international efforts to reduce poverty and enrich resource management have missed out of efforts to aid developing nations in creating databases with the preliminary data needed to implement IWRM. Creating these would require coordination between institutions of higher education, all government levels, and international developers. There is also a lack of equipment that can be used in the field for quick and accurate results. It is imperative that these instruments be made so that they can be used in developing countries that do not have the resources to maintain the various large and expensive instruments currently used to analyze water quality. Partnerships could also be built between educational institutions to allow for students to collect data and preform studies to better understand geology, pedology, and ecological studies that are essential to understanding and managing space.

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APPENDIX

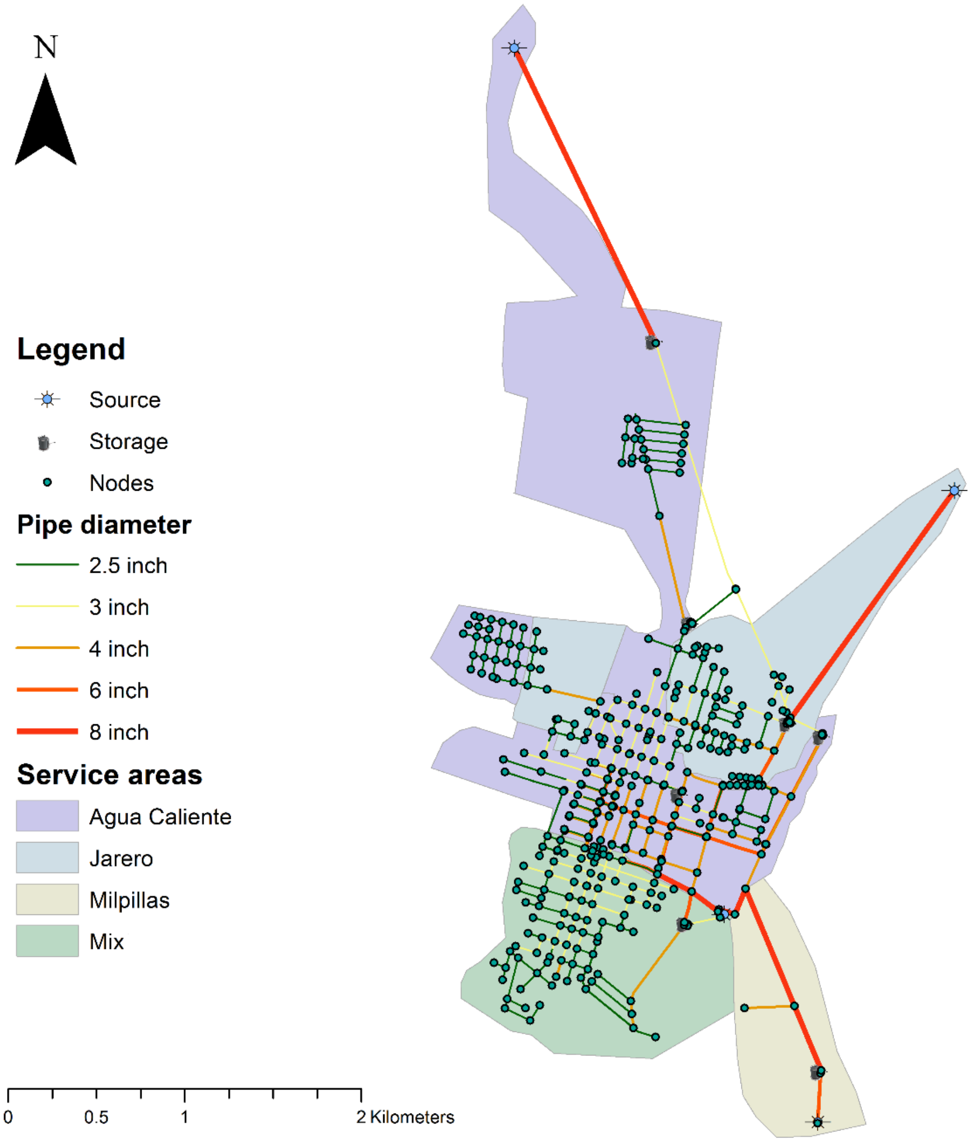

Figure 46 EPANET water distribution system model of San Jose de Gracia. Map by Janet Torres using own data and town CAD data.

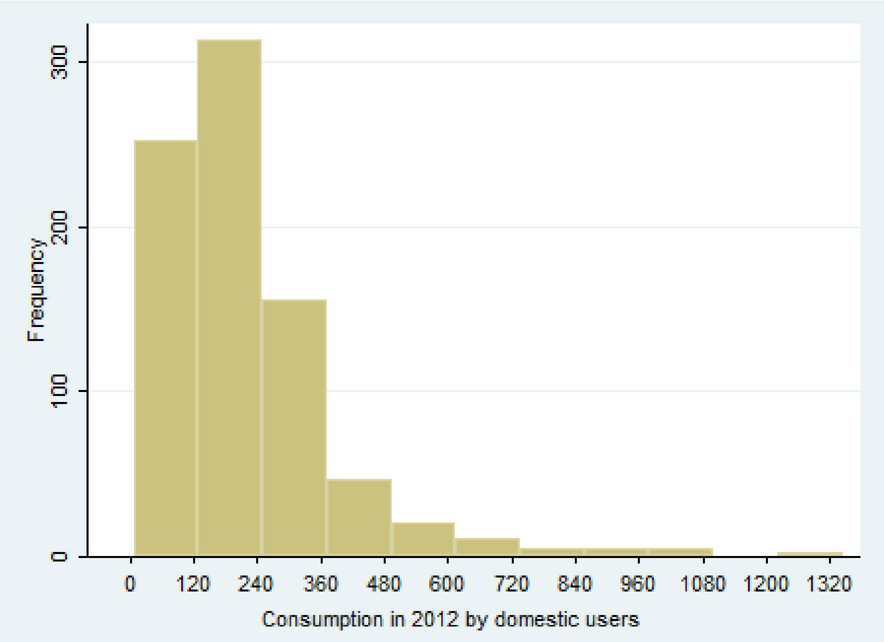

Figure 47 Histogram of water users' consumption in 2012

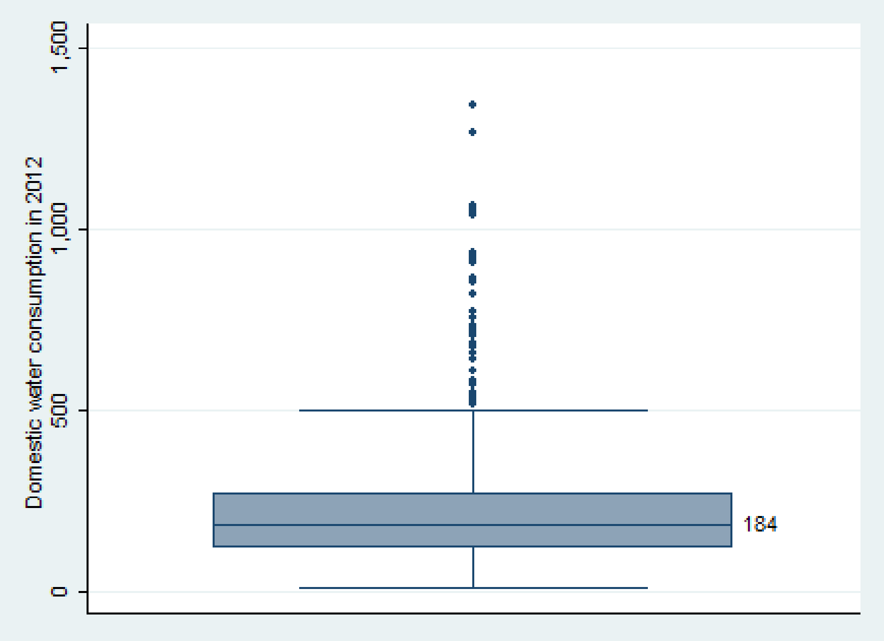

Figure 48 Distribution of water consumption by domestic users

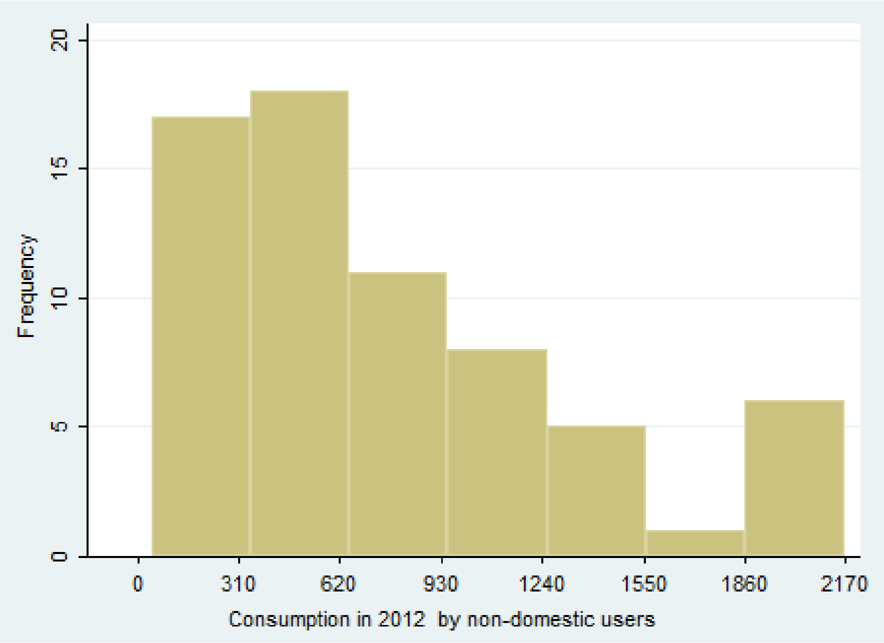

Figure 49 Frequency of water consumption by non-domestic users

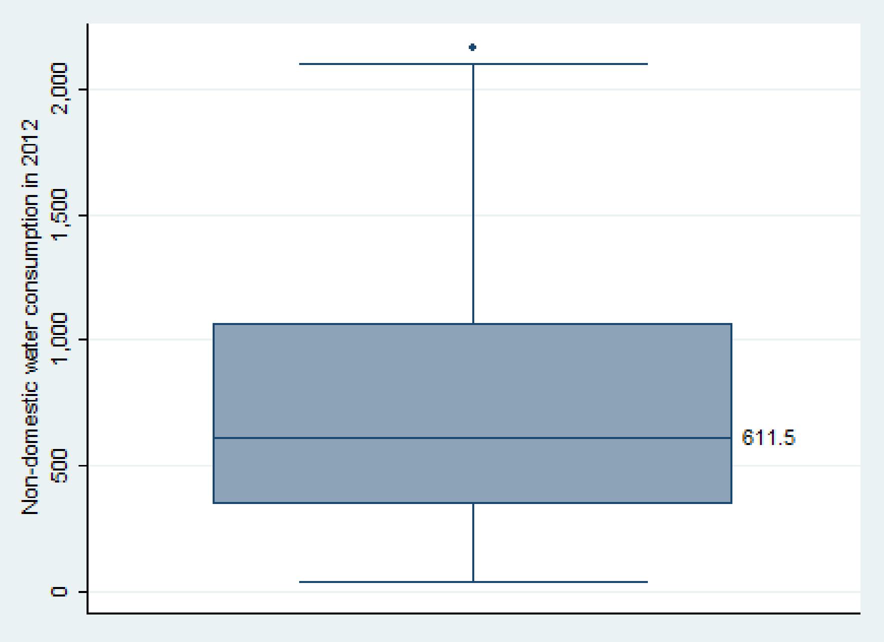

Figure 50 Distribution of water consumption by non-domestic users

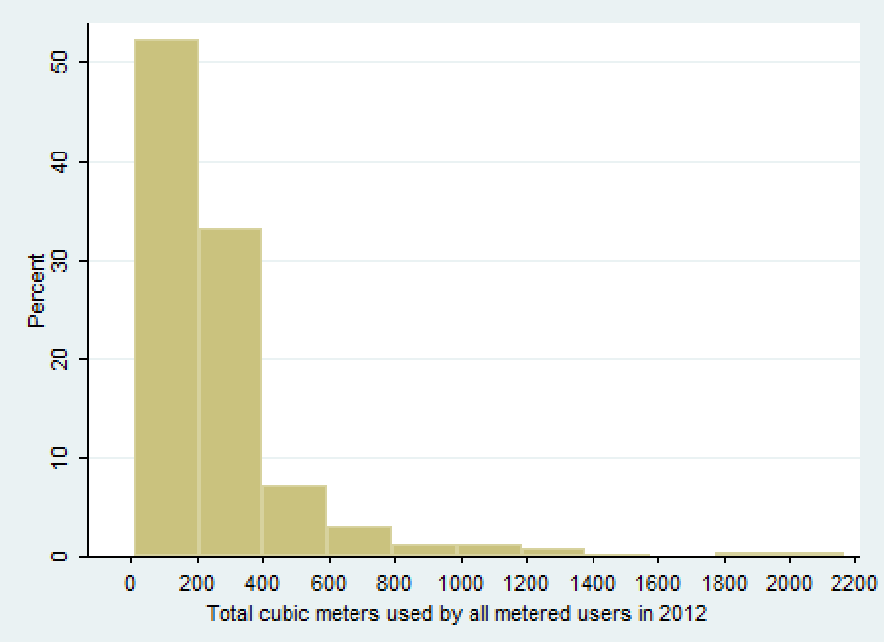

Figure 51 Consumption of all metered users

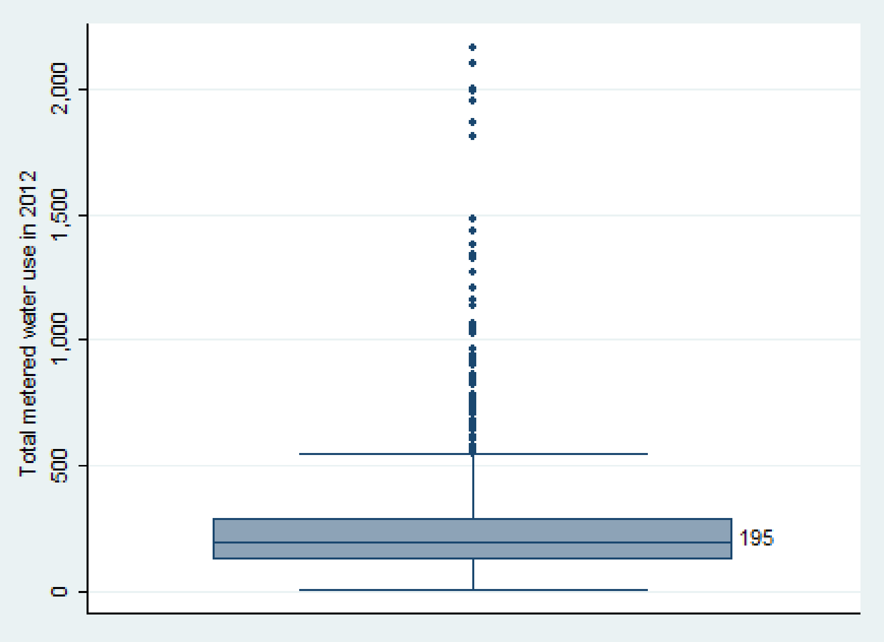

Figure 52 Distribution of water consumption by all metered users

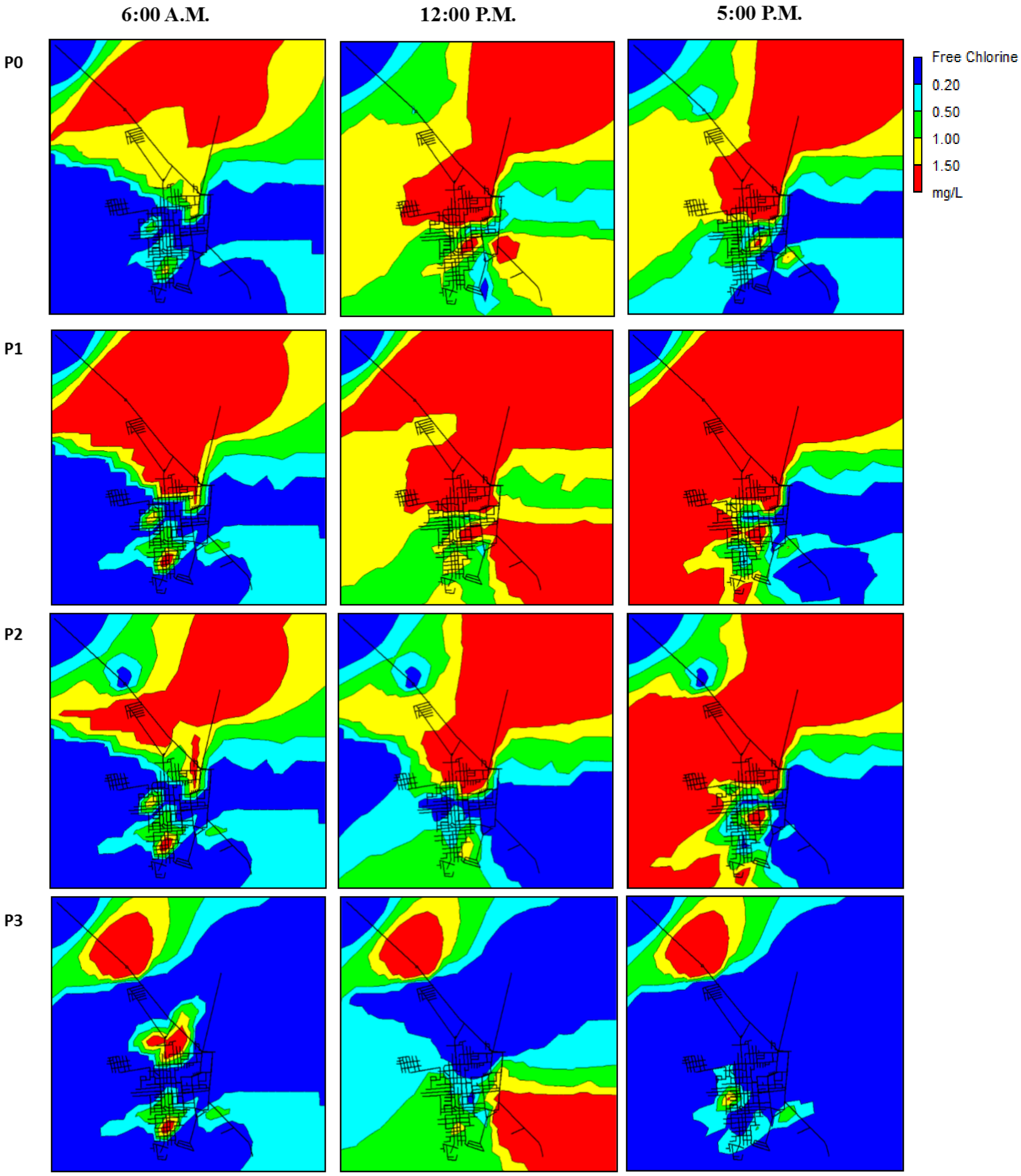

Figure 53 Contour of free chlorine predicted by models P0-P3

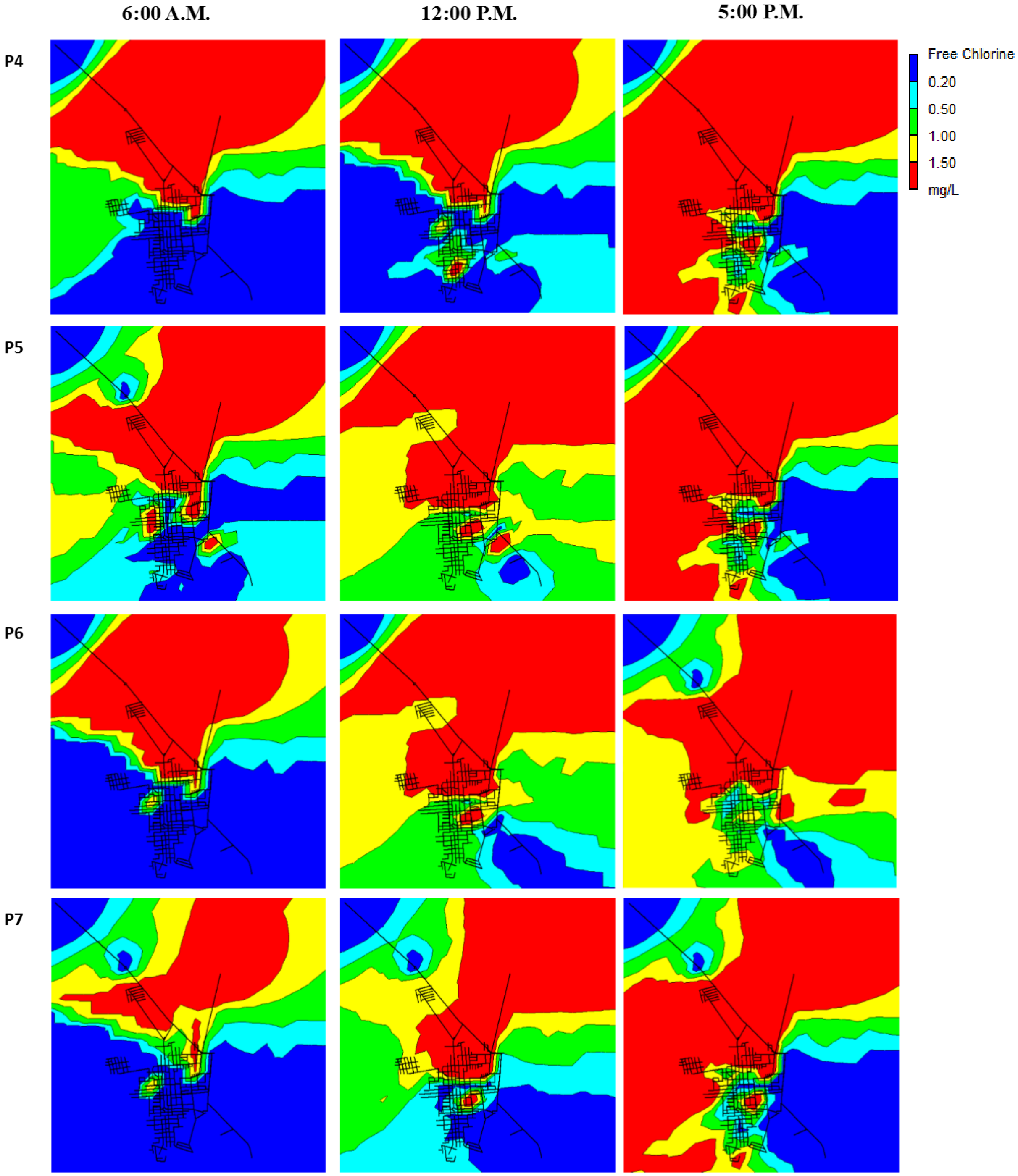

Figure 54 Contour of free chlorine predicted by models P4-P7

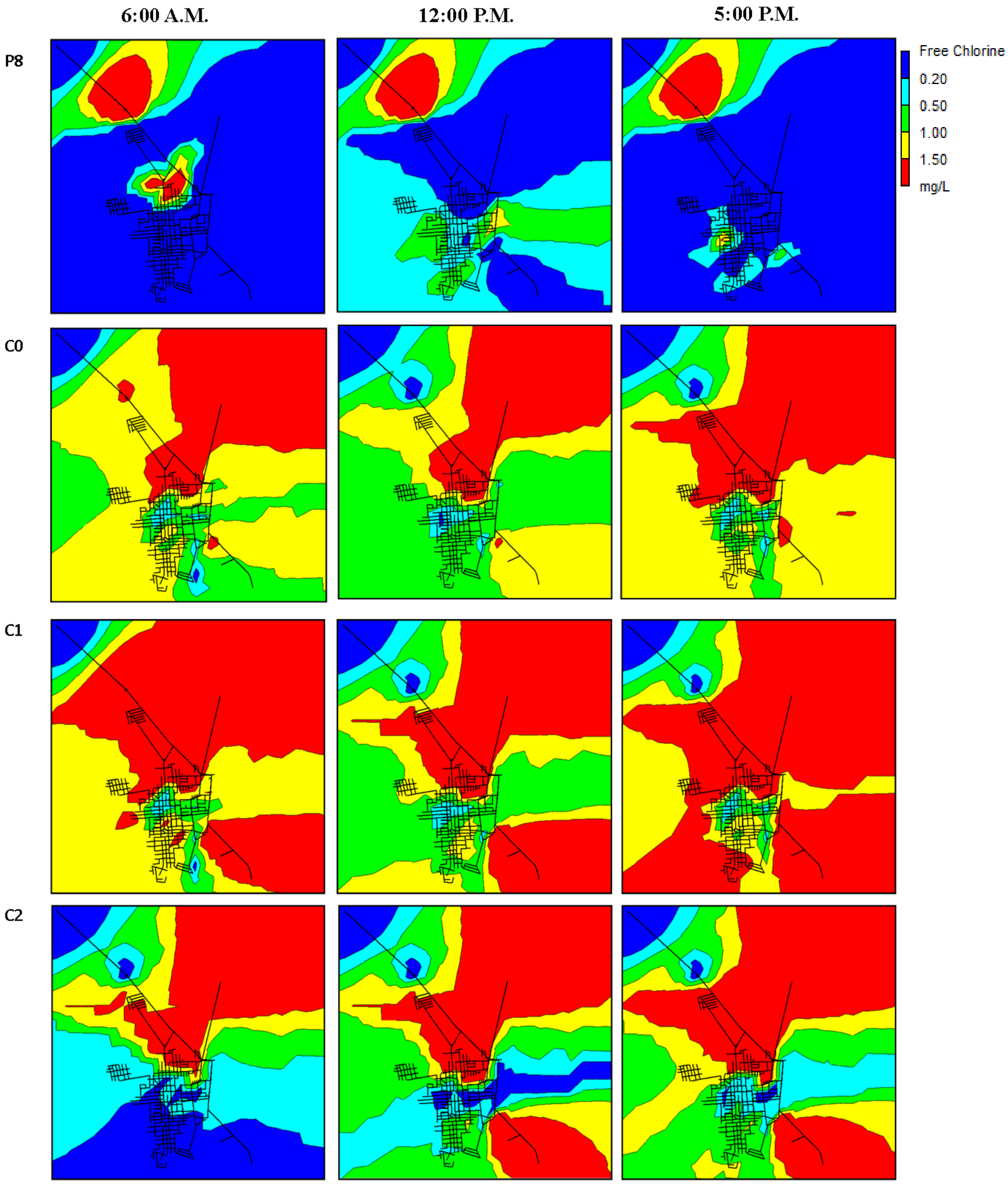

Figure 55 Contour of free chlorine predicted by models P8-C2

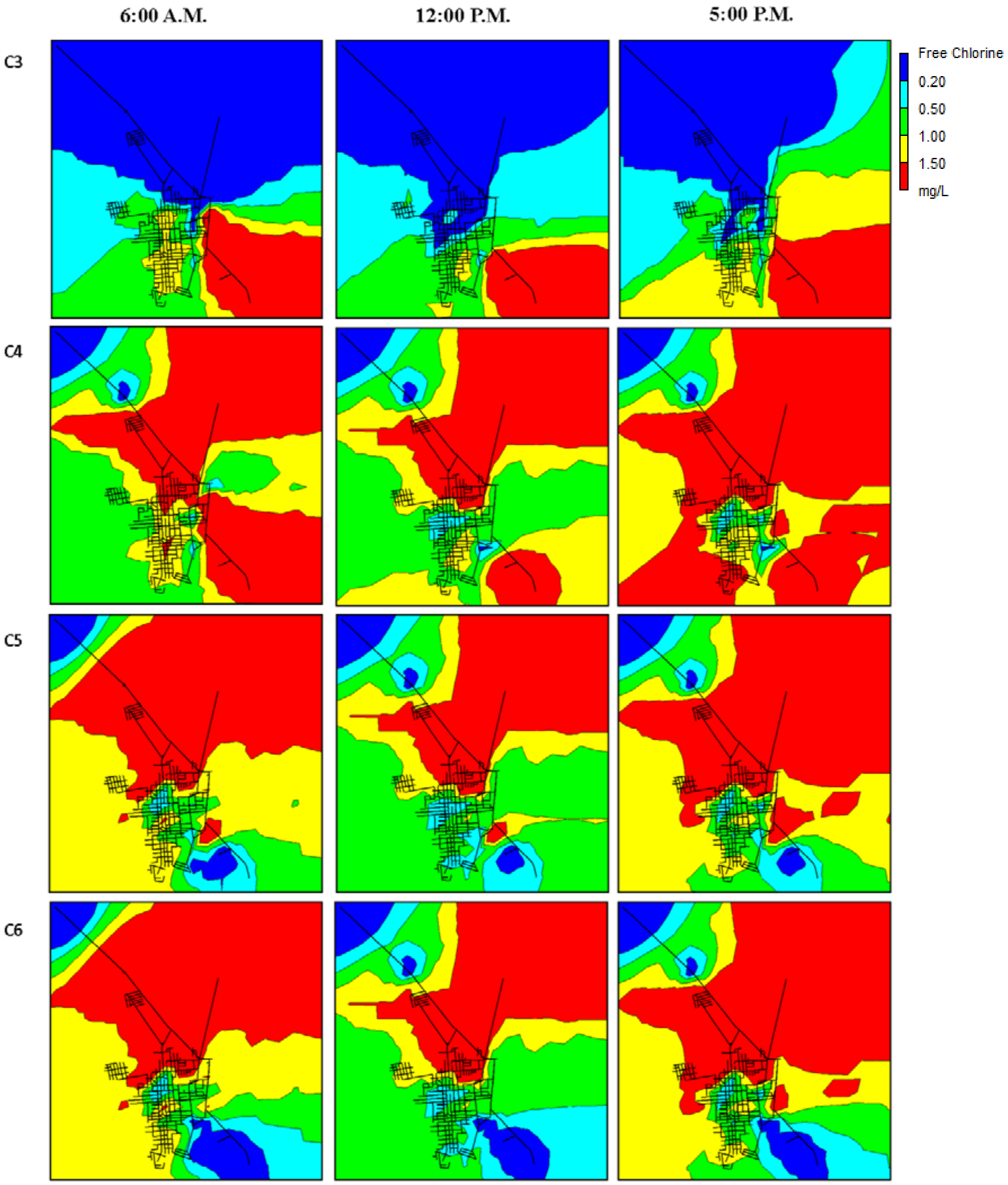

Figure 56 Contour of free chlorine predicted by models C3-C6

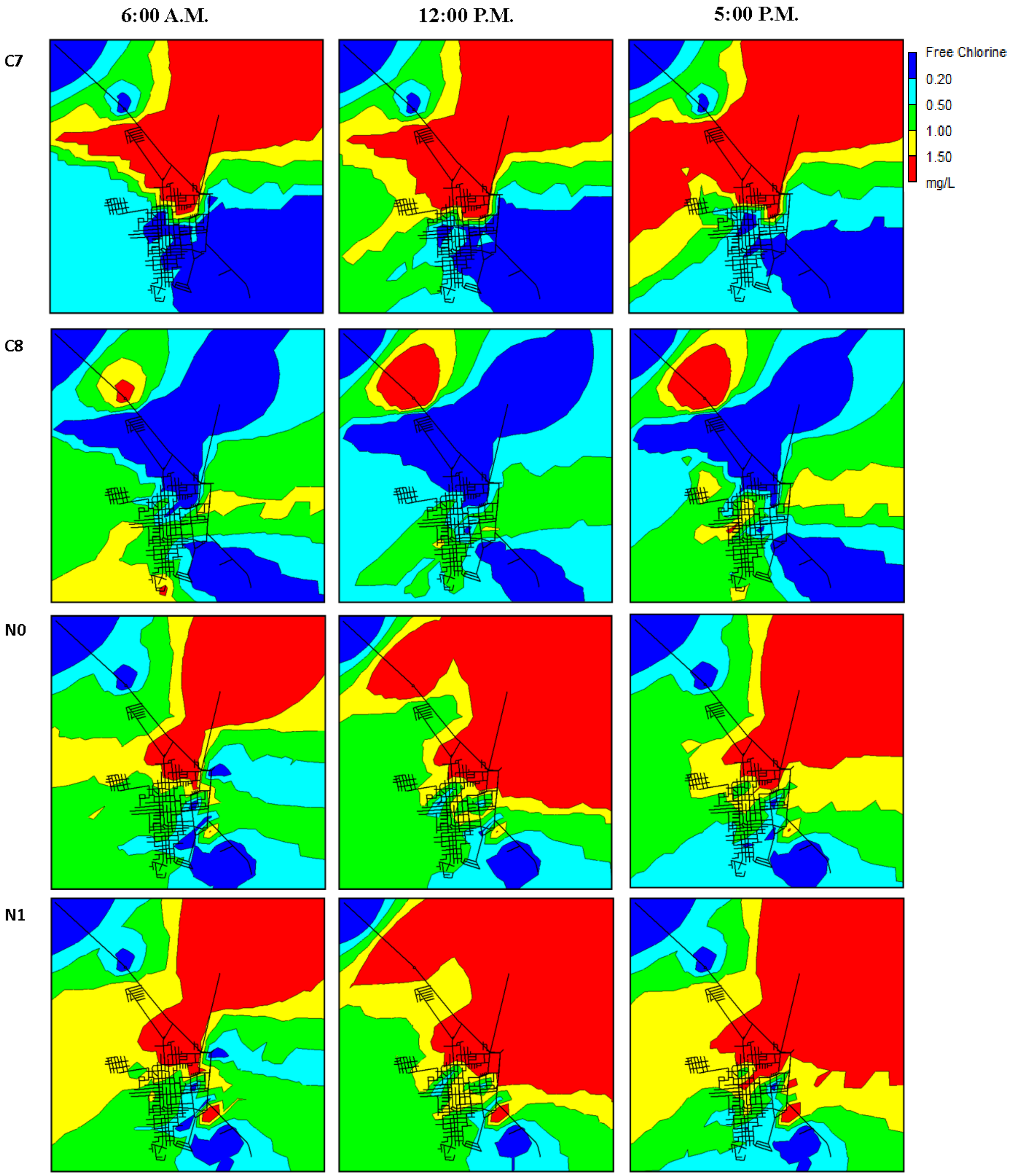

Figure 57 Contour of free chlorine predicted by models C7-N1

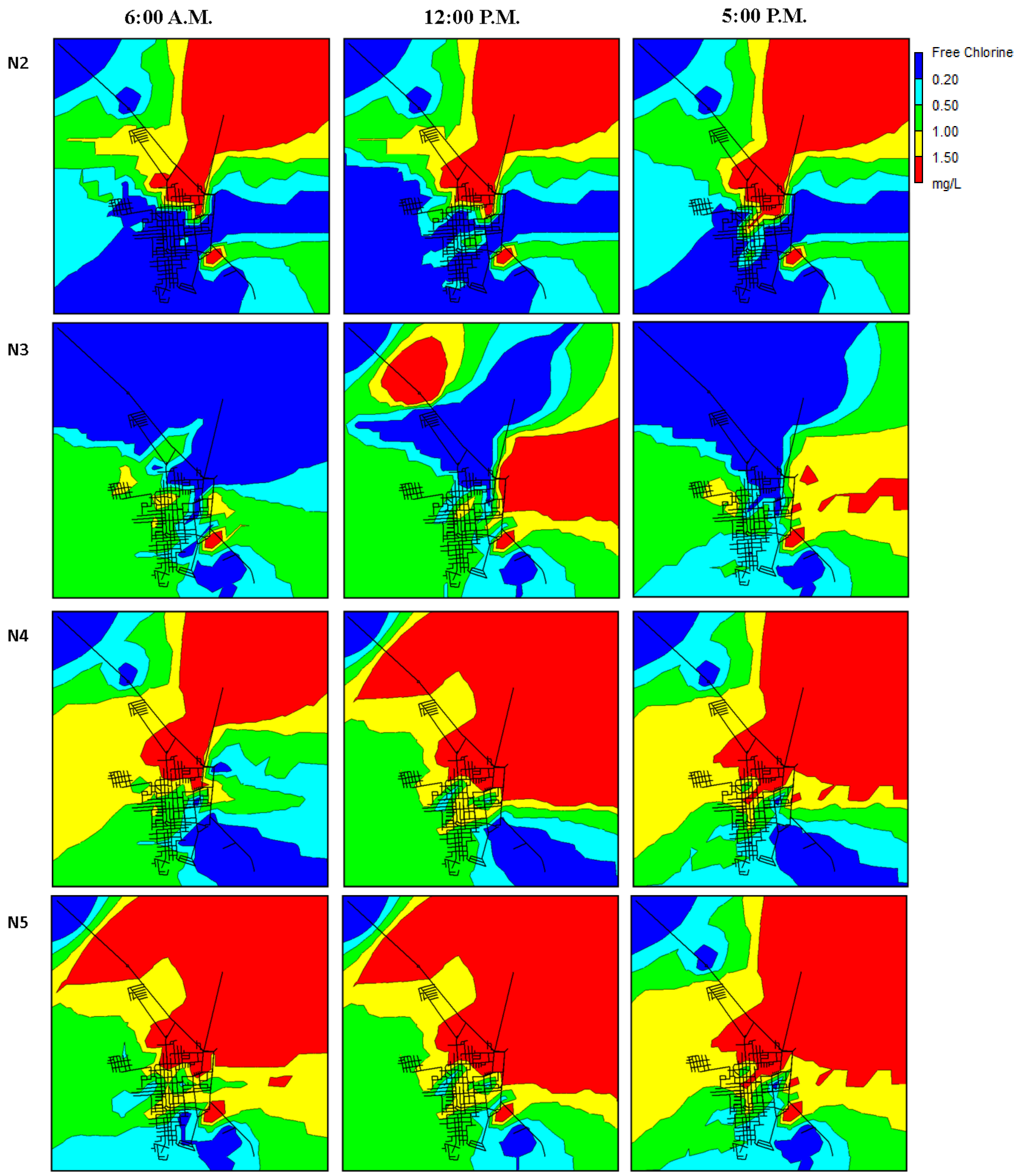

Figure 58 Contour of free chlorine predicted by models N2-N5

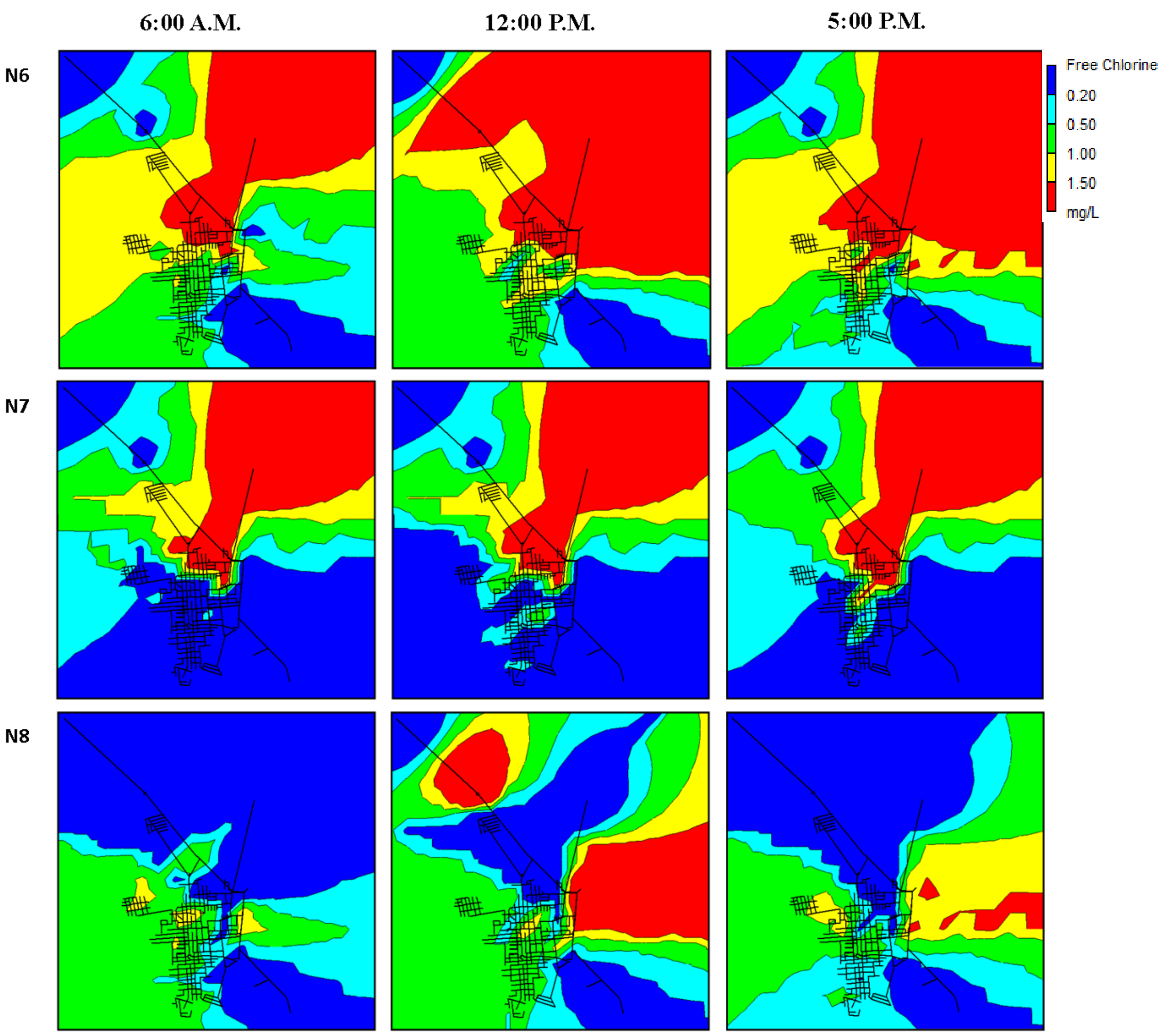

Figure 59 Contour of free chlorine predicted by models N6-N8

Table 11 Overview of sample sizes for each test

Sample type	**Number of samples**	**Year taken**
Storage tanks	3	2012
Storage tanks	3	2013
Households	12	2012
Households	18	2013
Supply	6	2012
Supply	4	2013
Surface	4	2012
Coliscan® Easygel® kit	16	2012
Coliscan® Membrane Filter	21	2013
Watersafe® Well Water Testing Kit	18	2012
Hanna Instruments Model HI 98129	26	2013
Hach Company Model CN-70	25	2013
Dionex ICS 1000	14	2012
Shimadzu TOC-VCSH	25	2013
Total visit 1	25	2012
Total visit 2	26	2013
Total	51	