Evaluating Stream Degradation in Villa De Allende, Mexico: The effect of rural development on the taxonomic richness and relative abundance of benthic macro-invertebrates in Mexican headwater streams

by
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EXECUTIVE SUMMARY

I examined the anthropogenic effects on the water quality of headwater streams in the western mountains of the state of Mexico. Rural development has negative effects on the ecology of local streams by diverting and pumping surface and groundwater, removing riparian forests for the construction of buildings, roads, and agricultural fields, and dumping refuse in stream channels. Local development, construction, roads, and agriculture also are sources of pollution that enter the streams during rain events. These negative ecological effects are common to many streams in the watershed of the Chilesdo dam. The combined effects of human development negatively affect the quality of surface water and groundwater aquifers.

The issue of anthropogenic effects on the water quality of headwater streams is relevant ecologically because of likely effects on flora and fauna that depend on these streams and because of the role of headwater streams in the context of the larger watershed. Effects on upstream areas directly affect people, animals, and plants downstream. This issue is relevant economically because rural communities depend on the availability of water of suitable quality for agriculture and livestock. In addition, local water quality directly affects the cost of water purification downstream at dams that feed the Cutzamala system, a major source of Mexico City's drinking water. This issue is relevant socially because the local community depends on this water for domestic consumption. Compromising water quality and abundance could destabilize the lives of local people because poor water quality and water contamination are a public health concern. Additionally, climate change is likely to make this resource scarcer. Projections for all major scenarios used by the International Panel on Climate Change indicate elevated year-round temperatures and decreased overall precipitation in the region (IPCC 2013).

I addressed concerns over water quality by testing differences among streams with anthropogenic alterations and a stream that had few anthropogenic alterations. I sampled benthic macro-invertebrate communities as indicators of water quality within the streams. Benthic invertebrates are a useful bio-indicator for water quality and environmental disturbances in river systems because different taxonomic groups of invertebrates have different tolerances to water pollution. I measured the abundance and taxonomic richness of invertebrates that exhibit different sensitivities to water quality.

My results revealed that taxonomic richness was lower in streams that had anthropogenic alterations. My results also revealed that the abundance of "sensitive" and "somewhat sensitive species" were lower and that the abundance of "pollution-tolerant species" was higher in streams with anthropogenic alterations. The stream with few anthropogenic alterations had the highest taxonomic richness and largest number of sensitive and somewhat sensitive species. These results indicate that human activities are having negative effects on water quality.

Given my results, I suggest that restoration of degraded streams should reduce water diversion, riparian encroachment, and refuse disposal. I propose solutions to guide these restoration efforts. My data suggests that a coordinated local and regional effort is

required to reduce the negative effects of human development and to restore local streams to an ecological condition that will sustain water quality and quantity to enable local communities and the local environment to thrive.

ACKNOWLEDGMENTS

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DEFINITIONS

ACRONYMS AND ABBREVIATIONS

BCIT – The British Columbia Institute of Technology

CABIN – Canadian Aquatic Biomonitoring Network

SFU – Simon Fraser University

IPCC – International Panel on Climate Change

WATER QUALITY

This is defined in my study as the suitability of water for human use and consumption. Ideally, water quality should be assessed based on physical, chemical, and biological characteristics to integrate the full spectrum of available information into water management (Metcalfe 1989). This study uses taxonomic richness of benthic invertebrates and abundance of sensitive invertebrates as a surrogate for measuring water quality suitable for human use.

BIOLOGICAL INDICATORS

Biological indicators ("bio-indicators") are species that have known responses to changes in the environment so that measuring the biological response of the bio-indicator can be used as a surrogate for measuring the change in some environmental parameter. The use of bio-indicators for the monitoring of water quality is based on data linking certain organisms to threshold levels of water quality (Li et al. 2010).

Experiments on many continents have demonstrated that monitoring benthic (i.e. bottom-dwelling) macro-invertebrates provides information on water quality, ecological functioning, the presence of disturbances, and other imbalances in a variety of freshwater ecosystems. This type of monitoring has been integrated into national water quality monitoring plans in Canada, the United States (Mandaville 2002), the European Union (Stoddard et al. 2006), and Australia (Chessman, 1995). There are several reasons why this is the case. (1) Benthic invertebrates are ubiquitous. They are affected by perturbations in many environments. (2) The large number of invertebrate species produce a range of responses. (3) Benthic invertebrates are sedentary and respond to local small-scale perturbations. (4) Stream invertebrates are relatively long-lived and can provide information about past perturbations and longer time periods. Also, (5) sampling is relatively easy and inexpensive (Mandaville 2002).

STRESSOR

The influences or factors that affect organisms and ecosystems are central to the study of ecology. The extent, frequency, and intensity of environmental factors determine the nature of their effects on organisms. These effects can be beneficial or detrimental. When environmental factors cause detrimental effects to organisms in an environment, these factors are classified as stressors. Examples of common detrimental effects associated with anthropogenic stressors include mortality of organisms and changes in structural elements (e.g., species composition, spatial distribution of biomass) (Freedman 2015).

There are several categories of stressors of interest to ecologists. Climatic stressors are associated with temperature, wind, precipitation, and solar radiation. Chemical stressors are excessive or deficient levels of substances that affect biological or physiological characteristics of organisms. Physical stressors are changes to the physical structure of an environment that alter physical processes or kinetic events that are intense enough to damage organisms or physical ecosystems (e.g., fire, floods, seismic activity). Biological stressors are negative effects on interactions between organisms. These include actions that disrupt trophic interactions and actions that reduce reproduction or survival of specific species. Finally, functional stressors affect ecosystem processes such as productivity and nutrient cycling (Freedman 2015).

RESILIENCE

Ecological resilience is defined as the capacity of a system to dynamically absorb a disturbance and reorganize during the process of change to maintain relationships and state variables. A resilient system retains essentially the same function and structure while undergoing changes brought on by a disturbance or stressor (Holling 1996).

SUSTAINABILITY

For the local people with whom I worked on this project, sustainability is a central tenet of their vision for the future. For these people, sustainability reflects the creation of ecological, economic, and social conditions that enable the local people to meet their needs in the present without compromising the needs of future generations (Bruntland 1987). This definition emphasizes the necessity of environmental sustainability and frames natural capital as something that cannot be duplicated or replaced.

In ecology, sustainability has been meant to refer to the persistence of a self-sustaining ecosystem that is resilient to disturbance and maintains the diversity of biological components and ecological functions through time (Clewell and Aronson 2013). Ecological sustainability is also a priority for the project sponsors and a reason for the current study.

DEVELOPMENT

I define “development” as a form of sustainable growth that integrates economic, social, and environmental domains with a focus on intergenerational equity. Traditional ideas of development prioritize economic growth and the priorities of markets. These measures of development have undervalued or ignored services provided by social and environmental capital, which are estimated to far exceed traditional economic measurements such as Gross National Product or Gross Domestic Product (Costanza 1997). Social and environmental capital in regions with highly diverse and productive ecosystems, such as Mexico, are likely to be even more valuable (Valero et al. 1998).

Because current patterns of development favour the exploitation of resources to prioritize short-term economic growth, consideration is rarely given to potential damage to social and ecological systems in the long term. A definition of development that accounts for the unique and irreplaceable contributions of social and environmental factors is necessary for a shift towards sustainability in the region (Banuri 2013).

Refuse

I define refuse as unwanted materials or substances discarded by local residents. This includes both items collected as municipal solid waste and improperly disposed waste products (discarded into environment or incinerated). In common usage, the term refuse is interchangeable with garbage, trash, or litter. The term “refuse” is used throughout the document for consistency.

INTRODUCTION

The research question as defined by the project sponsors asks what effect anthropogenic alterations typical of rural development have on the ecology of local streams. The assessment of the physical and biological state of river systems is a difficult and complex issue. River systems are the product of complex geomorphic, hydrologic, and biotic feedbacks operating at various scales in time and space (Poole 2002). The movement of sediment, water, and nutrients through the system create a continuum with specific features located at different parts of the system (Vannote et al. 1980). To provide relevant information for management, assessment should focus on a quantifiable measure that is sensitive to human actions. This study uses water quality, as indicated by invertebrate communities, as a quantifiable measure.

The following introductory sections provide foundational ecological knowledge requested by the sponsors. These sections will also place the current efforts in a broad regional context and provide necessary information for the sponsors to expand their vision of a sustainable regional environment.

STREAM ECOLOGY AND THE LEGACY OF DEGRADATION

Rivers are the natural arteries of landscapes that have sustained human populations for millennia. These freshwater channels cross the landscape and provide access to potable water, transportation, agricultural irrigation, a source of energy, and a variety of cultural and economic services (Brierley and Fryirs 2008). River systems are integral to the ecological functioning of entire landscapes, affecting both terrestrial and aquatic biota as well as human populations. Similarly, the physical landscapes and human populations have a large influence on the function and quality of stream systems (Allan 2004). Protecting these systems from the negative effects of anthropogenic land use change, water diversion, pollution, and physical modification is essential for a sustainable future.

There is scientific consensus on the widespread damage to river systems worldwide (Millennium Ecosystem Assessment, 2005) and there is severe pressure on the water resources that countless species depend on for a sustainable future (Brierley and Fryirs 2008). Threats to water quality are direct threats to global biodiversity. Over the past century, human actions have accelerated the natural rate of species loss by over 1000 times the background rate. Freshwater ecosystems such as the stream systems of Mexico have the highest rate of species loss (Millennium Ecosystem Assessment 2005). Current land-use changes and development patterns are expected to significantly increase the rate of biodiversity loss in coming decades.

Stream systems have been modified in almost every part of the Earth. Restoration actions have the ability to restore landscapes that have been degraded by human populations. The extent of current changes to river systems and the growth of populations often make restoration to historical pre-disturbance conditions unfeasible. River restoration practices should focus on slowing or reversing the trends of degradation (Brierley and Fryirs 2008).

Ecosystems affected by human activities can display a host of ecological problems. Some examples include invasive species that outcompete native vegetation, loss of native species, and decreased water and soil quality. These effects can often be reduced or eliminated with planning and restoration. A first step to enable this process is the elimination or reduction of system stressors. This can set the stage for natural successional processes to resume with minimal human maintenance. This is accomplished by creating a set of relationships and conditions that favour the natural systems suited to a specific area (Clewell and Aronson 2013). Examination of ecological principles, biological systems, and the underlying physical structure of the Earth can provide a vision for a complex and productive natural system in the degraded areas (Rieger et al. 2014). The science of ecological restoration is dedicated to reversing this process of degradation and restoring the earth for the benefit of humans and the environment.

The protection and restoration of river systems in Mexico has a number of challenges. Despite a comprehensive legal system, a national water authority, and a system of water rights, several challenges remain. These include lack of funding, few background data, low levels of community support, weak government enforcement of existing regulations, and the absence of adequate environmental education that promotes local stewardship (AQUASTAT 2013).

An analysis of in-stream benthic macro-invertebrate populations in local streams (both anthropogenically altered and relatively undisturbed) is intended to demonstrate the adverse effects of water diversion, riparian encroachment, and refuse disposal on the water quality of the study streams. Benthic invertebrate type and abundance are useful indicators for a variety of changes in streams, including inadequate flows, altered nutrient levels, and the presence of toxins (Chessman 1995). My research provides a basis for local and regional efforts to restore and protect streams.

HEADWATER STREAMS IN THE LANDSCAPE CONTEXT

A regional watershed, also known as a drainage basin, is defined as a geographic area where all surface water converges to a single point. The purpose of delineating watersheds is that the hydrological cycle ties terrestrial and aquatic processes together and creates a single functional landscape with a shared and interdependent ecology (Gordon et al. 2004).

All restoration projects should be embedded within the larger landscape. The linkages among terrestrial and aquatic processes throughout a drainage basin mean that successful restoration should be planned and executed at a watershed level. Restoration work that takes a holistic perspective will be effective by taking into account potential changes from upstream regions. Hill slope stabilization and the normalization of altered drainage patterns are necessary before work can be done successfully in downstream areas (Slaney and Zaldokas 1997).

The sources of most regional watersheds, including the watershed that drains to the Chilesdo dam, begin on forested mountain slopes with a network of headwater streams. Headwater streams are the networks of small high-elevation streams that are the origin of most rivers. These streams comprise up to 80% of all river systems and regulate the movement of sediment throughout the watershed. Headwater streams have unique characteristics that differentiate them from downstream reaches. Streams are typically incised into V-shaped valleys with steep slopes. The channel consists of coarse gravels and boulders. Water temperatures are usually lower than downstream reaches and relatively stable due to high vegetative cover. Most nutrients for fungi, bacteria, and invertebrates are supplied by inputs from the surrounding riparian area and surrounding hill slopes (Gordon et al. 2004).

Headwater streams are strongly coupled to the hill slopes that surround them. Sediment and nutrients flow from hill slopes into stream channels. Tributaries are also strongly coupled to main channels, having strong effects on downstream confluences (Brierley and Fryirs 2008). Accordingly, changes to the function of headwater streams can have negative effects on downstream reaches. Effects on water quality from stream alterations or pollution in headwater streams have cascading effects throughout entire river systems. Changes in the upstream catchment affect downstream hydrology and ecology (Gordon et al. 2004).

Forest cover removal in headwater areas can have effects on the entire watershed. Forest removal influences interception, precipitation, and evapotranspiration. Excess soil moisture and increased susceptibility to wind events can lead to tree windthrow and erosion. This process further contributes to forest loss in a positive feedback loop that repeats the cycle, leading to further degradation (Benda et al. 2005). Vegetation removal due to logging or conversion to agriculture changes the patterns of hydrological flow and sediment transport. Construction can be a major source of sediment, and the creation of impervious surfaces for housing and roads increases total runoff and the magnitude of peak flows (Gordon et al. 2004).

Ecosystem services provided by headwater streams include the recharge, purification, and distribution of surface and ground water, the movement of nutrient-rich sediments, and the ecological and physical processes that produce diverse terrestrial and aquatic ecosystems. Headwater streams that are partially fed by groundwater spring sources can provide refugia for invertebrates when seasonal surface flow conditions are low. These areas of refuge become essential for aquatic invertebrate species when anthropogenic flow diversion causes an amplification of seasonal low flow conditions (Thorp and Rogers 2011). Aquatic and terrestrial ecosystems throughout an entire watershed depend on the timing, magnitude, and temperature of stream flows. Alterations to streams that affect these characteristics can have effects that cascade throughout the entire watershed.

Headwater streams also perform physical functions in a water basin. The material transport of sediments within stream systems is a critical function in the regional ecology. Transport of wood, water, and sediment, primarily through debris flows and alluvial transport in flood events, is an influential component in the creation of the downstream physical environment used by fish and other aquatic species. Headwater streams recruit, transport, and store sediments that are released into higher-order streams over time. These processes are natural but have been amplified by anthropogenic alterations either directly (road construction, timber harvest), or indirectly (changes to flood and fire disturbance regimes) (Benda et al. 2005).

The linkages among headwater processes and stream networks at lower elevations cannot be over-emphasized. Harvesting of timber resources at upstream locations can destabilize hill slopes and result in debris flows and landslides that damage property and infrastructure. The scale and frequency of natural disturbances can be exaggerated by forestry and agricultural practices. Flows of sediment and debris can overwhelm a stream system and make their way downstream to areas that are already degraded (Benda et al. 2005).

Pollution from nutrient flows and toxins in headwater streams also contribute to serious problems in downstream reaches. The potential for severe ecological, economic, and social consequences make the protection of headwater streams important in regional ecological restoration. Any regional vision for sustainable and responsible development will benefit from a watershed-scale perspective. This perspective is critical when protecting, restoring, or altering the physical and biological environment of any stream.

Surface Water and Ground Water

Rural development in Mexico is characterized by a reliance on local ground and surface water resources (UN 2006). Studies in the United States have demonstrated the linkages between groundwater resources (aquifers) and surface water (lakes and streams). Much of the groundwater contamination in the U.S. is in shallow aquifers with direct connections to surface stream. Pollution in surface streams can affect the water quality of sub-surface aquifers (Winter 1998).

In Mexico, over 70% of water bodies have some degree of contamination that causes concerns for human health and the dynamic stability of many ecosystems (AQUASTAT 2013). Contamination of groundwater is a threat to human health. The primary threats to water quality also include the over-exploitation of groundwater resources and alteration of environmental flows (AQUASTAT 2013). The unsustainable patterns of water use that have led to this situation in much of rural Mexico are evident in Villa De Allende.

It is assumed by local residents that the water quality of groundwater is safe for consumption without treatment. Demonstrated linkages between surface water contamination and shallow aquifer contamination show that the actual picture is more complicated. The connections between ground and surface water are complex and assist in regulating water quality (Winter 1998). Groundwater sources were previously widely believed to be impervious to pollution by regulators in the United States. Decades of research have gradually proven this assumption false (Cunningham and Cunningham 2006). Groundwater resources are closely linked to surface water and soil processes.

Contamination sources include septic tanks, waste disposal sites, agricultural fertilizers and pesticides, animal wastes, and atmospheric contaminants carried in rainwater (Cunningham and Cunningham 2006).

The incidence of cancers and other chronic diseases has been correlated with the presence of increased levels of nitrates in surface and groundwater sources (Millennium Ecosystem Assessment 2005). Infiltration of nitrates into groundwater resources is common in rural areas with high levels of agricultural land conversion. Populations reliant on groundwater for domestic consumption are at risk.

The interactions between surface water and ground water in headwater streams is particularly variable. Seasonal changes cause an alternating pattern of surface and ground water infiltration (Winter 1998). This has implications for the transfer of pollution and contaminants from the surface to deeper groundwater sources and vice versa. Hydrological connectivity between surface and groundwater occurs through various temporal and spatial scales. The extent of this connectivity is determined by local morphological conditions and catchment geology. The hyporheic zone enables interchange between surface flows and shallow aquifers (Hancock, Boulton, and Humphreys 2005). During dry periods, interstitial flow connects surface water to deep groundwater resources (Stanford and Ward 1993).

The withdrawal of water from shallow aquifers can affect on the movement of water among the aquifer and surface water streams. Possible effects include the reduction of surface flow, changes in the direction of aquifer-stream interactions, and alteration of the pattern of recharge and discharge. The combined effect of multiple pumping locations or wells can be regional in scale and can extend far beyond the location of pumping (Winter 1998).

Rural Development and the Ecological Balance

In recent decades, the population of Mexico has been undergoing a shift towards living in urban areas. The population of Mexico has quadrupled since 1950, putting enormous pressure on resources. With most of this growth occurring in urban areas, development has transformed the landscape of many areas unrecognizably. Still, 23.5% of the population lives in rural areas. This amounts to almost 25 million people as per the 2010 census (Conagua 2010). These populations have patterns of development quite different from those of urban populations. Rural areas are characterized by higher rates of poverty, low rates of drinking water provision, and a lack of improved sanitation coverage. Waste collection is also quite rare in rural areas, with burning and illegal dumping commonplace.

The most pressing concern for water resources in Mexico is scarcity. Local systems are often unable to provide water of sufficient quantity or quality to growing populations. The causes of this scarcity are the increasing and unregulated demand of groundwater resources, population growth and economic development, deforestation and soil erosion, pollution and contamination, and the escalating effects of climate change (AQUASTAT 2013). The patterns of rural development in upstream regions such as Villa de Allende directly affect the quantity and quality of water in downstream reaches. This has social, economic, and ecological repercussions for millions of people in the region.

The pollution or contamination of groundwater resources can lead to serious consequences for the health of rural populations. Rural communities in Mexico often rely on untreated ground and surface water resources for local consumption (AQUASTAT 2013). Because this water is not regularly tested or treated, the possible effects of toxins, algae blooms, industrial and agricultural effluents, and human wastewater are potentially severe. Toxic pollutants from urban sources are also likely to find their way into local surface and ground water. These include nitrates, sulphates, arsenic, cadmium, mercury, and other toxins from fossil fuel combustion. Rural areas such as Villa de Allende are still at risk from these sources due to atmospheric transport from regional urban areas like Toluca and Mexico City. Toxic organic compounds such as DDT, PCBs, and dioxins are also transported long distances by atmospheric winds (Cunningham and Cunningham 2006).

The rural communities depend economically on the availability of water of suitable quality for agriculture and livestock. Also, the water quality of upstream areas directly affects the costs of water purification downstream at the dams that feed the Cutzamala system, a major source of Mexico City's drinking water (Conagua 2010). The cumulative effects of small incidents of contamination upstream can transform into serious costs at water purification facilities.

There are also ecological consequences for effects on stream water quality. The flow between surface and ground water creates a dynamic ecosystem used by aquatic invertebrates near the surface. Numerous studies have shown that these organisms are part of a food web that sustains a diverse ecological community (Winter 1998). Disrupting this complex and interdependent system can have far reaching implications.

Forest cover loss in the rural areas of Mexico State is caused mainly by land use conversion to agriculture and (largely illegal) logging. However, these processes are amplified by losses in existing forest density for subsistence use by local populations. These changes are much harder to track than full forest loss due to land-use changes (Franco-Maass et al. 2008). The loss of regional forest cover has been positively correlated with decreases in precipitation (Millennium Ecosystem Assessment 2005). Land use changes in the Villa de Allende that result in the removal of forest cover are likely to place further stress on local water resources.

The forests of the region have been extensively exploited as a part of the pattern of rural development. Pine trees are the most desirable for their high quality and are the target of both legal and illegal logging. Clear cutting and burning is also often done to clear land for agricultural purposes (Valero et al. 1998). The result of this logging and land conversion is an alteration of the physical environment used by local animal species and soil erosion. The abrupt topography creates the conditions for accelerated erosion rates when combined with the removal of vegetation coverage. This surface erosion leads to poor water retention, reducing infiltration to groundwater resources (Valero et al. 1998). Loss of forest cover is also linked to a loss of nesting locations for local bird species and a reduction in the extent of over-wintering areas used by threatened Monarch butterfly populations (*Danaus plexippus*). Fragmentation of forested areas due to agricultural land conversion is a reason for recent declines in Monarch populations (Conabio 2013).

Fragmentation of landscapes due to land-use changes is a threat to preserving local biodiversity. Villa de Allende is already a priority area for biodiversity protection under Mexican law (Saenz et al. 2006). Much current research focuses on the importance of refuge areas for wildlife as well as the importance of connections among these areas. Stream channels help maintain connectivity among the forests at higher elevations and downstream areas where land use conversion is more prevalent (Rieger et al. 2014). Maintaining the connectivity of landscapes is a critical factor in sustainable rural development.

ATTESI STREAM RESTORATION

PROJECT OVERVIEW

I examined the effect of rural development on the ecological pattern of benthic macro-invertebrate population richness and abundance in four Mexican streams. I used the presence or absence of three common anthropogenic alterations (water diversion, refuse disposal, and riparian encroachment) to determine if a particular stream reach has been affected by rural development. I measured benthic macro-invertebrate communities because these species are a biological indicator of water quality and environmental change over time (Li et al. 2010). I used a reference system approach (Hughes et al. 1986) to compare community richness and relative abundance of defined taxonomic classes between degraded ("treatment") streams and a minimally affected ("control") stream.

I collected data on the relative abundance and richness of benthic macro-invertebrate communities using the Surber sampling method commonly used in shallow streams, a standardized method used by many invertebrate monitoring programs in the U.S.A. and Canada (Page and Sylvestre 2006). I sampled in stream reaches defined by the presence or absence of rural development effects. I chose streams for similarities in size (bank full width), tributary stream order, flow, and temperature. I classified the collected invertebrates into three general categories of pollution sensitivity based on common classifications used in stream assessment by the Streamkeepers Program created by Fisheries and Oceans Canada (Fisheries and Oceans Canada 2000).

PROJECT BACKGROUND

In 2016, Attesi coordinated with the Ecological Restoration Graduate Program at SFU and BCIT to perform a study of the local stream ecology. I conducted a study focused on a single stream running through the Attesi permaculture farm in Villa de Allende, Mexico. The study aimed to improve understanding of the stream system and the pressures from human development in the region. My study provides recommendations to guide Attesi's vision of a sustainable local development.

HISTORIC CONDITIONS

A pattern of sustainable land use for agriculture has existed in the region for thousands of years. Indigenous populations grew maize, beans, and squash in the region long before European contact. At the time of contact, the area was under the jurisdiction of the Aztec empire in the adjacent Valley of Mexico. Historical agricultural patterns involved a series of crop rotations which prevented erosion and conserved nutrients in the soil (Saenz et al. 2006).

Human pressure on local ecosystems expanded after the Spanish conquest. New settlements were established to support gold and silver mines in the area and increasing amounts of forestland were cleared for agriculture, domestic animals, and construction materials. The 20th century saw an extensive amount of regional environmental change due to population growth, agricultural expansion, illegal logging, and the construction of new settlements (Farfán et al. 2007).

Since the establishment of the state of Mexico, the forested western regions of Mexico state have been steadily converted to agricultural fields. Expansion of agricultural areas has reduced forest cover by an estimated 70% (Valero et al. 1998). Construction of transportation networks and other infrastructure projects has also increased the amount of impervious surfaces in the region and affected hydrological patterns.

Water consumption has increased steadily throughout the twentieth century, with an increasing reliance on groundwater resources to supplement rainfall and surface water flows (Conagua 2010). Mexico now has one of the highest per capita water consumption rates in the world (UNDP 2006). Past models of development emphasized the provision and security of water resources with little thought for environmental sustainability or social consequences. This led to the rapid exploitation of water resources and severe alterations of regional drainage patterns (Brierley and Fryirs 2008). The installation of small scale pumping systems is commonplace. These most often connect to spring water sources, underground aquifers, and surface water sources. Each water user collects pumped water in individual water tanks. Local municipalities and community groups usually regulate access and use.

Recent changes in agriculture in the region include a shift towards single crop monocultures (mainly maize) and an input-heavy model reliant on industrial fertilizers and pesticides. Mechanized agriculture has become the primary method of cultivation (Municipal Geographical Information Handbook of the United Mexican States 2009). This has resulted in a steady decline in soil productivity over the past few decades with some plots being abandoned due to an inability to afford the high costs of these inputs in the face of decreasing yields. The main causes of losses in soil productivity are the removal of vegetative cover, lack of crop rotation, inappropriate use of fertilizers, overexploitation of aquifers, non-adoption of soil conservation practices, and overgrazing (Saenz et al. 2006).

STAKEHOLDERS

Stream management involves taking into account the varying and occasionally conflicting interests and perspectives of various stakeholder groups. These priorities include recreation, wildlife conservation, water supply, drainage, irrigation, industrial use, and social or cultural uses. These priorities affect the way stream resources are valued and successful management should find a way to balance the varying needs and interests of all stakeholders (Gordon et al. 2004).

Goals of restoration activities are likely to be broadened by co-operation with local and indigenous perspectives. These goals can include the restoration of subsistence-use activities, a focus on cultural keystone species, developing sustainable local economies, restoring traditional land management, and the revitalization of language, culture, and traditional knowledge (Kimmerer 1998). Reconnecting people to the land is one of the most powerful ways to protect it.

Project Sponsor – Attesi: Cultura en Transición

Attesi is an organic farming collective and permaculture education group. Founders Gabriel Mondlak and Moy Schwartzman have led the Attesi project since 2013. Attesi sponsored the current study to begin to understand the degradation of local landscapes.

The Attesi permaculture farm and education centre is in the municipality of Villa De Allende, Mexico. The centre works to explore strategies for revitalizing local agriculture through the integration of sustainable "permaculture" techniques. The centre focuses on soil rehabilitation techniques, intentionally using seasonal patterns of mixed crops to improve yields, store nitrogen, remove contaminants, build biomass, and restore productivity.

Indigenous Groups

The Mazahua people, the largest indigenous group of Mexico, have occupied the region since before European contact. Over three hundred thousand Mazahua people live in Mexico in the border regions between the states of Mexico and Michoacán, including the municipality of Villa de Allende (Figure 1). Other local indigenous groups include the Matlatzinca, Otomi, Nahua, and Purhupecha (Farfán et al. 2007). The Mazahua economy is mainly agricultural, producing maize, beans, wheat, barley, potatoes, and livestock. Gathering of local plants compliments the economy by providing food, medicine, and tradable goods.

Disconnection of indigenous communities from water and landscapes due to colonial history and modern development created a long-lasting legacy of degradation, mismanagement, and an institutional distrust that complicates restoration efforts (Connor et al. 2004). Local feelings of alienation might be amplified by lack of access, cultural changes, or lack of input in local or regional management. For a more detailed analysis of indigenous groups and water rights in the region surrounding Mexico City, please refer to Appendix E.

Figure 1 - Region occupied by Mazahua Indigenous Group (Farfán et al. 2007) with project location indicated, Michoacan and Mexico State, Mexico.

LOCAL COMMUNITY - VILLA DE ALLENDE

The municipality of Villa de Allende is one of 125 municipalities in the State of Mexico. The municipality is located in the regional valley of Quencio (also known as the valley of Zitacuaro). Villa de Allende covers an area of 309.28 km^2. The population is 52,641, as of the 2015 census (Instituto Nacional de Estadística Geografía e Informática, Mexico 2015).

The closest town to the project site is San José Villa de Allende. The town covers 0.609 km^2. The population is 1354, as of the 2010 census (Instituto Nacional de Estadística Geografía e Informática, Mexico 2010). The local community uses local ground and surface water resources. These users include several hundred inhabitants in unincorporated areas surrounding San José Villa de Allende.

Rural areas typically rely on environmental services in a variety of ways that are rarely measured or taken into account by national statistics or poverty assessments. This is especially true in forested areas. Recent studies with data synthesized from 17 countries have shown that 22% of income in rural households comes from sources not accounted for in national statistics (Millennium Ecosystem Assessment 2005). These include harvesting wild food, fuel-wood, fodder, medicinal plants, and timber. Studies in local indigenous communities confirm that this pattern of reliance on ecosystem services is an essential contributor to the economy of Villa de Allende (Farfán et al. 2007).

A collection of geographical and statistical information about the municipality is included as Appendix F (Municipal Geographical Information Handbook of the United Mexican States 2009).

PROJECT SITE

The project site is in the municipality of Villa De Allende in the state of Mexico - a mountainous region 140 km west of Mexico City at an elevation of 2380 m. The average temperature is 14.9 C. The region experiences an average rainfall of 982 mm/year, with the majority of the rainfall occurring in summer (Saenz et al. 2006). The local environment features a network of forested headwater streams draining to the Chilesdo dam. Forests consist primarily of Montezuma pine (*Pinus montezumae*) and white cedar (*Cupressus lindleyi*).

Attesi is near the town of San Jose Villa De Allende. The economy is primarily agricultural, growing corn, wheat, potatoes, beans, and livestock. Riparian areas have been reduced to the edges of stream channels to convert available land to agriculture. The managers of Attesi are interested in reducing the reliance of local farmers on industrial farming and using ecological restoration to improve the condition of the local environment.

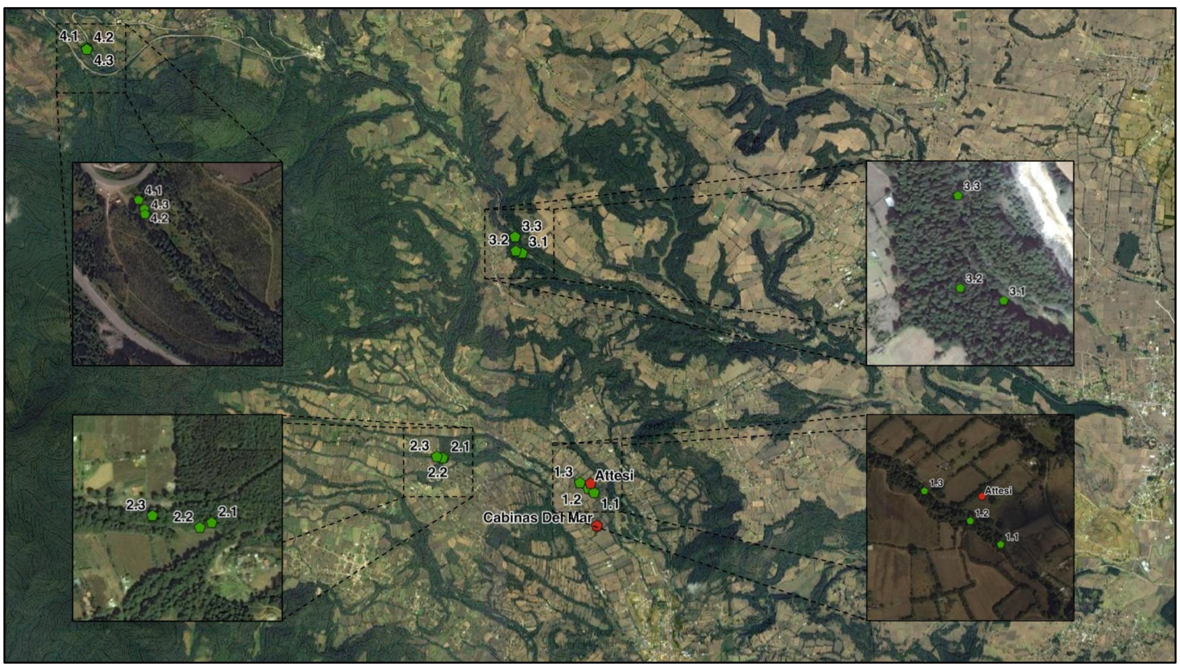

Figure 2 - Map of Attesi and sample locations (inset), Villa De Allende, Mexico. Map Scale = 1:20000, Inset Scale = 1:2500.

CURRENT CONDITIONS

Mexico is classified into over 50 ecological zones that reflect the climate and weather patterns. The project site is located within the Trans-Mexican Volcanic Belt pine-oak forest eco-zone (Ecological Regions Of Mexico 2017).

Conabio, the Mexican conservation agency, has designated Villa de Allende a priority region for conservation due to its unique biological characteristics and the threats and pressures on flora and fauna from human populations and development (Saenz et al. 2006). Some common threats to the general ecology of the region include high levels of air pollution from Mexico City, commercial logging, land conversion for cultivation, overgrazing by livestock, and fragmentation of remaining forest patches (WWF n.d.).

Physical Conditions

Villa de Allende has a subhumid temperate climate. Average monthly temperatures range from 10-18 degrees Celsius. Average precipitation ranges from 1000-1200 mm annually, mainly falling in summer (Municipal Geographical Information Handbook of the United Mexican States 2009).

Land use in Villa de Allende is primarily agricultural and pastoral (59%), with forests mostly on mountain slopes and along streams and rivers (39%). Urban development occupies only about 2% of current land use (Municipal Geographical Information Handbook of the United Mexican States 2009).

The region of Villa de Allende is noted for the mountains of Sierra de San Miguel in the West. These mountains provide refuge for endemic plant and animal species (Saenz et al. 2006). The drainage point of the local topography is the Bordo Presa Chilesdo (Chilesdo Dam).

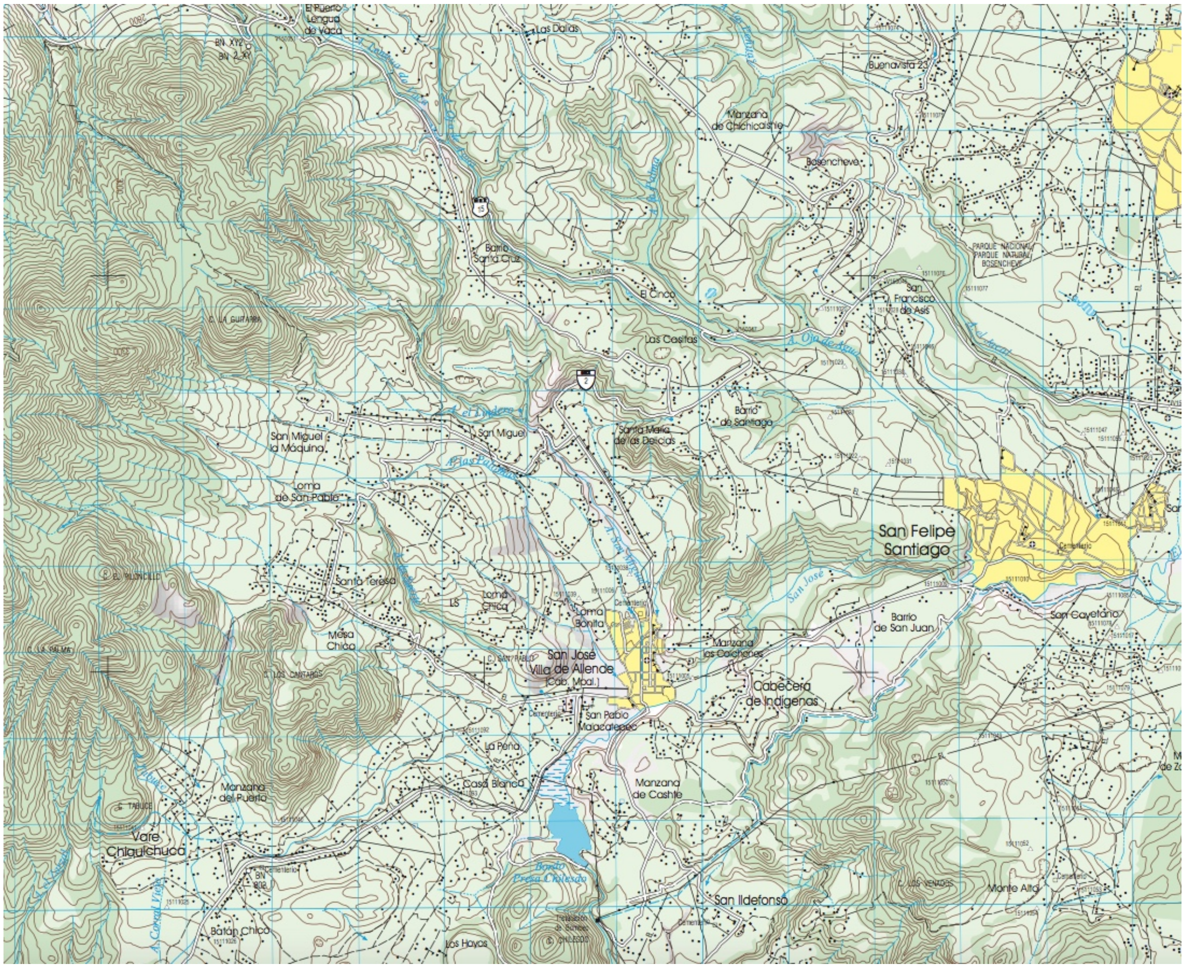

Figure 3 - Topography of Chilesdo Dam Watershed, Villa De Allende, Mexico. The drainage point is the Bordo Presa Chilesdo in the bottom centre of map. Scale = 1:50000.

Soil degradation and erosion are common in Villa de Allende due to the removal of vegetative cover (Saenz et al. 2006). Deforestation, agriculture, and urbanization all increase rainwater surface flows, reduce interception and infiltration, and alter stream flow patterns. These changes can also often have adverse effects on groundwater quality (Galatowitsch 2012b).

A network of headwater streams characterizes the regional hydrology. These form ravines and gullies in the landscape. Soil erosion due to land conversion amplifies this natural process (Saenz et al. 2006). These streams are all part of the Rio Tilostoc water basin in the Balsas hydrological region (Municipal Geographical Information Handbook of the United Mexican States 2009). The local watershed drains to the Chilesdo dam, one of seven regional dams that feed the Cutzamala system. The dam is at 2396 m elevation and has a capacity of 1.5 million litres (Agua.mx.org 2009). This water goes to the larger Valle de Bravo dam and reservoir. Figure 4 shows the Chilesdo dam in the regional network of dams and reservoirs that is the Cutzamala system.

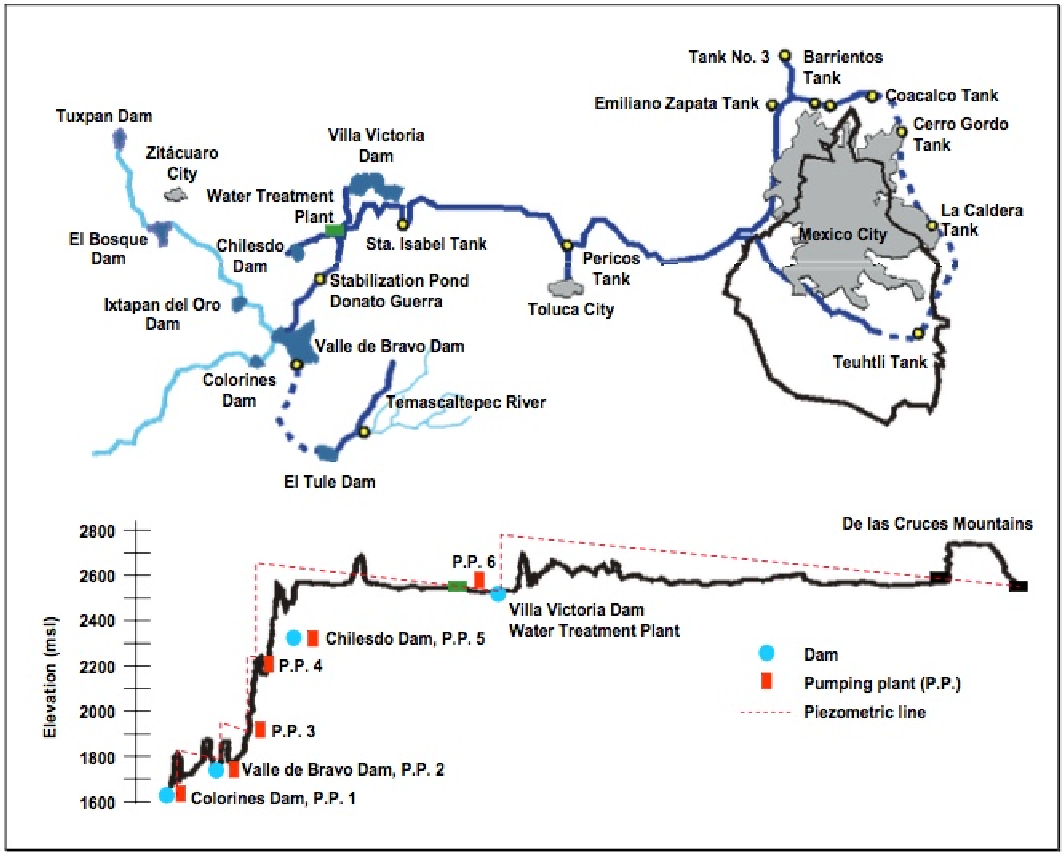

Figure 4 - Overview of Cutzamala system, Mexico State, Mexico (Tortajada 2006).

Municipal reports identified a number of risks to water quality in Villa de Allende. These include sewage discharge, excess use of agricultural chemicals (i.e. fertilizers and pesticides), animal waste, and discharge of household soaps and detergents (Saenz et al. 2006).

Local users drink the groundwater untreated and often unfiltered, suggesting acceptable levels for human consumption. However, effects on human health due to contamination might take time to become evident in local populations. Chemical water quality testing can determine specific levels of contaminants. Water quality guidelines from Health Canada are provided in the recommendations section pertaining to chemical testing (Health Canada 2017). In addition, the current standards for water discharge in the state of Mexico are included in Appendix D for reference (Conagua 2010).

Biological Conditions

The forests of the Trans-Mexican Volcanic Belt are a home to over 370 endemic plant and animal species (WWF n.d.). Villa de Allende contains many unique plant communities representative of this system and is a biological corridor for animals in a zone of biogeographic transition (Saenz et al. 2006). Measures to protect the physical environments that support many species have been repeatedly complicated by land conversion to agriculture and illegal logging (Saenz et al. 2006).

The forests of the Trans-Mexican Volcanic Belt feature the highest diversity of reptiles and amphibians in Mexico (WWF n.d.). The Trans-Mexican Volcanic Belt is home to the volcano rabbit (*Romerolagus diazi*) and the Mexican volcano mouse (*Neotomodon alstoni*), both endangered species (WWF n.d.). The regional forests are the winter hibernation grounds of the Monarch butterfly. The Monarchs travel between 4,000 and 6,500 km annually, the longest migratory route known for any insect (WWF n.d.). Development and agricultural land conversion have led to a loss of regional breeding areas for the Monarchs and their numbers have experienced a steady decline in the past few decades (Flockhart et al. 2015). The Monarchs do not currently use the forested areas of Villa de Allende for breeding.

Dominant canopy vegetation in the local streams include the Montezuma pine and white cedar. Understory vegetation includes a diverse group of shrubs, herbs, and grasses. Forests of *Pinus* and *Cupressus* are common in Villa De Allende. At lower elevations, forests of *Pinus* and *Quercus* (oak) are common.

Mexico is one of the greatest reservoirs of traditional ecological knowledge in the world because of its natural and cultural diversity. Ethnobotanical studies have identified over 5000 useful plant species with patterns of traditional use by over 58 indigenous ethnic groups. A 2007 study of indigenous plant use in the Mazahua village of Francisco Serrato in Michoacan (less than 30 km from Attesi) detailed 213 useful plant species and 31 species of edible mushrooms. Over 75% of these occur only in wild areas. The most commonly consumed local fruit species are blackberries (*Rubus liebmannii*), capulin (*Prunus serotina*), and tejocote (*Crataegus Mexicana*). Several species of leafy greens are also consumed, with *Brassica campestris* being the most popular. *Satureja macrostema* is commonly used to produce a stimulant tea and *Agave atrovirens* is used to prepare the alcoholic beverage “pulque” (Farfán et al. 2007). These culturally important species are possible candidates for planting in future restoration actions.

STRESSORS

I identified four main stressors to the area around the Attesi Permaculture Centre: 1) Stream diversion and pumping, 2) Riparian forest encroachment, 3) Refuse disposal in the stream channels, and 4) Construction activities in the stream channel.

STREAM DIVERSION

Stream diversion and channel alterations are evident in several local streams. Streams have been diverted to enable road and bridge construction and to channel water to collection areas for agricultural irrigation. Altered flow regimes can influence the mobility of organisms, dissolved oxygen levels, temperature, the cycling of organic nutrients, riparian vegetation, and in-stream biota (Gordon et al. 2004).

Flow manipulation and diversion is the greatest human effect on river systems worldwide (Postel and Richter 2003). There are several reasons why flow manipulation can severely affect river ecosystems and biotic communities. (1) Flow regimes shape the physical environments for plant and animal species specifically adapted to local conditions, (2) Survival and reproductive strategies of many species are dependent on flow regimes, (3) Many species require adequate depth at critical times for refuge, reproduction, or movement, and (4) Altered flow regimes can favour exotic and invasive species (Bunn and Arthingon 2002).

Pumping of groundwater is extensive in the rural areas of Villa De Allende. Inadequate municipal water infrastructure means that local populations often rely on groundwater pumping for domestic use. A cooperative municipal council manages the local water resources in San Jose Villa De Allende. A lack of comprehensive hydrological information about underground aquifers and recharge suggest that this management could benefit from an in-depth study. Sustainable groundwater extraction is only possible if managers fully understand the local water budget.

Culverts have been installed in several areas to enable road or bridge construction. Several of these are constructed with a considerable gap between the outflow and the stream channel below. This leads to scouring outflows in high water events and contributes to sedimentation and stream erosion. Both of these effects are associated with low water quality (Slaney and Zaldokas 1997).

Riparian Zone Encroachment

The riparian zone is the area of interface between terrestrial ecosystems and a river or stream. This region extends beyond the stream channel and changes here can influence water quality and other in-stream processes (Figure 5). These areas serve important functions in both terrestrial and aquatic ecosystems (Clewell and Aronson 2013).

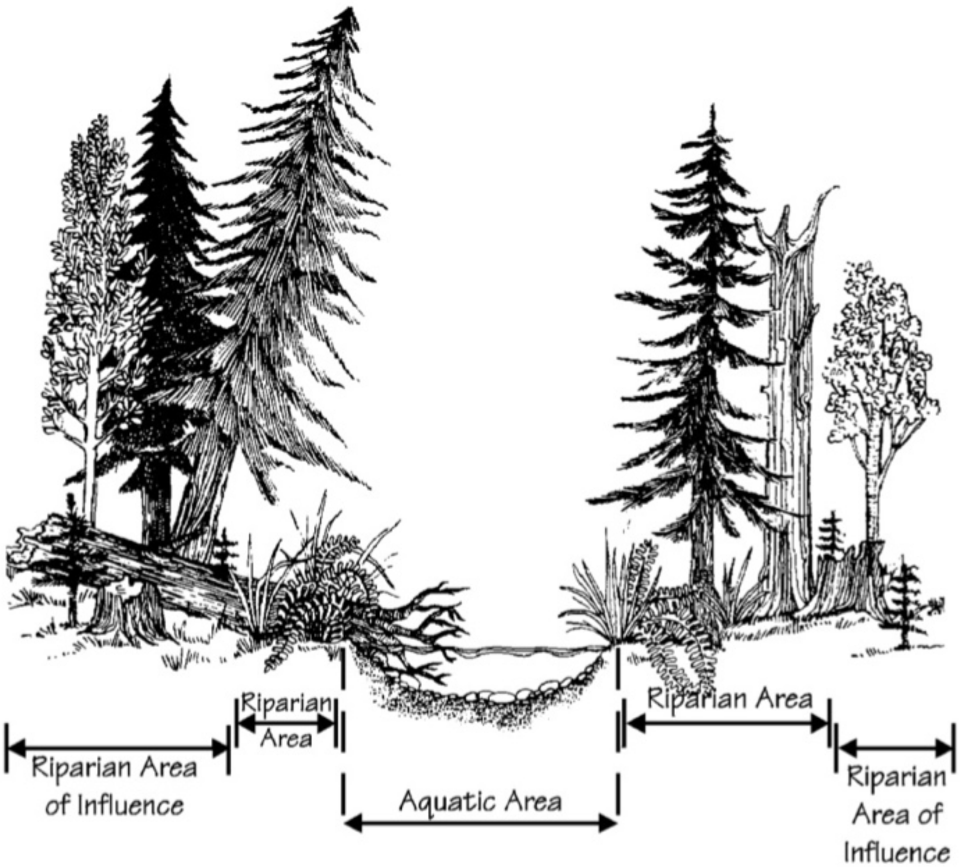

Figure 5 - Riparian Zone with zone of riparian influence indicated (BC Streamkeepers 2000).

Riparian areas in Villa de Allende consist mainly of forested patches along the edges of stream channels. These areas are often less than 10 m wide and are inadequate to filter organic pollutants, nutrients, and contaminants from the surrounding landscape (Hawes and Smith 2005).

Historical aerial photos show little change in the extent of agricultural development over the past 30 years. However, land use changes in the modern era have resulted in a loss of over two thirds of the forest cover in the state of Mexico (UN 2006). Locally, almost all available land has been converted to agricultural use, leaving only steep high elevation areas unsuitable to agriculture and stream corridors with dense forest coverage (Saenz et al. 2006). Land-use changes have a significant effect on stream systems by affecting sediment inputs, runoff rates, flow regimes, and introducing chemical pollutants. Agricultural processes that till the soil and remove surface vegetation reduce rainwater infiltration. Conversion of land to agriculture has been shown to increase peak flows and reduce base flow (Gordon et al. 2004).

Remaining forests are concentrated in steep highland areas unsuitable for agricultural use and along ravine channels of headwater streams. Common ecological results of forest cover loss include soil erosion, increased susceptibility to floods and landslides, loss of biodiversity, and imbalances in the hydrological cycle. Land conversion for agriculture also causes increased erosion of stream channels and incising in headwater streams. Siltation of the stream bed substrate occurs as runoff from exposed soils and enters the stream in rain events (Gordon et al. 2004).

Illegal logging is also a serious problem in the municipality of Villa de Allende. This occurs mainly in the upper part of the Sierra de San Miguel, in the border area with the state of Michoacán. In the 1990s large areas of the already depleted forest were felled, estimated to be more than 1% of the territory of Villa de Allende, including protected areas of the Monarch Butterfly Reserve (Saenz et al. 2006). The threat of continued deforestation due to logging remains because of a passive attitude among federal and state authorities. Small-scale logging continues to occur within forested areas.

A network of trails exists both within the stream and in the surrounding riparian forest. The local community use these trails to access and cross the stream. No current regulations exist to regulate this trail network.

Refuse Disposal

A variety of waste items are disposed of in local stream channels. Initial stream surveys revealed items such as discarded tires, old pipes used for pumping ground and surface water, wrappers and other plastic items from commercial food products, diapers, shoes and clothing, broken glass, aluminium cans, household rubbish, and lengths of barbed wire from discarded fences. These items were distributed throughout local stream channels, occasionally in large quantities. This reduces the aesthetic beauty of the stream system and could have effects on the quality of surface water.

Municipal reports identify the reasons for refuse accumulation in local river systems. These include inadequate collection service, a lack of guidance and enforcement of waste management practices, an abundance of disposable plastic products, and difficulties accessing waste collection services (Saenz et al. 2006).

Construction

Construction within the stream channel and its tributaries is a cause for concern. A pool constructed by Attesi in the winter of 2016 has the potential to negatively affect the stream due to the diversion of water from a groundwater source spring and the removal of riparian vegetation. Due to the absence of adequate background data, the precise effect of this construction will remain unknown. Still, enough research exists to say that the effect of in-stream construction is unlikely to be positive (Slaney and Zaldokas 1997).

Research Question

The question as framed by the project sponsors is “are human activities causing negative effects on the water quality of the stream?” The presence of a variety of stressors in the initial field survey suggests that this might be the case.

Scientific inquiry is intended to provide data-based answers to quantifiable questions. To approach this question, I designed a study that provided insight into the extent of these effects on the local ecology. I asked, “What is the effect of rural development on the taxonomic richness and relative abundance of benthic macro-invertebrates in local headwater streams?” My study approaches the evaluation of general water quality from the perspective of in-stream biotic communities dependent on water quality and environmental stability.

To look at the larger question of anthropogenic influence, a number of such studies might be necessary. Essential information includes a general understanding of local river and groundwater hydrology. This understanding will inform the long-term vision of improved community management of this resource. Human presence in the region requires the determination of safe levels of use that balance human needs with the flow requirements of the river. Human settlements and agriculture near Attesi pose a risk for toxins and contaminants. The sponsors want to find a way to test water purity because of the importance of a long-term water source for their project and the community. Although chemical analysis could accomplish this, the long-term effort and cost are a deterrent and the search for alternative options led to the current study.

Desired Future Conditions and Restoration Goals

The goals of the project as outlined by the project sponsors include a general diagnosis of the stream ecology as well as a prescription for actions to restore and protect the system.

The Attesi organization aim to increase their understanding of the stream and riparian ecology to better protect and preserve this environment in the future from negative anthropogenic effects. The sponsors want to understand the effects of current rural development practices (stressors mentioned above) on the water quality in the river. The sponsors would like to be provided with evidence that the actions of the local community are affecting the current water quality and the future resiliency of the river and groundwater resources. The sponsors also want a proposal for alternatives that can minimize the effects of current practices, especially with regard to maintaining a natural flow. The project sponsors have outlined the following desired future conditions and restoration goals for the project.

Improve Water Quality

Regional dependence on groundwater resources makes the protection and improvement of groundwater resources an essential focus in ecosystem management. Groundwater contamination is a large concern as local water is mostly drawn from spring and aquifer sources.

Increase In-Stream Flow

A scarcity of local data makes the precise determination of historical stream flow levels difficult. However, local people remember times in the past (approximately 30-40 years ago) when water levels were high enough for swimming in some local streams. Current averages observed in field data from sampling suggest an average depth of less than 0.3 m in the streams bordering Attesi.

Reduction or Elimination of Human Stressors

The sponsors have concerns about water quality and the physical condition of the local stream system. The sponsors recognize that some human uses are essential and even desirable, but that many interactions can be improved to better protect streams from the negative aspects of human actions. The reduction or elimination of non-essential human actions will reduce the overall stress to the system. This includes the removal and future prevention of in-stream refuse disposal. This goal is mainly aesthetic, but has been identified as central to the project sponsors vision of sustainability. This goal is not guided by the results of the benthic invertebrate study, but by the desires of the project sponsors.

Restore Balance in Human-Environment Relationship

Reintegrating environmental stewardship into the local community value system is an over-arching goal held by the sponsors. This goal ties into other organizational goals such as creating a system of sustainable agriculture in the region and regenerating some of the degraded ecosystems that decades of rural development have created. This overarching goal has been integrated into the current report by focusing on sustainability. Sustainable environmental management focuses on inter-generational equity. For this reason, many suggestions contained here are based on a precautionary approach to ecosystem management based on common ecological effects identified in ecological literature. The presence of degradation (e.g. refuse in stream channels) warrants precautionary action even if the complete scientific understanding of the ecological effects is still incomplete.

Additionally, many of the restoration prescriptions focus on social and cultural restoration. Patterns of development have often resulted in a social disconnection from the landscape for individuals and communities. In many of these cases, the alienation from the landscape associated with modern development has been associated with physical and biological degradation in rivers (Parkes and Panelli 2001). In order for integrative river restoration to be successful, community values and cultural concerns should be meaningfully incorporated. Scientific assessments should connect to community values (Harris, 2006).

Local Ecological Context

Rationale for the Project

The focus of my project is the water quality in a 1-km stretch of the river flowing through the agricultural lands held by Attesi, the project sponsor. Three anthropogenic stressors are affecting the regional stream system and have the potential to reduce water quality in the system either directly (e.g. plastics and other waste in the river) or indirectly (e.g. increased nutrient flows from surrounding fields due to loss of riparian buffers).

The river and the associated riparian system are sensitive to changes. Anthropogenic changes associated with rural development in the region are likely to affect both the river and the biota that depend on it. The community also depends on the water for domestic consumption. Many local people have no alternative source of water other than local river and groundwater. Depletion of groundwater resources through over-pumping could make it unavailable as a viable source of water in the future.

The community also depends on the water for agricultural needs. These include small-scale irrigation and water for livestock. Compromising the quality and abundance of this resource could destabilize economic activities that local villagers depend on for their livelihood. Lack of access to this resource would necessitate the installation and maintenance of a municipal water supply with its associated economic costs.

The quality of local water also has a regional importance. Over 20% of Mexico City's drinking water comes from the Cutzamala system. This system is directly responsible for providing water for over 4 million people (Oswald Spring 2011). With so many downstream users, upstream contamination could have serious consequences for human health.

In addition to the role of the region in the conservation of wild flora and fauna, the forests of Villa de Allende and surrounding areas provide other goods and services: soil retention, infiltration and maintenance of aquifers, reduction of carbon-dioxide levels, recreation, livestock fodder, etc. (Saenz et al. 2006). In Mexico, timber products and the use of wood for fuel have been considered the most important tangible benefits of forests.

Benthic Invertebrate Study

To address my question about the effects of anthropogenic alterations on the river, I conducted a benthic macro-invertebrate survey of the project site and two other local streams that feature the same set of anthropogenic stressors. I also conducted a benthic invertebrate survey in a local stream that lacked the stressors. I used benthic macro-invertebrate populations as a bio-indicator of water quality. Using a reference system approach, I compared the taxonomic richness and relative abundance of invertebrate communities among treatment and reference areas to demonstrate differences in water quality.

Study Objectives

I designed the study to measure the effect of rural development on the taxonomic richness and relative abundance of benthic macro-invertebrates in Mexican headwater streams. Macro-invertebrates are defined as invertebrates over 2 mm and are visible to the naked eye or with a hand-held magnifying glass (Thorp and Rogers 2011). Because invertebrate communities are a bio-indicator of water quality, the demonstration of a clear and measurable difference in invertebrate communities among treatment (degraded) and control (reference) streams can support restoration and conservation actions at Attesi and in the local community.

Many factors contribute to the type, abundance, and taxonomic richness of benthic invertebrates. These include longitudinal changes in the stream (Vannote et al. 1980), substrate type and size, thermal and chemical characteristics, the type and availability of nutrients, and flow regimes (Thorp and Rogers 2011). Headwater streams have many similarities that make them ideal for comparison in studies of invertebrate populations. Physical conditions, substrate, and flow regimes tend to be similar at similar reaches within the drainage basin (Vannote et al. 1980). Most nutrients enter headwater streams from riparian vegetation and hill slopes. Invertebrate communities are dominated by shredders and collectors and generally feature lower macro-invertebrate diversity than downstream reaches (Brierley and Fryirs 2008). These similarities are a foundation for the reference system approach when looking at benthic invertebrate communities. The river continuum concept (Figure 6) shows the differences that emerge as river systems change with elevation and tributary connections. Study streams are classified as either second-order or third-order streams.

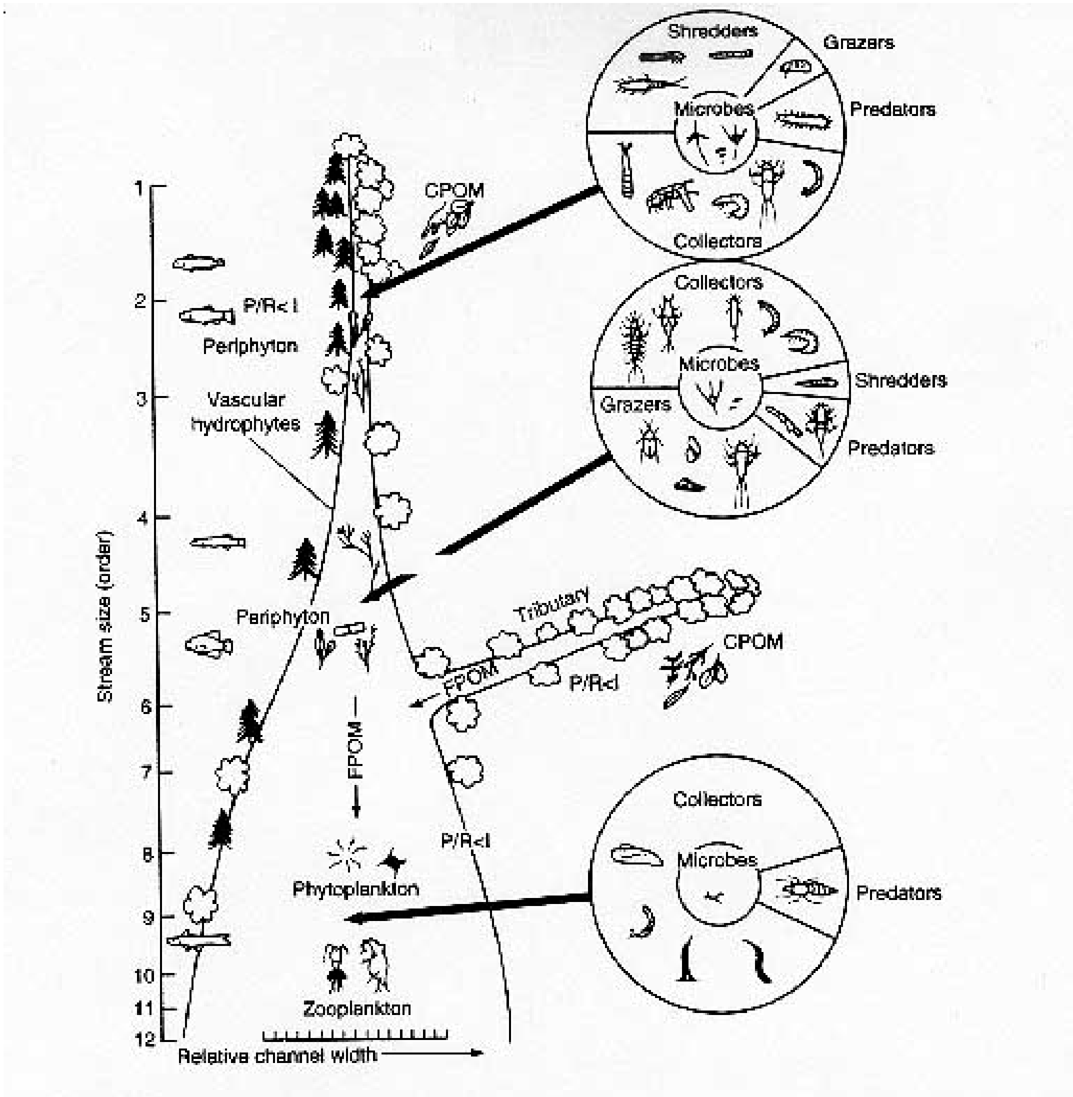

Figure 6 - General relationship between stream size (order), energy inputs, and invertebrate communities (Vannote et al. 1980).

Benthic Macro-Invertebrates as Bio-Indicators

I followed methods outlined in the British Columbia Streamkeepers manual for benthic invertebrate survey sampling protocol (Fisheries and Oceans Canada 2000). I chose these protocols because of their applicability in rapid assessments of invertebrate community assemblages. These techniques have been shown to be effective for studies where the focus is on the detection of localized effects rather than the specific quantification of separate disturbances (Chessman 1995). Because the current study cannot separate specific effects and treats them as a collective treatment, and because of the time and distance required for sampling, aspects of this rapid assessment approach were used within the B.C. Streamkeepers framework.

Benthic invertebrate sampling is best done under seasonal conditions of low flow. There are several reasons for this: (1) Most benthic taxa are in the aquatic stage at this time, (2) low flow conditions make sampling easier to conduct, and (3) sampling is done in stable perennial areas of stream flow (CABIN 2014). I chose January as an ideal time to sample based on regional hydrograph data (Climate-Data.org n.d.). Sampling is best at this time because it is during the winter dry months before the return of heavy rains and higher flows in May.

CABIN protocol requires that reference and treatment streams share several common characteristics to be comparable. Common stream order classification (Strahler 1957) among streams corresponds to similarities in the invertebrate community. This helps ensure that comparisons of results are based on comparable sites (CABIN 2014).

Benthic invertebrates provide useful information on water quality, changes in local conditions, and the presence of pollutants or toxins when compared to suitable reference conditions or background data (Stoddard et al. 2006). Benthic invertebrate sampling is also known as a 'citizen science' method that can be taught in a relatively short time and can be carried on by the project sponsors in the absence of restoration professionals. This will be included in the recommendations for future monitoring and engagement. For these reasons I chose it as the method of data collection for this pilot study.

Benthic Invertebrate Pollution Sensitivity Classes

Benthic invertebrates display variation in their sensitivity to water quality. A number of metrics have been developed to sort invertebrates into general classes based on their response to changes in water quality. I used a division created by Fisheries and Oceans Canada in co-operation with the British Columbia Streamkeepers project (Table 1). Family-level and Order-level taxonomic groupings are sorted into three general tolerance levels: (1) 'sensitive' insects that require high water quality levels and are sensitive to disturbances in flow regimes and environmental toxins, (2) 'somewhat sensitive' insects that can withstand some degraded conditions and are more resilient to disturbances, and (3) 'tolerant' insects that can live and reproduce effectively in low quality water and are resilient to environmental disturbances (Fisheries and Oceans Canada 2000).

Table 1 - Taxonomic Groupings and Pollution Sensitivity Classification. Tolerance class groups displays differences in pollution and stress tolerance. Differences in collected invertebrates were used to indicate the degree of anthropogenic effects on the sample area. Invertebrates in Table 1 are representative of group and family taxonomic groups detected in the current study only.

Pollution Tolerance Class	Taxonomic Grouping
Group 1 Sensitive	Ephemoptera (mayfly)
	Plectoptera (stonefly)
	Tricoptera (caddisfly)
Group 2 Somewhat Sensitive	Anisoptera (dragonfly)
	Nematocera (cranefly)
	Athericidae (watersnipe fly)
	Coleoptera (beetle)
Group 3 Pollution Tolerant	Chironomid (midge)
	Simulidae (blackfly)
	Hirudinea (leech)
	Hydracarina (water mite)
	Oligochaeta (worm)

HYPOTHESIS AND STUDY DESIGN

HYPOTHESIS

The hypothesis in this study is that benthic invertebrate type and density will vary based on the presence or absence of anthropogenic alterations. Because communities of invertebrates respond to stressors in their environment at different sensitivities, the presence and abundance of certain invertebrate classes can provide information about water quality and ecological conditions. This leads to three predictions that I tested with my experimental design.

1 – The relative abundance of benthic macro-invertebrates with high sensitivity to water quality (‘sensitive and ‘somewhat sensitive’ groups) will be higher in the control stream and lower in the treatment streams.

2 - The relative abundance of benthic macro-invertebrates with low sensitivity to water quality (‘tolerant’ group) will be higher in the treatment streams and lower in the control stream.

3 – The taxonomic richness of collected benthic macro-invertebrates will be greater in the control stream than the reference streams.

Experimental Design

I designed the study to demonstrate a difference between the taxonomic richness and relative abundance of benthic macro-invertebrate groups between control and treatment stream sites. I used Order-level and Family-level groups for identification. This level of classification has been shown in the literature to be sufficient as a bio-indicator of water quality and environmental stress (Fisheries and Oceans Canada 2000). Quantifiable measures include: 1) the relative abundance of individuals in each family or class outlined in the study design and 2) the taxonomic richness of different family or class groups outlined in the study design. Both of these measures are indicators of water quality and environmental stress. My hypothesis (that rural development is adversely affecting water quality) will be supported if species richness is higher in reference streams and if the abundance of pollution and stress intolerance classes or families is higher in reference streams.

Control Site

Scientific controls are essential to experimental design for comparison with test results. Field experiments cannot control all variables or randomize replicates the way a laboratory test can. Because of this limitation, an attempt is made to choose test and control sites that are as similar as possible. This is always constrained by feasibility, budget, and time constraints. The choice of a reference condition as a control site is based on the standard of the best available condition. This choice often requires a value judgment based on the data that has been collected (Reynoldson et al. 1997).

Reference conditions are physical, chemical, and biological conditions that describe the most minimally impaired streams in a region. The difficulties of finding a truly “untouched” reference stream are well documented (D. Hughes et al. 2009). Because of this, the use of a site with minimal disturbance is often used. An established reference condition is the basis for making comparisons and assessing changes in sampled test streams.

I identified and sampled one control site within the local watershed. The stream is located approximately 8 km from the restoration site and is located at a similar elevation. I chose sampling locations within the reference stream based on similarities in depth, flow rate, and substrate to improve sample uniformity.

The control site needed to lack any of the three features of rural development previously identified (water diversion, refuse disposal, riparian encroachment from agricultural fields). This control site displayed none of these characteristics except for the presence of a single road approximately 800 m upstream. The stream passed under the road in an unobstructed bridge structure with no significant diversion or blockage. No agriculture was present in upstream reaches. Some adjacent areas showed presence of previous logging but were adequately reforested to indicate that this disturbance was at least a decade old.

Several conditions were used in the assessment of the suitability of the site as a reference. The Canadian Aquatic Biomonitoring Network (CABIN) suggests that suitable reference conditions are necessary to compare the water quality among streams (CABIN

2014). Grouping of potential reference sites by characteristics of their physical environments such as catchment area, stream order, and water source improve the likelihood of ecological data from the reference sites reflecting potential data values that could be attained by restoration of the treatment sites (Yates and Bailey, 2010). The control stream sampled was a second-order headwater stream following Strahler's stream order classification system (Strahler 1957), as were the three treatment sites. This decision was based on the stream continuum concept, which states that stream reaches of the same order support similar communities of benthic invertebrates (Corkum 1989). Additionally I used percent cover of stream vegetation, bank full width and wetted width, temperature, and the presence of a riffle, run, pool sequence as conditions for site selection.

Treatment Sites

The initial treatment site is the stream passing through the Attesi property. Approximately 1 km of this stream passes adjacent to Attesi's agricultural fields. The condition of this stream is a major concern of the project sponsors. A spring source in this stream is used to provide water for drinking and domestic use by the project sponsors.

I identified two additional treatment sites based on similarities in stream order, percent cover of riparian vegetation, stream width, temperature, and the presence of a riffle, run, pool sequence. All sites were required to be reasonably similar to the target Attesi stream (Site 1) to make comparisons relevant and meaningful.

Sampling Equipment

A variety of sampling methods are used for sampling of in-stream benthic communities worldwide, each with their own advantages and disadvantages. The Canadian national standard for monitoring of streams using benthic invertebrates is outlined by CABIN. This protocol uses a kick-net sampling method as a standard sampling method (CABIN 2014). Kick-net sampling can be ineffective in shallow streams with low flow levels. For this reason I used a sampling method developed in the 1930s using a Surber sampler. The Benthic Index of Biological Integrity (B-IBI) system uses a Surber sampler as its standard collection method. Analysis and comparison of the Surber and kick-net methods has demonstrated no significant differences between the two methods (Page and Sylvestre 2006). Either method can be used interchangeably depending on the site conditions. The Surber sampler is recommended for use in riffles (erosional zones) of shallow streams. It is especially suited to shallow lotic environments (Merritt and Cummins 1978) such as those in the headwater streams of Villa de Allende. Because of the shallow streams in the study area, I used the Surber sampler for collecting benthic invertebrates in the current study.

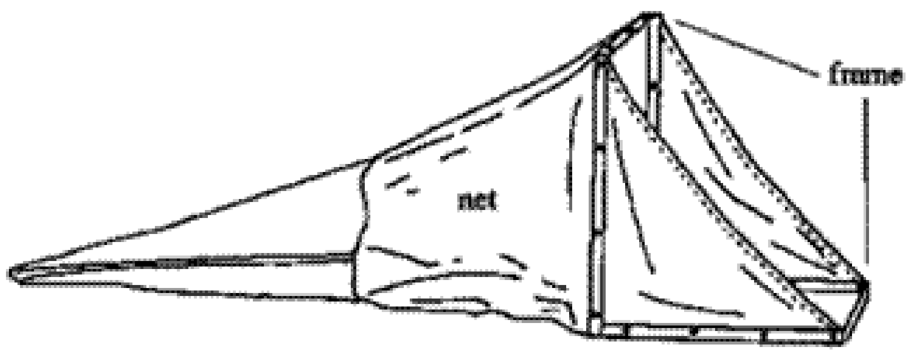

Figure 7 - Surber sampler used for Benthic Invertebrate study, Villa de Allende, Mexico (for.gov.bc.ca).

I used the following equipment in the study to collect site data, collect and process invertebrate samples during Site Visit 2 in January 2017.

Table 2 - Sampling equipment and associated tasks for benthic invertebrate study, January 2017.

Sampling Task	Equipment	Purpose
Site Data	Thermometer	Stream temperature measurements
	Tape Measure/Ruler	Stream width measurements
	Ruler	Scale in site photos, steam depth measurements
Collection	Surber Sampler	Invertebrate collection
	Squeeze bottle	Sample processing
	Stopwatch	Sample timing
Preservation & Transport	Bucket	Sample transportation
	Sample jars	Sample transportation
	Isopropyl alcohol	Sample preservation
	Cooler for sample jars	Sample preservation
Processing	Neoprene gloves	Sample processing
	Squeeze bottle	Sample processing
	Sample sorting trays	Invertebrate sorting
	Spoon/Tweezers	Invertebrate sorting
	Magnifying Glass	Invertebrate identification
	Glass Dissection Trays	Invertebrate identification

Sampling Design

Sampling design for the study involves a series of replicates designed to permit the result to be generalized beyond the specific stream reach intended for restoration. These include three treatment and one reference stream (Figure 8). Not all variables can be controlled in field-based experiments. Some studies have demonstrated that benthic communities do display some variation within a drainage basin, and are not necessarily uniformly distributed in similar streams (Corkum 1990).

I sampled at four separate stream locations, representing discrete experimental units. These include: 1) three treatment streams (replicates) with anthropogenic alterations and 2) one control stream (relatively undisturbed).

Each replicate (experimental unit) was divided into three separate stream reaches (sample units). I chose these locations based on sample parameters suggested by CABIN sampling protocol. I took five individual samples in each reach.

I chose sampling locations for individual samples within treatment (disturbed) stream reaches based on sampling suitability. Pumping and diversion have made some stream sections unsuitable for sampling because of low flow. I aggregated results from five sampling locations within each sample unit. I chose sampling locations in reference streams within acceptable reaches. Results from the three sample reaches in each each experimental unit were collected for data analysis. These were compared with data collected at the treatment and control sites.

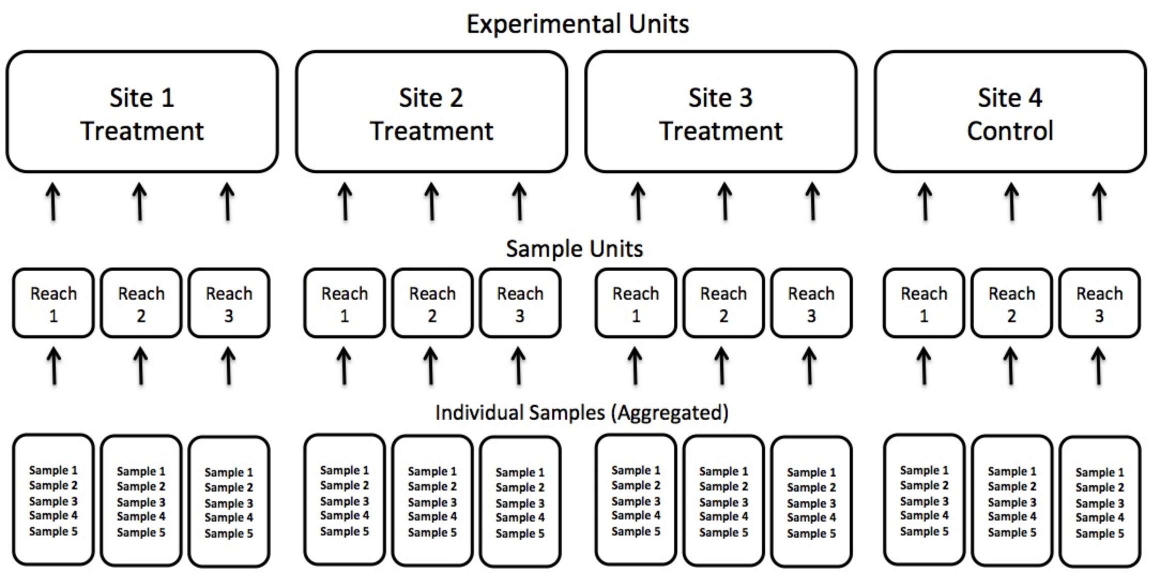

Figure 8 - Sampling Design used in Benthic Invertebrate study, Villa de Allende, Mexico, January 2017.

METHODS

Using a method of invertebrate collection (the Surber sampler method) recommended by the B.C. Streamkeepers Project, I collected benthic macro-invertebrates from sample reaches in treatment and control streams (Fisheries and Oceans Canada 2000). I compiled and analysed these data to determine the differences in richness and abundance of macro-invertebrate communities between treatment and control sites. Site data was collected prior to invertebrate sampling.

SITE DATA

Stream measurements were taken using methods outlined and collected in the manual for Stream Hydrology (Gordon et al. 2004). The following criteria were used to determine the suitability of treatment and reference sites for inclusion in the study. I used the main treatment site adjacent to Attesi (Site 1) as a standard for comparison because it is the stream of interest to the project sponsors. All collected site data is presented in Appendix A.

A system of stream order classification is commonly used in benthic invertebrate studies because invertebrate communities display similarities or differences depending on their location in a general watershed stream continuum (Vannote et al. 1980). To increase the comparability of results, I chose streams of the second or third order using Strahler's system (Strahler 1957). All study streams were classified as second-order or third-order streams.

The amount of vegetative cover directly affects invertebrate communities because shading affects water temperature and dissolved oxygen levels in stream. The canopy also provides organic material used as food and cover for benthic invertebrates (CABIN 2014). I used percent cover of canopy vegetation as a site selection criterion. I determined this by making three separate estimates of canopy cover at random locations within each sample site. A field assistant repeated this estimation and I recorded the average value.

I used the bankfull width and the wetted width as measurements of stream width. The bankfull width is used in the CABIN system to delineate sample reaches, defined as six times the bankfull width (CABIN 2014). I took three independent measurements for both parameters and calculated the average value for each sampling location.

The presence of a run, riffle, and pool within a defined stream reach is a common method of delineating sample reaches in the CABIN system (CABIN 2014). I used the presence of these three stream features as a condition of site selection to improve comparability among sampling reaches. All site reaches contained these three features. The presence of shallow riffles and runs are essential for effective sampling using the Surber sampler (CCME 2011).

Temperature is a key variable affecting the physical, chemical, and biological factors that influence aquatic organisms. Wide differences in temperature can have effects on the benthic invertebrate community within a stream (CABIN 2014). I took three temperature measurements at a depth of 0.1 m in each sampled stream reach. I calculated and recorded the average of the three values.

Stream Invertebrate Sampling

The invertebrate collection methods followed the protocol developed for the Surber sampler as outlined in the B.C. Streamkeepers Sampling Guide (Fisheries and Oceans Canada 2000) and the water sampling protocols developed by the Canadian Council of Ministers of the Environment (CCME 2011). I placed the sampling device in a riffle or run within the stream reach. I manually disturbed the substrate at the sample sites for a 5-minute interval with the Surber sampler collection device placed downstream. I moved and lightly brushed any stones that were in the sample site. The natural flow of the stream brought the macro-invertebrates into the collection device. I took five individual samples in each stream reach. These samples were aggregated within the collection device to give a representative sample of the entire stream reach.

I sampled three reaches in each treatment and control stream. The collected samples were preserved in a solution of water and isopropyl alcohol for post-sampling analysis. I sorted the samples into specific family or order level taxonomic groups (Figure 9).

I sorted the collected invertebrates from each sample site into taxonomic groupings. I classified the collected invertebrates into three general categories of pollution sensitivity based on common classifications used in stream assessment by Fisheries and Oceans Canada (Fisheries and Oceans Canada 2000). I recorded the number of individuals collected from the population in each sample. The number of individuals collected from each taxonomic grouping provided the value for relative abundance at each sample site.

I determined the taxonomic richness of each sampling unit. I recorded the total number of invertebrate groups present. I identified these groups down to Family-level or Order-level groupings. This level of classification is suitable for distinguishing among groups of differing sensitivity to water quality levels (CABIN 2014).

Taxonomic richness indicates the number of species present in the local community. Low taxonomic richness has been demonstrated to indicate low water quality levels and physical modifications on stream systems (Barbour et al. 1999)

Figure 9 - Benthic Invertebrate Sample Processing and Sorting, Villa de Allende, Mexico, January 2017.

DATA AND ANALYSIS

I analysed the collected data by comparing the relative abundance and taxonomic richness of each group between treatment and control sites. I sorted benthic invertebrate samples into general family classes. The abundance of invertebrates and the family type were organized to compare between treatment and reference streams (Figure 10). This approach has been shown to provide useful bio-monitoring data (Corkum 1989). Species level identification is not necessary for general water quality sensitivity classification.

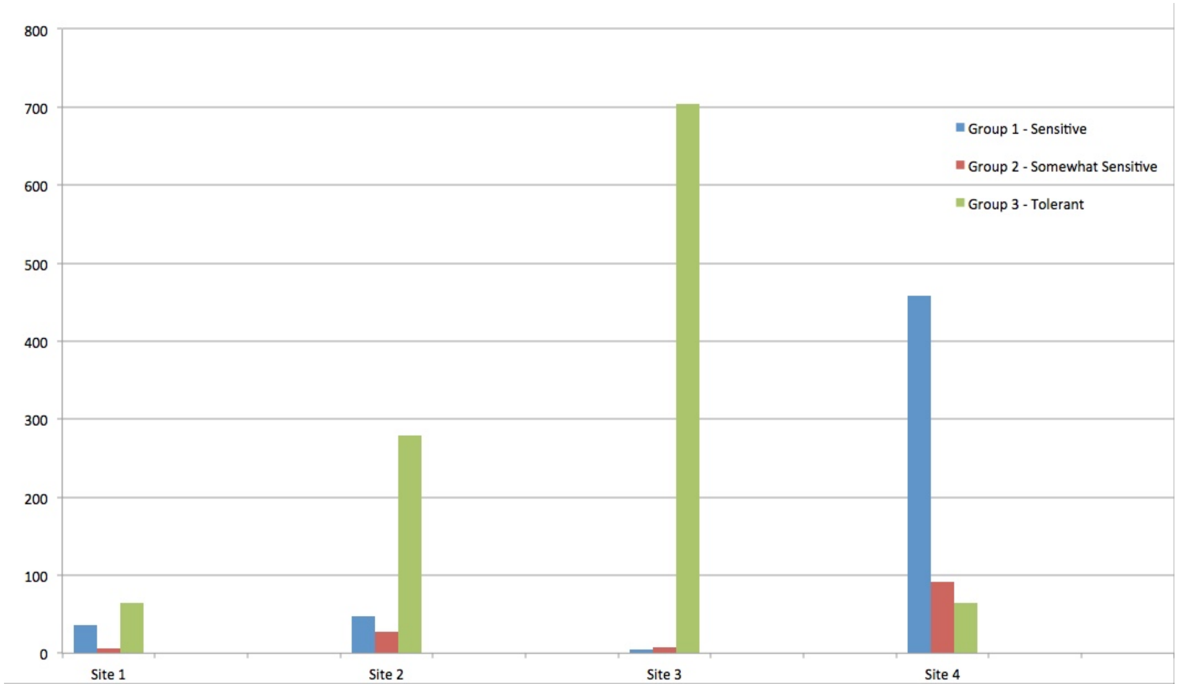

Figure 10 - Collected Invertebrates by site, differentiated by sensitivity class. Number of invertebrates collected is displayed on the Y Axis. Villa de Allende, Mexico, January 2017.

Statistical Analysis

I sampled in four separate streams. These streams are the four experimental units included in this study. These include: 1) three treatment sites with anthropogenic alterations (Site 1, Site 2, and Site 3) and 2) one control site with few anthropogenic alterations (Site 4).

I divided each experimental unit into separate stream reaches, with three sample units per stream. Each sampling unit had five sample elements. Each of the five sample elements was an individual in-stream sample that I collected in each sample unit (i.e., each stream reach). The sample size for the analyses is derived from the number of sampling units (i.e., n = 3).

I calculated the mean for each water quality sensitivity group and for taxonomic richness within each experimental unit. I calculated the mean using the values observed in the three sampling units within each stream. The mean values for these parameters were used to draw inferences about the abundance and richness in each sampled stream. The mean taxonomic richness of invertebrates and the mean abundance of invertebrates from each water quality sensitivity group for each of the sampled streams are presented in figure 10 below. The standard error of the mean is presented as well.

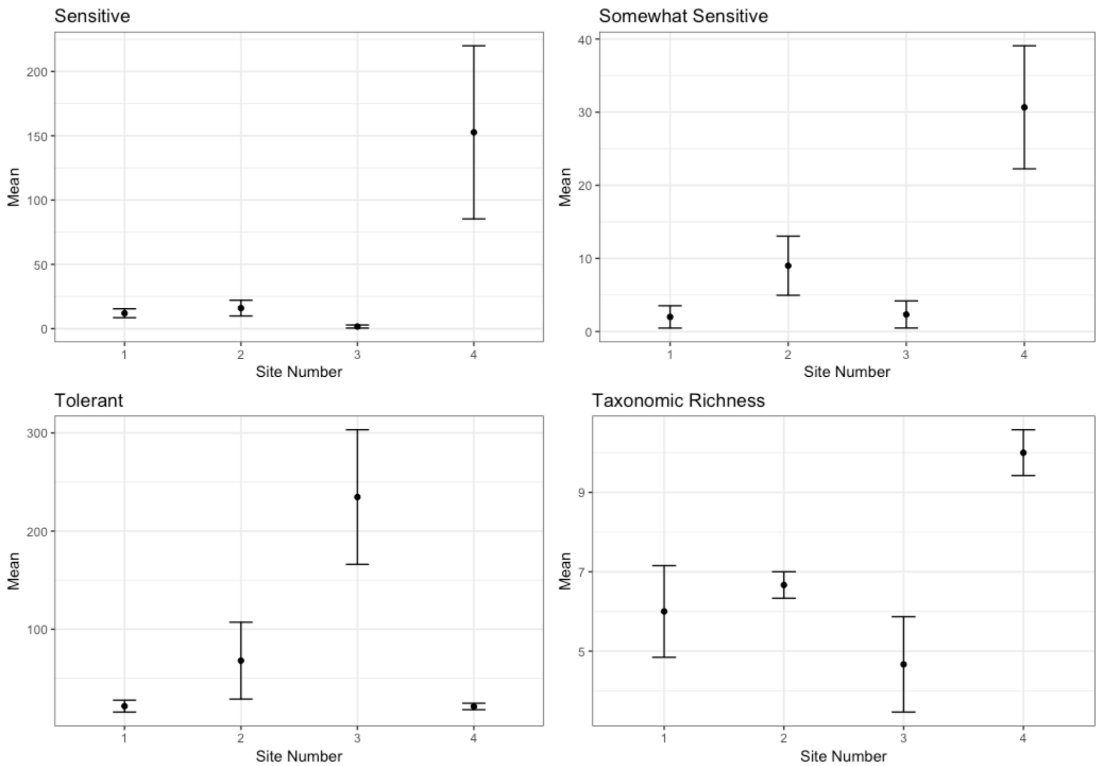

Figure 11 - Mean and Standard Error of the Mean for abundance of benthic invertebrates of differing water quality sensitivity (sensitive, somewhat sensitive, tolerant), and taxonomic richness in stream sites, Villa de Allende Mexico.

STATISTICAL DESIGN

I used a One-Way ANOVA to test the hypothesis that there are no significant differences among the means of the four streams. I kept independence both within and among sample units by having a minimum of 50 m among stream reaches, sampling downstream sites first to avoid disturbance, and having separate streams (independent replicates) for each experimental unit. ANOVA tests have been shown to be robust enough to handle non-normal data (Schmider et al. 2010). I used Levene's test to determine if the differences in variance in stream sites were significant for each variable. The tests showed a P-value higher than 0.05 for each variable, meaning that there is no significant difference among the variance of each parameter and that this condition is met by the data.

I used the Tukey HSD post hoc test to determine if the mean differences among pairs of experimental units were significantly different for each measured parameter. I chose this test in order to determine if there is was difference in taxonomic richness and relative abundance among the means of my treatment sites and my control site. I also used the test to determine if the treatment sites were significantly different from each other. The generated values for these tests among the four sampled sites for each measured parameter are presented in Appendix C.

RESULTS

The differences for the abundance of ‘sensitive’ group invertebrates are significant with 90% confidence (adj. P value between 0.05 and 0.10). The differences for the abundance of ‘somewhat sensitive’ group invertebrates are significant using a 95% confidence interval in two cases and a 90% confidence interval in the remaining case. The differences for the abundance of ‘tolerant’ group invertebrates are only significant in one case using a 95% confidence interval.

The differences for the taxonomic richness were significant in one case using a 95% confidence interval and one case using a 90% confidence interval (statistical results are presented in Appendix C). A 95% confidence interval is commonly used as a standard for significance. The failure to meet the 95% confidence level in several cases is a possible result of a low sample size and could be improved in future studies.

The differences among treatment sites were not statistically significant in all cases for all measured parameters with one exception. This result was expected and suggests a broad similarity across the treatment sites for taxonomic richness and relative abundance of benthic invertebrates with different water quality sensitivity levels. The one exception was the difference between site 3 and site 1 which was significant using a 95% confidence interval (see Appendix C). This is likely due to the large amount of ‘tolerant’ group midges collected in the samples at site 3.

DISCUSSION

As indicated above, several of the cases meet a 90% confidence level but would not reject the null hypothesis if we adhere to the standards of statistical orthodoxy (95%). This is not to say that the observed results are not indicative of real differences among the sites. The ‘significance’ of a finding can be measured in other ways than a P value. I would suggest that weighing the measured confidence intervals qualitatively in the context of the study itself as well as the existing knowledge about ecological effects of human alterations is a better way to evaluate the significance of the findings than a yes/no decision based on an orthodox 95% figure. I am accepting the significance of my statistical results with 90% confidence. Future studies can provide additional evidence by expanding the number of experimental units and sample units.

A more detailed treatment of the statistical tests performed is presented in Appendix C. Definitions, explanations, and all calculated values are available for the specialist or interested parties.

The data reveal the degree of difference between benthic macro-invertebrate community richness and abundance in stream reaches with and without the anthropogenic stressors described above. The abundance of groups with higher sensitivity to water quality (‘sensitive’ and ‘somewhat sensitive’) was greater in the control site than in stream reaches with diversion, refuse, and riparian encroachment. The abundance of ‘tolerant’ group invertebrates was greater in the treatment streams than the control stream with the highest abundance observed in Site 3. I also observed a higher taxonomic richness of family or class groupings in the control site than any treatment site.

My results showed that a demonstrable and significant difference exists between the abundance of invertebrate groups in treatment and control sites. Taxonomic richness was also greater in the control site than in the treatment sites. Significance was determined in this case by a 90% confidence interval. I also suggest that the data collected presents a strong argument for the biological significance of the measured effects. This supports my recommendations for restoration actions in the next section. This study is also a resource to demonstrate to the local community that their collective actions are putting water resources at risk and that future suggestions for community action are warranted.

RESTORATION DIRECTIONS AND DISCUSSION

The ecological data collected suggest that there is insufficient flow and/or water quality to support resilient populations of benthic invertebrates in human-altered streams. The exact causes of the differences in benthic invertebrate communities cannot be ascertained with certainty from the current study, but decades of ecological research suggest that all of the anthropogenic alterations previously described play a part in altering stream chemistry, nutrient levels, and physical structure (Brierley and Fryirs 2008). As discussed above, benthic invertebrate species act as biological indicators for a variety of issues that might be affecting the streams. My data suggests that streams featuring anthropogenic alterations are changing the invertebrate community in ways that suggest negative effects on water quality. The following recommendations are intended to address some common anthropogenic impacts on water quality that occur in Villa de Allende. The data do not allow me to say with certainty which of the recommended actions will have what effect on overall water quality levels. The intention is that the simultaneous confrontation of various stressors will reduce the pressures on the system that come from patterns of rural development. Future studies are needed to separate the relative influence of individual stressors on water quality.

I suggest that the community implement the following ecological restoration options. These options are suggested to improve water quantity, riparian vegetation, seasonal flow levels, and water quality. All of these conditions are important for benthic invertebrate communities (Brierley and Fryirs 2008). The potential benefits of taking a precautionary approach to protecting groundwater resources, riparian forests, and water quality are numerous, and the potential for disaster if these resources are permanently degraded or destroyed warrants immediate action. Climate change is likely to exacerbate the effects of water consumption and further threaten water resources. This makes protection and action now even more critical.

The guiding principle of this section is that of leading by example. Attesi has expressed the desire to become a leader in ecological stewardship in the community as a part of their vision for a sustainable future for the region. Implementing some or all of the following recommendations at Attesi can act as an example and an educational paradigm for the local community.

I am providing the following recommendations to guide future projects and actions. There is no specific timeline for the implementation of these recommendations. The suggested actions should be used and implemented in whatever order and locations are feasible. Further detail on each recommendation is provided in the associated sections below.

1. Actions should be taken to increase water volume of stream flows. Because the stream system is partially fed by groundwater, this involves reducing draws from groundwater sources such as local springs and aquifers. Rainwater collection methods can to be supplemented in the local communities to reduce pressures on in-stream and groundwater flow.

2. Riparian vegetation should be maintained at current levels or increased along the edges of the river. Further development of intact riparian forest should be stopped. Rain gardens can be built at riparian edge zones to expand the riparian buffer capacity and protect against overland nutrient flows and contaminants.

3. Human alterations in and around the streams should be maintained at current levels or reduced. This includes trails, vegetation removal, landscaping, and in-stream construction. Culverts that cause erosion, sedimentation, and fragmentation should be replaced.

4. Refuse dumping in the river should be stopped and the streams should be cleaned of current refuse. Community stewardship programs, sign installation, and local education will help reduce effects by clean-up efforts and through future changes in refuse disposal practices.

5. Water Quality should be regularly tested to protect local water users.

RESTORATION PRESCRIPTIONS

REDUCING STREAM DIVERSION / PUMPING

Groundwater resources require replenishment through processes of rainwater infiltration. Conversion of land to agricultural fields can lead to reduced infiltration due to soil compaction and water uptake by commercial crops. Additionally, impervious surfaces such as roads, parking lots, and foundational structures prevent infiltration (Galatowitsch 2012b).

The alteration of the local water balance due to reduced infiltration and groundwater extraction can lead to long-term depletion of local aquifers and seasonal fluctuations in the availability of water. The replenishment of depleted groundwater resources can in many cases take centuries or millennia to occur (Galatowitsch 2012b). Restoration of historical flow regimes by reducing diversion and groundwater pumping can still be constrained by low water quality due to pollutants, agricultural runoff, and human waste. These can limit recovery even when flow conditions are restored (Paul and Meyer 2001).

Further studies are necessary to determine the water balance and the extent of groundwater resources in the region. Future studies could also determine the range of historical and current changes to flow levels within the system. However, a lack of complete knowledge should not be a reason for inaction. Due to the importance of this resource for the local community, a precautionary approach should be used to limit the potential for overdrawing from aquifers and protecting the overall quality of the surface and ground water.

To increase water volume in the stream, the following options exist. As suggested, Attesi should implement these methods to provide a model of ecological stewardship. The successful implementation of alternative water collection methods, riparian protection, and stream restoration can also be used to educate local community about the importance of ecological protection.

Rainwater Collection

Rainwater collection is a viable alternative to groundwater pumping and can be effective at mitigating draws from groundwater sources. A theoretical water use analysis is presented here and is intended to provide data on local consumption. I will use this information to provide alternative collection methods to offset pumping and diversion of in-stream and groundwater flows. I will use the population of San Jose Villa de Allende as an example for this exercise.

Water use in the region is for domestic consumption (cooking, cleaning, drinking) and livestock, and is rarely used for irrigation. An estimation of water use permits a quantification of current draws from the river and aquifer system by pumping. Calculations were made for average water consumption based on current United Nations Development Programme (UNDP) data for water use in Mexico. The 2006 Human Development Report estimates daily water use in Mexico at 366 Litres (UNDP 2006). I will conservatively half this number due to the lack of municipal sewage infrastructure and adequate rainfall to minimize local irrigation needs. An additional calculation estimates the available surface area for rainwater collection on existing roofs (houses, barns, etc.). I use an average of two 50 m^2 roofs per household (family of 4). This estimate comes to 677 roof structures in the town and surrounding area. This is based on observations and is likely a conservative figure due to the large number of roof structures to shelter domestic livestock. I will use 1000 mm as a conservative average annual rainfall for the calculation (Municipal Geographical Information Handbook of the United Mexican States 2009). The conversion to water volume is 1 mm annual precipitation = 1 L/m^2.

I calculated that the installation of rainwater collection systems on 677 roofs in Villa de Allende could offset water usage by 37%. This estimate is likely conservative because there are more available surfaces than my calculation took into account. This estimate is for illustration purposes only but points to the benefits of rainwater collection for reducing pumping of groundwater sources and increasing in-stream flows.

Table 3 - Estimated water use offset from rainwater collection in San Jose Villa de Allende, Mexico.

Average Daily Per Capita Water Use - Mexico (L)	Average Annual Per Capita Water Use - Mexico (L)	Annual Precipitation - Villa de Allende (mm)
183	66795	1000
Population - San Jose Villa de Allende	Projected Annual Water Use (L) - San Jose Villa de Allende	Annual Precipitation - Villa de Allende (L/m2)
1354	90440430	1000
Number of Roofs	Impervious Roof Surface (50 m2 average)	Potential Annual Collection (L)
677	33850	33850000
		Potential Offset (%)
		37.43%

Rainwater harvesting is an effective method to reduce the dependency on groundwater aquifers. The collection of rainwater from impervious surfaces such as roofs also reduces the effects of flooding and erosion. Rainwater can be used to supplement local supply of water (drinking, bathing, cooking), as well as other uses such as livestock watering and landscape irrigation. Rainwater quality often exceeds the quality of ground and surface water and also has very low hardness levels, reducing the amount of soaps and detergents needed for cleaning (Dunnett and Clayden 2007).

Rain barrels are a common method of domestic rainwater collection. These should be UV protected to avoid contamination from the storage material, and made of opaque materials (metal, wood, or opaque plastic) to discourage bacterial growth. Additionally, adding a tablespoon of vegetable oil can provide a surface layer to protect against mosquitos using the water for breeding by depriving them of oxygen.

Rainwater filtration through low-cost sand/charcoal collection devices has the additional benefit of delivering purification and a dependable water quality that pumping of river water cannot deliver. These are low cost, easy to install, and use easily gathered materials. A variety of plans for construction are freely available online (Figure 12). This can alleviate some of the main concerns over water quality expressed by the project sponsors and can be an effective precautionary adaptation to the effects of climate change (Pandey et al. 2003).

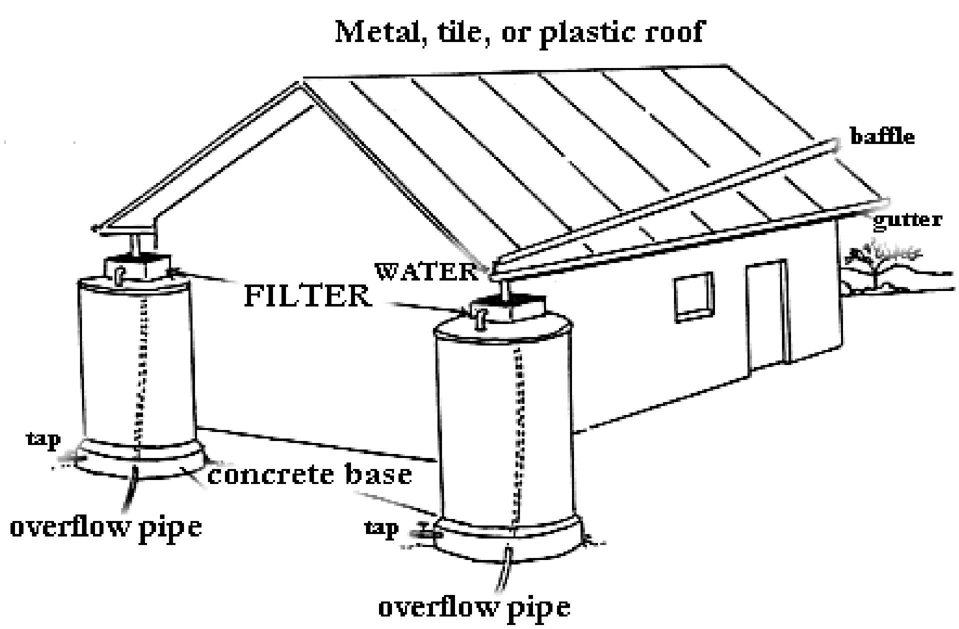

Figure 12 - Example of low-cost rainwater collection system. Baffles installed on roof direct rainwater to rain barrels fro collection and storage (Source: Permatopia.com).

RIPARIAN ZONE PROTECTION / EXPANSION

My data do not allow me to say the extent of the influence of riparian encroachment on local water quality. Research has shown that reducing the buffering capacity of streamside vegetation makes streams far more susceptible to toxins entering the stream channels from adjacent areas (Cunningham and Cunningham 2006). Agricultural activity in the surrounding region can contribute to degraded water quality in local streams. This is due to overland flows of nutrients such as phosphorus and nitrogen from fertilizers and animal wastes. These can cause a variety of problems in streams. In agricultural areas, as much as 25% of fertilizers and pesticides spread on farmland is carried off by runoff (Cunningham and Cunningham 2006). This effect is amplified in areas with high levels of precipitation such as Villa de Allende. Much of this runoff enters streams as non-point pollution. Other non-point pollutants enter stream channels from animal wastes in pastureland. Animal waste can contain viruses, bacteria, nitrates, phosphates, and other contaminants (Cunningham and Cunningham 2006).

Riparian vegetation can improve water quality in a stream by providing a buffer against overland nutrient flows and pollution associated with transportation infrastructure and agricultural development (Slaney and Zaldokas 1997). This results from sedimentation, which increases turbidity and siltation in water bodies. Increased sediment loads also cause a narrowing of channels and provide nutrients that encourage colonization by invasive species (Hawes and Smith 2005). Riparian areas act as a buffer between stream channels and the surrounding landscape.

Recreating forest cover in upland reaches is critical for stabilization of watershed ecology (Benda et al. 2005). Forests in stream systems slow surface runoff, capture sediments, nutrients, and pollutants, and store excess water through infiltration. Soil activity can transform nitrates and other pollutants into less harmful substances (Hawes and Smith 2005). Studies have shown that a minimum of 15 meters of riparian forest is necessary in order to filter nutrients, pesticides, and bio contaminants at a minimal level. Maximum efficiency is attained when the riparian buffer approaches 100 meters (Fischner and Fischenich 2000).

Many plant and animal species also depend on riparian buffers for foraging, nutrients, and refuge. For example, shading of stream channels regulates dissolved oxygen levels in stream and provides detritus for benthic invertebrates. If the riparian areas are large enough, they also provide essential corridors for wildlife passage (Hawes and Smith 2005).

Rain Gardens

A common method of decreasing overland flows of nutrients into stream channels is the construction of rain gardens. Rain gardens act as a buffer between agricultural fields and stream channels. A depression reduces the velocity of surface flows, reducing erosion in the stream channel. The vegetation in the rain garden can also filter pollutants, sediments, and nutrients before reaching the stream channel, leading to improved water quality in stream. Rain gardens can also capture run off from impervious surfaces (roads) and increase infiltration and groundwater recharge (USDA 2014).

Rain gardens should be constructed with a slight depression of approximately 0.2-0.3 m (Figure 13). The depression should be planted with deep-rooted native plants. Soil should be kept rough and loose in order to facilitate infiltration. Care should be taken that only native species are used. Rain gardens should be placed adjacent to agricultural sites and impervious surfaces near stream channels. These will act as a primary buffer for the stream, with the riparian forest acting as a second later of protection. The overall result will improve the water equality and aid in aquifer recharge (Dunnett and Clayden 2007).

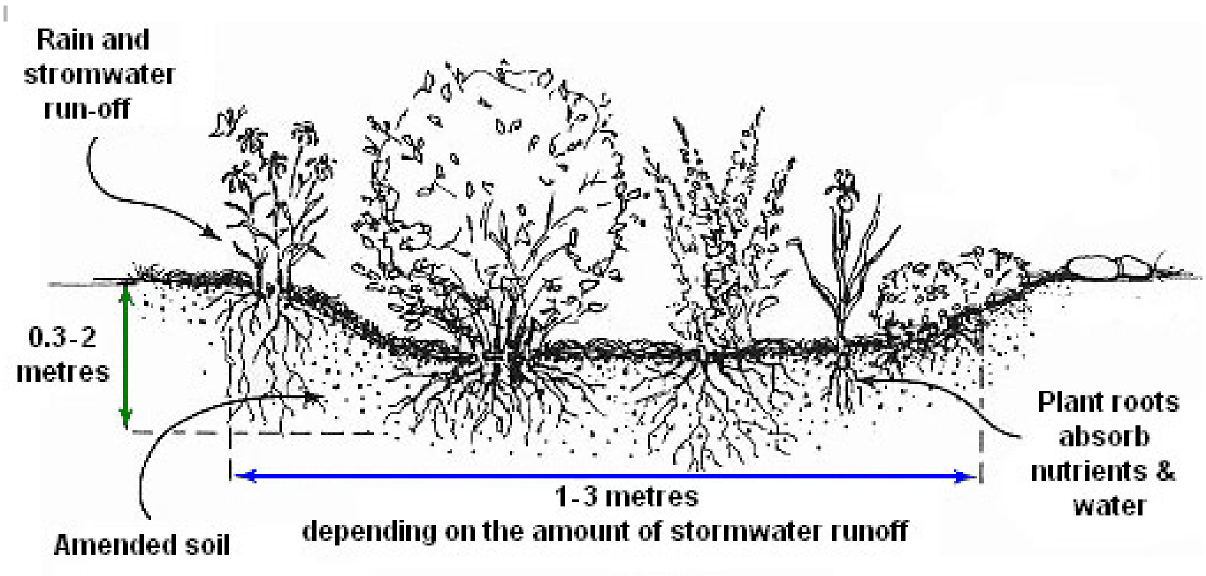

Figure 13 - Rain garden schematic diagram (Dunnett and Clayden 2007).

Physical Alterations

I recommend that human alterations in and around the streams should be maintained at current levels or reduced. This includes trails, vegetation removal, landscaping, and in-stream construction. This will require coordination with the local community. Future in-stream construction should be avoided. The precise contribution of physical alterations to changes in water quality cannot be determined from my study data, however studies of the effects of culverts have demonstrated significant impacts in numerous stream systems (Slaney and Zaldokas 1997).

Culvert Replacement

High levels of sedimentation are another factor that can contribute to reduced water quality and lower surface flow. All observed treatment streams featured embedded substrate and two treatment streams featured upstream culverts with scouring outflows. Culverts can create a number of ecological issues in stream systems. These include alteration of flow regimes, scouring flows causing sedimentation in downstream reaches, and impediments to the movement of terrestrial and aquatic species. These alterations can adversely affect water quality in the stream (Slaney and Zaldokas 1997).

Culvert replacement can reduce or eliminate the negative affects associated with bad culvert design. The elimination of elevation gaps between the inflow and outflow locations can prevent scouring outflows and sedimentation as well as restore connectivity among stream reaches. Culverts should be designed to be at least 0.3 m below the natural grade line of the stream. Structures that preserve the natural streambed are optimal for preserving physical stream structure and stream connectivity. Waste barriers can also be installed upstream of the culvert to prevent blockages (Slaney and Zaldokas 1997). Replacing these culverts with a better design is one way to rapidly improve the quality of the stream.

The pricing of culvert replacement in the Attesi stream is beyond the scope of the current project. Cooperation with the municipality is required to highlight the importance of proper culvert design and suggest alternatives to current culvert installation and maintenance procedures.

Refuse Clean-up

A first course of action in tackling the issue of illegal refuse disposal in local streams is to develop a solid waste collection and recycling program in the area. This involves organization with the local municipality and community leaders. Additionally, educational programs should emphasize the use of recyclable and biodegradable materials to reduce local sources of waste inputs.

Moving now to the condition of local streams, I recommend organizing to remove refuse from local and regional streams. This will provide both an immediate aesthetic reward (the stream will be clean of refuse and debris), as well as more subtle and long-term effects on the stream system. Slow leaching of contaminants from plastics and chemicals disposed of in-stream can contribute to local and regional water pollution. The precise effects of plastics and other waste products on local water quality cannot be ascertained from the data produced by the current study.

The relative ease and low cost of this measure make it a great option for beginning the long process of regional stream system restoration. Once the initial built-up load is removed, regular maintenance to remove new refuse or refuse washed down from upstream areas should be relatively simple. Refuse clean up is a great way to coordinate with the local community, provide education, and create real benefits by beautifying the stream channels.

The organization of community volunteers is a highly effective way to both remove the current refuse build-up and create an ethic of community stewardship. By integrating an educational component, the community volunteers will become invested in the stream restoration process and are unlikely to continue to contribute to the refuse disposal problem. Additionally, an educational component can easily be added to the stream clean up, further strengthening the ethic of stewardship.

Social Engagement / Outreach

Ecological restoration involves a long-term commitment to the land and local resources. Decisions made collectively are much more likely to achieve long-term goals and have the public support required to maintain progress. Involving as many stakeholders as possible in restoration decisions and actions creates the conditions for landscape level changes towards a more resilient ecosystem.

One of the best forms of environmental protection is an engaged local community. Community stewardship initiatives have been shown to be extraordinarily effective at promoting a more responsible and sustainable relationship to terrestrial and aquatic ecosystems. Research has demonstrated repeatedly that community-based restoration develops a strong connection to regional landscapes and improves the success of conservation and restoration initiatives (Clewell and Aronson 2013).

The simultaneous restoration of the environment and social-cultural systems has the potential to engage mainstream society with the land and renew the connection between humans and place. This can enable people to reclaim their responsibility for sustaining the environment that sustains them. The ultimate goals of restoration activities should expand to include changing the human community (Higgs 2005).

One precondition for community stewardship is increasing public awareness of ecological issues and ensuring access for the local community. I suggest the transformation of a section of the stream adjacent to the Attesi site into a community area. This section can be used as a centre for educational initiatives and an example of stewardship for the community.

Installing educational signs in stream areas prone to refuse disposal can also be effective at creating an ethic of community participation by raising awareness about ecological issues that directly affect the community. These signs should be posted in areas with access to the stream channel and in locations of high visibility. Signs should contain a brief message directed at the local community and their collective need for adequate water quality (Figure 14).

Figure 14 - Examples of educational signs for installation in Villa de Allende, Mexico (Image source: ambienteecologicovital).

Local Education

The local population in Villa de Allende is very young, offering extensive opportunities for educational engagement. Over 45% of the population is under the age of 19 years old, with 23% of the population less than 10 years old (Instituto Nacional de Estadística Geografía e Informática Mexico, 2015). Educating the next generation is an incredibly powerful force for raising environmental consciousness. Studies have demonstrated that education about water quality, pollution sources, and riparian ecology is effective in creating an awareness of ecological impacts and promoting an ethic of stewardship (Herringshaw et al. 2010).

Environmental education aimed at instigating an ethic of stewardship and awareness of environmental degradation is most effective in youth education. This can create a generational shift in environmental consciousness. There is a potential for educational events to take place in the stream that runs through Attesi's current agricultural lands. These 15 hectares border two sections of the Attesi stream totalling over 1 km. It was concern over how to best manage and protect this resource that led to the current study. This can assist with cultivating a respect for nature and natural processes, a deeper understanding of the relationship between humans and their environment, and an ethic of stewardship that translates directly into conscious behavioural changes.

Integrating educational programs into restoration work has been successful at increasing ecological awareness in schools and universities throughout the U.S.A. and Canada (Orr, 1994). Even the placement of educational signs and enabling access to conservation areas can greatly increase local support for protection and reduce human effects (Clewell and Aronson 2013). Engaging citizens in scientific research and field studies provides incredible opportunities for local education and can promote environmental stewardship through a connection to local landscapes.

Social and Political Aspects of Restoration

A number of social and political reasons have been identified in municipal reports for environmental degradation. These include changes in land use, lack of vigilance and enforcement of environmental laws, corruption, low social participation, a lack of environmental education, exploitation of groundwater resources, and an insufficient infrastructure for distribution of regional water supplies (Saenz et al. 2006). The establishment of protected areas is the most common strategy for conservation in Mexico. Many studies have shown that the creation of protected areas can cause socio-economic conflicts that threaten conservation objectives and regional development (Camou-Guerrero et al. 2013).

Landscape scale restoration is intended to create a mosaic of connected ecosystems that protect and restore ecological and cultural values. The reintegration of fractured landscapes through the restoration of small-scale local ecosystems can benefit landscapes by reconnecting physical processes and enabling the movement of wildlife species (Clewell and Aronson 2013). Global projects that focus on small-scale rehabilitation initiatives and reconnect local communities to their river systems are demonstrating great success. This approach is providing hope that larger scale change is possible (Brierley and Fryirs 2008). With a vision and passion, leadership in ecological initiatives can extend far beyond the local project and inspire larger regional changes. Just as a large number of small disturbances can lead to regional degradation, small actions of stewardship, restoration, and protection can combine to create positive regional change.

Many successful restoration projects are holistic in scope. Holistic projects aim to integrate ecological concerns with cultural regeneration in order to emphasize the relationship of people and the land. This includes a strong focus on language and local community empowerment (Battiste 2000). Opportunities for cooperation and partnership with local indigenous communities are a great way to increase community engagement and learn valuable information that can be applied to restoration efforts. Traditional people all over the world possess knowledge of the local natural resources and the ecosystems they have historically occupied. The magnitude and complexity of many ecological problems and the lack of pristine reference systems in many areas make this knowledge critical to understanding local conditions (Uprety et al. 2012).

Additionally, integrating local communities into a shared and cooperative vision for regional restoration improves the probability of successful change and enables the creation of a vision shared by all stakeholders. Studies in America, Europe, Australia, and Asia have shown that unless restoration projects are “owned” by the communities involved, long-term success is unlikely to be achieved. Linking ecological and scientific goals to social and cultural goals can lead to increased success (Camou-Guerrero et al. 2013). Studies have demonstrated that the production and use of natural resources in community-managed commons does not have significant effects on the functional properties of these ecosystems (Berkes and Turner 2006). Oftentimes, the co-evolution of the ecosystem and culture has led to an increase in biological diversity due to heterogeneity within the landscape.

Projects in Michoacán have established Community Conservation Areas (CCA) based on reconstructions of local socio-economic history. The establishment of CCAs in three case studies demonstrated that they promoted collective action, created dialogue concerning long-term resource use, engaged local communities in conservation initiatives, and provided alternative conservation options (Camou-Guerrero et al. 2013).

Traditional land management has been very successful in Mexico at preserving local ecosystems. Over 75% of forests in Mexico are managed by *ejidos* and *comunidades indigenas*, collective forms of land ownership created after the Mexican Revolution in 1910. These communities have demonstrated the efficacy of traditional resource management practices generated over centuries or millennia of continuous habitation (Camou-Guerrero et al. 2013). Common lands under the control of traditional cultures have many resources that improve the potential for successful restoration projects. Elders or community leaders can act as the administrative body and the entire community can conduct restoration work. Problems such as lack of local funding can be overcome through community support and enthusiasm. Local ecological education and leadership can contribute to the creation and success of local initiatives (Clewell and Aronson 2013).

Federal and state authorities in Mexico and Michoacán currently promote conservation in community-managed lands through economic incentives. These include payment for environmental services, forestry management, and wildlife conservation areas. However, little has been done to explore the role that traditional practices have in maintaining biodiversity (Camou-Guerrero et al. 2013).

Current models of Payment for Environmental Services (PES) in Mexico State assume that economic values can be accurately placed on environmental services. Differences in the location of costs and benefits, as well as defining relevant stakeholders for payment complicate the issue further. Payments are often inadequate when compared with potential profits from the illegal sale of timber. Other criticisms often focus on the lack of engagement with local communities in order to increase conservation, participation, and direct the use of PES payments towards social benefits for marginalized communities (Franco-Maass et al. 2008). Despite these issues, PES systems can contribute to ecological conservation, especially as a compliment to other policies such as subsidies for sustainable agricultural practices, water preservation, and soil conservation techniques.

The Monarch Butterfly Conservation Fund has been successful at mitigating some of the pressures of development by integrating the needs of the community with conservation goals. The fund (1) pays logging permit holders not to harvest timber in sensitive areas, (2) provides compensation payments to communities to supplement income lost by logging, and (3) provides funds to support alternative economic activities and local law enforcement (WWF n.d.).

Overall, a greater engagement with local communities and indigenous groups is necessary to create a truly inclusive model of development. Integrating the social, environmental, and economic needs of marginalized and powerless groups can lead to regional resiliency and sustainability.

Directions for Future Research

This study presents a preliminary overview of some of the stressors and restoration options that are available for the study streams. Further study would enable a better understanding of the local hydrology, vegetation, wildlife, and annual variation within the system. Future studies should focus on increasing understanding of the effect of each stressor on the system independently. This will allow more effective recommendations aimed at directly removing or reducing the stressors most directly contributing to reduced water quality.

Management Plan for Future Monitoring

The importance of continuing data collection is essential for the success of future restoration efforts. To effectively gauge changes with future restoration work, adequate background data should be collected prior to action. This enables an adaptive management approach where alternative treatments can be implemented and learning can take place from the results. Without a knowledge of the background conditions (pre-treatment), evaluation of restoration work is made much more difficult. This can compromise the success of the entire project (Clewell and Aronson 2013).

I recommend repeating the benthic invertebrate study annually. This should be done in winter low flow conditions for consistency. Study sites can be expanded using the existing framework for site selection and classification. Continued monitoring requires the purchase of appropriate sampling equipment (i.e. Surber Sampler) and equipment for effectively gathering field data. The hiring of a trained biologist is necessary for the first year but local personnel could be trained in sampling and identification for future sampling.

I recommend a seasonal physical survey of stream conditions. This is intended for the collection of background data and to track any changes occurring seasonally or annually. The existence of easily collected background data will improve the design of future research and enable the determination of more robust conclusions. Parameters for a seasonal physical survey are detailed in Appendix B. I designed this survey to be integrated with local educational initiatives.

Full Biological Survey

A full biological survey was beyond the scope of the current study. I recommend further research focused on the plant and animal communities of the local region in order to better understand the regional ecology. Local resources could help with this process and local traditional knowledge could be a valuable resource. Indigenous perspectives can be useful for identifying native species of cultural importance (Uprety et al. 2012). Collaboration and partnership with local indigenous communities is recommended in future vegetation and wildlife studies.

Sampled invertebrate family groupings provide information on local stream invertebrate communities. This study could provide the basis for a full invertebrate survey of regional headwater streams. Laboratory analysis could improve classification resolution to species level taxonomic identification and could be useful for future studies.

In the stream survey, I came across the skeletal remains of several small mammal specimens suggesting that local small mammal species forage or live in the stream and riparian areas. The Trans-Mexican Volcanic Belt is home to the volcano rabbit (*Romerolagus diazi*) and the Mexican volcano mouse (*Neotomodon alstoni*), both endangered species (WWF n.d.). Further study is necessary to determine if these endemic species are locally abundant. I recommend conducting a full wildlife survey of the stream system. The potential presence of endemic and endangered species should be confirmed or denied. This survey will require a trained local wildlife biologist.

I also recommend conducting a full vegetation survey of the stream system. Common problems in riparian areas that are in close proximity to agriculture and development include the loss of local endemic species and the introduction of non-native or invasive species. A full survey will determine if any endemic or invasive species are present. This survey will require a trained local plant biologist.

The presence of non-native or invasive species is one of the greatest threats to biodiversity worldwide (Clewell and Aronson 2013). If invasive species are locally present, removal options should be explored. Invasive communities can out-compete native species, block hydrological flow in affected stream reaches, and reduce the overall biodiversity of the stream system. A diverse community of native species can protect against the establishment of non-native species (Levine and D'Antonio 1999).

Chemical Water Quality Testing

Initial sampling designs discussed with the project sponsors involved chemical water quality analysis. This would require the collection of background baseline data as well as continuous seasonal monitoring in the future. Because of a lack of community support and a scarcity of funding, this option is costly and potentially unfeasible in the long term. Options for future chemical testing of water supplies are provided below. Parameters are based on Health Canada's Guidelines for Canadian Drinking Water Quality (Health Canada 2017).

Sampling should be done at both groundwater sources (springs) and stream channels. I suggest a minimum of three sampling locations located both upstream and downstream of the Attesi site. These locations should be marked and remain consistent for future sampling. Samples should be stored in refrigeration or coolers until processed by an appropriate laboratory.

The following test parameters are most relevant to the current project site because of the water use for human consumption and stream proximity to agricultural fields. The following table provides parameters and acceptable limits in Canadian standards (Health Canada 2017; Table 4). These standards can be applied in Mexico because the use of the resource is the same (drinking). This table is not intended to be exhaustive or to be used to guarantee that all water is suitable quality for drinking. It is intended to indicate potential issues or problems with groundwater sources that should be further investigated by trained professionals. Additionally, Conagua's standards for the discharge of treated water in the state of Mexico are included in Appendix D.

Table 4 - Water quality chemical test parameters (Health Canada 2017).

	Parameter	Guideline	Common Sources	Health Considerations	Application
Microbiological Parameters	Enteric Protozoa: *Giardia* and *Cryptosporidium*	Presence - Removal or Inactivation	Human and animal faeces	gastrointestinal upset (nausea, vomiting, diarrhoea), infections	Monitoring for Cryptosporidium and Giardia in source waters will provide valuable information for a risk-based assessment of treatment requirements.
	Enteric Viruses	Presence - Removal or Inactivation	Human faeces	gastrointestinal upset (nausea, vomiting, diarrhoea), central nervous system infections	Can be used as an indicator of contamination from human waste
	Escherichia coli (*E. coli*)	Presence - None Detectable per 100 ml	Human and animal faeces	gastrointestinal illnesses	E. coli is used as an indicator of the microbiological safety of drinking water; if detected, enteric pathogens may also be present.
	Total Coliforms	Presence - None Detectable per 100 ml	Human and animal faeces, natural sources	Used for monitoring changes in water quality	The presence of total coliforms may indicate that the system is vulnerable to contamination, or it may be a sign of bacterial regrowth.

	Parameter	Guideline	Common Sources	Health Considerations	Application
Chemical and Physical Parameters	Dissolved Oxygen (DO)	Minimum 5.5 mg/L			The most fundamental water quality parameter. Levels below 5.5 mg/L create conditions unsuitable for aquatic life
	Nitrate	Maximum 45 mg/L	Leaching or runoff from agricultural fertilizer use, manure and domestic sewage	Possible carcinogen, Methaemoglobinaemia (blue baby syndrome) and effects on thyroid gland function in bottle-fed infants	Indicative of overland nutrient flows from agricultural runoff. Can cause reduced water quality by creating algal blooms
	Nitrite	Maximum 3 mg/L	Leaching or runoff from agricultural fertilizer use, manure and domestic sewage	Possible carcinogen, Methaemoglobinaemia (blue baby syndrome) and effects on thyroid gland function in bottle-fed infants	Indicative of overland nutrient flows from agricultural runoff. Can cause reduced water quality by creating algal blooms, eutrophication
	Pesticides (test for specific pesticides locally available)	Presence - Safe limit dependant on pesticide	runoff from agricultural application, groundwater leaching	Toxicity dependant on specific pesticide	Potential for groundwater contamination and bio-accumulation in plant and animal species
	pH	7.0 - 10.5			The control of pH is important to maximize treatment effectiveness, control corrosion and reduce leaching from distribution system and plumbing components.
	Total Dissolved Solids (TDS)	AO: < 500 mg/L	Naturally occuring, sewage, urban and agricultural runoff, industrial wastewate	Taste only	TDS above 500 mg/L results in excessive scaling in water pipes, water heaters, boilers and appliances; TDS is composed of calcium, magnesium, sodium, potassium, carbonate, bicarbonate, chloride, sulphate and nitrate.
	Total Phosphorus (TP)	.01-.02 mg/L	Leaching or runoff from agricultural fertilizer use, manure and domestic sewage		Indicative of overland nutrient flows from agricultural runoff. Can cause reduced water quality by creating algal blooms, eutrophication

Anticipation of Climate Change Effects and Adaptive Strategies

The extraction and combustion of fossil fuel resources is increasing the concentration of various greenhouse gases in the Earth's atmosphere. One result of this change is an increase in global temperatures and the modification and intensification of many climate processes (IPCC 2013). According to the United Nations Millennium Ecosystem Assessment, the direct drivers of climate change are expected to increase pressures on species and ecosystems worldwide (Galatowitsch 2012a). This means that threats to biodiversity will increase in many parts of the world. The ultimate severity and speed of these changes are uncertain and depend on human action globally. Local adaptation is one way to mitigate the effects of these changes.

Regional changes in weather and rainfall patterns due to anthropogenic climate change are likely to place further stress on water resources in Mexico. A 2013 United Nations report on Water resources in Mexico identifies the emerging effects of climate change as a primary pressure on water supplies. Changes in temperature and precipitation are likely to create an intensifying water scarcity in all regions of the country (AQUASTAT 2013).

Regional rainfall data is scarce, but general trends in Mexico show a 20% reduction in overall rainfall over the past 30 years, based on historical records dating back to 1900 (World Bank 2017). The most conservative estimates from global climate models predict a reduction in annual precipitation in the local region of between 3-4% by 2040, based on data from the National Oceanic and Atmospheric Association (Geo-Mexico 2010). Projections for all major IPCC scenarios indicate elevated year-round temperatures and decreased overall precipitation in the region (IPCC 2013). Continuing patterns of regional land conversion are likely to be the primary driver of ecological degradation and will be intensified by changes in water regimes. Higher temperatures and decreased precipitation are likely to amplify the negative ecological effects of these processes (Galatowitsch 2012a).

The impending changes resulting from anthropogenic climate change further reinforce the need for precautionary action now. Although much research remains to be conducted to truly understand the effects of human action on the ecological systems of Villa de Allende, this should not be a reason for inaction. The necessity for a guiding vision and action to mitigate or eliminate the effects of human action are critical.

Adaptive strategies implemented locally can help reduce the negative ecological effects of these changes. These actions should include local action to protect existing forests and streams. Groundwater resources are likely to be affected by changes in precipitation patterns. Minimizing human draws on groundwater systems is a critical first step towards protecting this resource. Rainwater collection is an effective method of adapting to reduced precipitation (Pandey et al. 2003).

Increasing the area of riparian forest cover can also assist with carbon sequestration. This reforestation should be done in a holistic way that attempts to recreate local ecosystems in order to be resilient and successful. The creation of living and detrital biomass in forested areas directly contributes to reducing global temperatures through carbon sequestration. Increased transpiration from densely vegetated areas also contributes to cooling of the biosphere. Riparian reforestation is a local strategy that can be used to mitigate the affects of global climate change (Clewell and Aronson 2013).

In the face of climate change, human relationships to the land can be the most enduring of all. The strength of a united community can increase the ability to successfully adapt to changes in climate and local resources. As conditions change, the survival of the community deepens the connection to the land (Martinez et al. 2008).

CONCLUSIONS

IMPLICATIONS OF RESEARCH

The research is meant to provide a solid foundation for future restoration actions in the region. The study demonstrates the effect of anthropogenic alterations on the stream system. Differences in benthic invertebrate community structure and abundance among` degraded and less affected sites demonstrate the effects of rural development on water quality. The specific effects contributed by each stressor to degraded water quality are still unclear.

Additionally, the use of benthic invertebrate metrics for assessment of water quality could provide a low cost feasible method of assessing stream conditions in the future. Studies have shown that after a short amount of training, volunteer and professional monitoring reach consistently equal levels (Moffett and Neale 2015). With proper training, local community members could undertake a regular sampling schedule and track changes in invertebrate communities. This could reduce the need for expensive chemical monitoring, a process unlikely to receive the necessary funding or long term commitment from the local community.

The research also demonstrates the feasibility of rainwater collection as a potential alternative to diversion and over-pumping. Reducing pumping enables more water to flow through the system. Leaving more water to enter the stream and infiltrate the groundwater reserves can contribute to the future sustainability of the community and improve stream conditions (Brierley and Fryirs 2008). By demonstrating an alternative that also eliminates the concerns about groundwater pollution the community will be able to provide an example for other similarly affected communities in the region.

Because ecosystem services and cultural services are interdependent, restoration can also develop place-based sustainable economies. These economies are characterized by their connection to local resources and short commodity chains where economic benefits remain largely within the community. This also involves a move away from relying on the importation of external goods and services. Ecological restoration can increase the understanding and availability of local resources and contribute to the growth of a sustainable local economy (Kimmerer 2011).

River restoration should incorporate both the condition of the river (physical and biological) as well as the connection to local social and economic factors. This enables the use of scientific knowledge as well as cultural attitudes towards to particular rivers or sections of rivers. This can create priorities for restoration and inform the creation of achievable and realistic goals (Higgs 2003). As Robin Kimmerer points out repeatedly in her work, it is not the land that is broken and degraded, but our relationship to it (Kimmerer 2011). The healing of this relationship should be the primary focus in regenerating the landscape for a sustainable future.

REFERENCES

Agua.mx.org. (2009). Agua.mx.org - Watersheds. Agua.org.mx. Retrieved from http://www.agua.org.mx/infografias/CuencaValleDeMexico/

Allan, J. D. (2004). Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, *35*, 257–284.

AQUASTAT. (2013). Mexico - United Nations Water Country Brief. UN-Water.

Banuri, T. (2013). Sustainable Development is the New Economic Paradigm. *Development*, *56*(2), 208–217. https://doi.org/10.1057/dev.2013.38

Barbour, M. T., Gerritsen, J., Snyder, B. D., and Stribling, J. B. (1999). Rapid bioassessment protocols for use in streams and wadeable rivers. *USEPA, Washington*. Retrieved from https://hwbdocuments.env.nm.gov/Los%20Alamos%20National%20Labs/General/14195.pdf

Battiste, M. (2000). *Reclaiming Indigenous Voices and Vision*. University of British Columbia Press. Vancouver, BC.

BC Streamkeepers. (2000). BC Streamkeepers Guide - Module 01 - Introductory Stream Habitat Survey. Fisheries and Oceans Canada - BC Streamkeepers.

Benda, L., Hassan, M. A., Church, M., and May, C. L. (2005). Geomorphology Of Steepland Headwaters: The Transition From Hillslopes To Channels. *Journal of the American Water Resources Association*, *41*(4), 835.

Berkes, F., and Turner, N. J. (2006). Knowledge, learning, and the evolution of conservation practice for social-ecological system resilience. *Human Ecology*, *34*(4), 479–494.

Brierley, G. J., and Fryirs, K. A. (2008). *River Futures : An Integrative Scientific Approach to River Repair*. Island Press.

Bruntland, G. H. (1987). *Report of the World Commission on Environment and Development: Our Common Future*. United Nations. Retrieved from http://www.ask-force.org/web/Sustainability/Brundtland-Our-Common-Future-1987-2008.pdf

Bunn, S. E., and Arthingon, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquaic biodiversity. *Environmental Management*, *30*, 492–507.

CABIN. (2014). Canadian Aquatic Biomonitoring Network Field Manual. Canadian Aquatic Biomonitoring Network.Environment Canada. Dartmouth, NS.

Camou-Guerrero, A., Ortiz-Avila, T., Ortiz-Avila, D., and Odenthal, J. (2013). Community Conservation Experiences in Three Ejidos of the Lower Balsas River Basin, Michoacan. In *Community Action for Conservation: Mexican Experiences* (pp. 47–61).

CCME. (2011). Protocols Manual for Water Quality Sampling in Canada. Canadian Council of Ministers of the Environment.

Chessman, B. D. (1995). Rapid assessment of rivers using macroinvertebrates: a procedure based on habitat-specific sampling, family level identification and a biotic index. *Austral Ecology*, *20*(1), 122–129.

Clewell, A. F., and Aronson, J. (2013). *Ecological Restoration : Principles, Values, and Structure of an Emerging Profession*. Island Press. Washington, DC.

Climate-Data.org. (n.d.). Climate San José Villa De Allende - Temperature, Climate graph, Climate table. Climate-Data.org. Retrieved from https://en.climate-data.org/location/1021718/

Conabio. (2013). Soy Monarca. Conabio. Retrieved from http://www.soymonarca.mx/en/santuarios.html

Conagua. (2010). Statistics on Water in Mexico. Mexico City, Mexico.

Connor, L., Albrecht, G., Higginbotham, N., Freeman, S., and Smith, W. (2004). Environmental change and human health in Upper Hunter communities of New South Wales, Australia. *Ecohealth*, *1*(2).

Corkum, L. D. (1989). Patterns of benthic invertebrate assemblages in rivers of northwestern North America. *Freshwater Biology*, *21*(2), 191–205.

Corkum, L. D. (1990). Intrabiome distributional patterns of lotic macroinvertebrate assemblages. *Canadia Journal of Fisheries and Aquatic Sciences*, *47*, 2147–2157.

Costanza. (1997). Value of Ecosystem Services and Natural Capital.

Cunningham, W. P., and Cunningham, M. A. (2006). *Principles of Environmental Science : Inquiry and Applications* (Third Edition). McGraw-Hill.

Dunnett, N., and Clayden, A. (2007). *Rain gardens: managing water sustainably in the garden and designed landscape*. Timber Press (OR).

Ecological Regions Of Mexico. (2017). Retrieved February 26, 2017, from http://www.worldatlas.com/articles/ecological-regions-of-mexico.html

Farfán, B., Casas, A., Ibarra-Manríquez, G., and Pérez-Negrón, E. (2007). Mazahua ethnobotany and subsistence in the monarch butterfly biosphere reserve, Mexico. *Economic Botany*, *61*(2), 173–191.

Fischner, R. A., and Fischenich, J. C. (2000). Design recommendations for riparian corridors and vegetated buffer strips. U.S. Army Research Center, Environmental Laboratory.

Fisheries and Oceans Canada. (2000). The Streamkeepers Handbook - Module 4: Stream Invertebrate Survey. Fisheries and Oceans Canada. Vancouver, BC.

Flockhart, D. T. T., Pichancourt, J.-B., Norris, D. R., and Martin, T. G. (2015). Unravelling the annual cycle in a migratory animal: breeding-season habitat loss drives population declines of monarch butterflies. *Journal of Animal Ecology*, *84*(1), 155–165. https://doi.org/10.1111/1365-2656.12253

Franco-Maass, S., Nava-Bernal, G., Endara-Agramont, A., and González-Esquivel, C. (2008). Payments for Environmental Services: An Alternative for Sustainable Rural Development: The Case of a National Park in the Central Highlands of Mexico. *Mountain Research and Development*, *28*(1), 23–25. https://doi.org/10.1659/mrd.0971

Freedman, B. (2015). Ecological Effects of Environmental Stressors. In *Oxford Research Encyclopedia of Environmental Science*. Oxford Research Encyclopedia of Environmental Science.

Galatowitsch, S. (2012a). Chapter 2 - Diagnosis and Goal Setting. In *Ecological Restoration*.

Galatowitsch, S. (2012b). Chapter 6 - Landforms and Hydrology.pdf. In *Ecological Restoration*.

Geo-Mexico. (2010). Expected impact on Mexico of global climate change. Geo-Mexico.com. Retrieved from http://geo-mexico.com/?p=3216

Gordon, N. D., McMahon, T. A., Finlayson, B. L., Gippel, C. J., and Nathan, R. J. (2004). *Stream Hydrology : An Introduction for Ecologists*. Wiley.

Greater Wellington Regional Council. (n.d.). Stream Health Assessment Worksheet. Greater Wellington Regional Council.

Hancock, P. J., Boulton, A. J., and Humphreys, W. F. (2005). The aquifer and its hyporheic zone: Ecological aspects of hydrogeology. *Hydrogeology Journal*, *13*, 98–111.

Harris, E. (2006). Development and damage: Water and landscape evolution in Victoria, Australia. *Landscape Research*, *31*, 169–181.

Hawes, E., and Smith, M. (2005). Riparian Buffer Zones: Functions and Recommended Widths. Yale School of Forestry and Environmental Studies. New Haven, CT.

Health Canada. (2017). Guidelines for Canadian Drinking Water Quality - Summary Table. Health Canada.

Herringshaw, C. J., Thompson, J. R., and Stewart, T. W. (2010). Learning about restoration of urban ecosystems: a case study integrating public participation, stormwater management, and ecological research. *Urban Ecosystems*, *13*(4), 535–562. https://doi.org/10.1007/s11252-010-0134-7

Higgs, E. (2003). *Nature by Design: People, natural process and ecological restoration*. Cambridge, MA: MIT Press.

Higgs, E. (2005). The Two-Culture Problem: Ecological Restoration and the Integration of Knowledge. *Restoration Ecology*, *13*(1), 159–164.

Holling, C. S. (1996). Engineering Resilience versus Ecological Resilience. *Engineering Within Ecological Constraints*. The National Academy of Sciences. *31-43*.

Hughes, D., Brossett, M., Gore, J., and Olson, J. (2009). *Rapid Bioassessment of Stream Health*. CRC Press. https://doi.org/10.1201/9781420090932

Hughes, R. M., Larsen, D. P., and Omernik, J. M. (1986). Regional reference sites: a method for assessing stream potentials. *Environmental Management*, *10*(5), 629–635.

Instituto Nacional de Estadística Geografía e Informática, Mexico. (2010). San Jose Villa De Allende. Instituto Nacional de Estadística Geografía e Informática, Mexico.

Instituto Nacional de Estadística Geografía e Informática, Mexico. (2015). Villa De Allende. Instituto Nacional de Estadística Geografía e Informática, Mexico.

IPCC, S. (2013). Annex I: Atlas of Global and Regional Climate Projections - Final Draft Underlying Scientific- Technical Assessment. Retrieved from https://ipcc.ch/meetings/session32/ipcc_IACreview_decisions.pdf

Kimmerer, R. W. (1998). Intellectual Diversity: Bringing the Native Perspective into Natural Resources Education. *Winds of Change*, 14–18.

Kimmerer, R. W. (2011). Restoration and Reciprocity: The Contributions of Traditional Ecological Knowledge. In *Human Dimensions of Ecological Restoration* (pp. 257–276). Island Press. Washington, DC.

Levine, J. M., and D'Antonio, C. M. (1999). Elton Revisited: A Review of Evidence Linking Diversity and Invasibility. *Oikos*, *87*(1), 15. https://doi.org/10.2307/3546992

Li, L., Zheng, B., and Liu, L. (2010). Biomonitoring and Bioindicators Used for River Ecosystems: Definitions, Approaches and Trends. *Procedia Environmental Sciences*, *2*, 1510–1524. https://doi.org/10.1016/j.proenv.2010.10.164

Mandaville, S. M. (2002). *Benthic macroinvertebrates in freshwaters: Taxa tolerance values, metrics, and protocols* (Vol. 128). Citeseer. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.516.2776andrep=rep1andtype=pdf

Martinez, D., Salmon, E., and Nelson, M. K. (2008). Restring Indigenous History and Culture to Nature. In *Original Instructions: Indigenous Teachings for a Sustainable Future* (pp. 88–105). Rochester, VT: Bear and Company.

Merritt, R. W., and Cummins, K. W. (1978). *An Introduction to the Aquatic Insects of North America*. Kendall / Hunt Publishing Company. Dubuque, Iowa.

Metcalfe, J. L. (1989). Biological water quality assessment of running waters based on macroinvertebrate communities: history and present status in Europe. *Environmental Pollution*, *60*(1–2), 101–139.

Millennium Ecosystem Assessment (Ed.). (2005). *Ecosystems and human well-being: synthesis*. Washington, DC: Island Press.

Moffett, E.R., and Neale, M.W. (2015). Volunteer and professional macroinvertebrate monitoring provide concordant assessments of stream health. *New Zealand Journal of Marine and Freshwater Research*, 49(3), 366-375.

Municipal Geographical Information Handbook of the United Mexican States. (2009). Villa De Allende, Mexico - Clave Geoestadistica 15111. Prontuario de información geográfica municipal de los Estados Unidos Mexicanos. Retrieved from http://www3.inegi.org.mx/sistemas/mexicocifras/datos-geograficos/15/15111.pdf

Orr, D. W. (1994). *Earth in Mind*. Island Press. Washington, DC.

Oswald Spring, Ú. (2011). Aquatic systems and water security in the Metropolitan Valley of Mexico City. *Current Opinion in Environmental Sustainability*, *3*(6), 497–505. https://doi.org/10.1016/j.cosust.2011.11.002

Page, N., and Sylvestre, S. (2006). Comparison of Two Benthic Invertebrate Sampling and Analysis Methods for Streams in Greater Vancouver. Vancouver, BC.

Pandey, D. N., Gupta, A. K., and Anderson, D. M. (2003). Rainwater harvesting as an adaption to Climate Change. *Current Science*, *85*(1), 46–59.

Parkes, M., and Panelli, R. (2001). Integrating catchment ecosystems and community health: The value of participatory action research. *Ecosystem Health*, *7*, 85–106.

Paul, M. J., and Meyer, J. L. (2001). Streams in the urban landscape. *Annual Review of Ecology and Systematics*, *32*, 333–365.

Poole, G. C. (2002). Fluvial Landscape Ecology : Addressing uniqueness within the river discontinuum. *Freshwater Biology*, *47*, 641–660.

Postel, S., and Richter, B. D. (2003). *Rivers for Life : Managing water for people and nature*. Island Press. Washington, D.C.

Reynoldson, T. B., Norris, R. H., Resh, V. H., Day, K. E., and Rosenberg, D. M. (1997). The Reference Condition: A Comparison of Multimetric and Multivariate Approaches to Assess Water-Quality Impairment Using Benthic Macroinvertebrates. *Journal of the North American Benthological Society*, *16*(4), 833–852. https://doi.org/10.2307/1468175

Rieger, J., Stanley, J., and Traynor, R. (2014). *Project Planning and Management for Ecological Restoration*. Island Press.

Saenz, F., Estrada, A., Estrada, C. A., Martinez, P., Morales, E., Moreno, H., and Lopez, R. (2006). H. Ayuntamiento de Villa de Allende 2003-2006. Gobierno del Estado de Mexico - Secetaria del Medio Ambiente. Retrieved from http://iisoc.sociales.unam.mx:9080/oit/sig/DocProbarorios/D_Locales/OETL70_POE_MUNICIPAL%20DE%20VILLA%20DE%20ALLENDE.pdf

Schmider, E., Ziegler, M., Danay, E., Beyer, L., and Bühner, M. (2010). Is It Really Robust?: Reinvestigating the Robustness of ANOVA Against Violations of the Normal Distribution Assumption. *Methodology*, *6*(4), 147–151. https://doi.org/10.1027/1614-2241/a000016

Slaney, P. A., and Zaldokas, D. O. (eds.) (1997). *Fish habitat rehabilitation procedures*. Province of B.C., Ministry of Environment, Lands and Parks, and Ministry of Forests. Watershed Restoration Technical Circular No. 9. Vancouver, B.C.

Stanford, J. A., and Ward, J. V. (1993). An ecosystem perspective on alluvial rivers: connectivity and the hyporheic corridor. *Journal of the North American Benthological Society*, *12*, 48–60.

Stoddard, J. L., Larsen, D. P., Hawkins, C. P., Johnson, R. K., and Norris, R. H. (2006). Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications*, *16*(4), 1267–1276.

Strahler, A. N. (1957). Quantitative Analysis of Watershed Geomorphology. Transactions of the American Geophysical Union. 38. 915-920.

Thorp, J. H., and Rogers, D. C. (2011). *Field Guide to Freshwater Invertebrates of North America*. Academic Press. San Diego, CA.

Tortajada, C. (2006). Water management in Mexico City metropolitan area. *Water Resources Development*, *22*(2), 353–376.

UN. (2006). Water: A Shared Responsibility - Case Study - State of Mexico. United Nations - World Water Development Report 2. New York, NY.

UNDP (Ed.). (2006). *Beyond scarcity: power, poverty and the global water crisis*. New York, NY: UNDP.

Uprety, Y., Asselin, H., Bergeron, Y., Doyon, F., and Boucher, J.-F. (2012). Contribution of traditional knowledge to ecological restoration: Practices and applications. *Écoscience*, *19*(3), 225–237. https://doi.org/10.2980/19-3-3530

USDA. (2014). USDA Rain Garden Factsheet. USDA.

Valero, A., Shipper, J., Allnut, T., and Burdette, C. (1998). Southern North America - Southern Mexico Ecoregions. World Wildlife Fund. Retrieved from http://www.worldwildlife.org/ecoregions/nt0310

Vannote, R. L., Minshall, G. W., Cummins, K. W., Sedell, J. R., and Cushing, C. E. (1980). The River Continuum Concept. *Canadian Jounral of Fisheries and Aquatic Science*, *37*, 130–137.

Winter, T. C. (Ed.). (1998). *Ground water and surface water: a single resource*. Denver, Colo: U.S. Geological Survey.

World Bank. (2017). Climate Change Knowledge Portal - Country Historical Climate - Mexico. World Bank. Retrieved from http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climateandThisCCode=MEX

WWF. (n.d.). Mesoamerican Pine-Oak Forests. World Wildlife Fund. Retrieved from http://wwf.panda.org/about_our_earth/ecoregions/mesoamerican_pineoak_forests.cfm

Yates, A. G., and Bailey, R. C. (2010). Selecting objectively defined reference sites for stream bioassessment programs. *Environmental Monitoring and Assessment*, *170*(1–4), 129–140. https://doi.org/10.1007/s10661-009-1221-1

APPENDICES

Appendix A – Benthic Invertebrate Sampling Data

Appendix B – Physical Survey Form

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Appendix D – CONAGUA Water Discharge standards – Mexico

Appendix E – Water Use and Indigenous Rights in Mexico City: Public, Private, and Community Approaches to Water Management

Appendix F – State of Mexico Municipal Data - Villa De Allende

APPENDIX A - BENTHIC INVERTEBRATE SAMPLING DATA

This appendix contains the data as well as specific site information from sampling conducted January 2017.

		Site 1			Site 2			Site 3			Site 4			Total
	Benthic Invertebrate Order or Family Group	Site 1.1	Site 1.2	Site 1.3	Site 2.1	Site 2.2	Site 2.3	Site 3.1	Site 3.2	Site 3.3	Site 4.1	Site 4.2	Site 4.3	
Group 1 - Sensitive	Ephemoptera (mayfly)	9	11	5	12	16	3	4		1	59	214	58	392
	Plectoptera (stonefly)	2			6	5					20	49	14	96
	Tricoptera (caddisfly)	7	1	1	2	3	1				14	24	6	59
Group 2 - Somewhat Sensitive	Anisoptera (dragonfly)	2					1				2		1	6
	Nematocera (cranefly)	1				1	1				22	9	18	52
	Athericidae (watersnipe fly)				1			1			4	8	25	39
	Coleoptera (beetle)	2		1	3	5	15	5	1		1		2	35
Group 3 - Pollution Tolerant	Chironomid (midge)	7	10	20	7	55	140	212	126	357	18	1	13	966
	Simulidae (blackfly)	25		1						3	5	11	1	46
	Hirudinea (leech)		1					1						2
	Hydracarina (water mite)						1	1	1			1	3	7
	Oligochaeta (worm)			1		1		1		2	3	2	6	16

		Site 1			Site 2			Site 3			Site 4			All Sites
Totals	Group 1 - Sensitive	18	12	6	20	24	4	4	0	1	93	287	78	547
	Group 2 - Somewhat Sensitive	5	0	1	4	6	17	6	1	0	29	17	46	132
	Group 3 - Tolerant	32	11	22	7	56	141	215	127	362	26	15	23	1037
	Total Invertebrates	55	23	29	31	86	162	225	128	363	148	319	147	1716
	Site Total	107			279			716			614			1716

		Site 1			Site 2			Site 3			Site 4		
Cumulative Site Totals	Group 1 - Sensitive	36			48			5			458		
	Group 2 - Somewhat Sensitive	6			27			7			92		
	Group 3 - Tolerant	65			279			704			64		
	Richness	8	4	6	6	7	7	7	3	4	10	9	11
	Site Richness	6.00			6.67			4.67			10.00		

Site 1

Site	1.1	Date	21.1.17	Time	13:20
Stream order	2nd	Treatment	X	Control	
Wetted Width	1 m	Bankfull Width	3.6 m	Sample Reach	21.6 m
# of Subsamples	5	Elevation	2486 m	Slope	2-5°
Depth	0.03 m	Temperature	13 °C	Velocity	0.28 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	80%	Dominant Vegetation	Desiduous		
Dominant Substrate	Gravel	Secondary Substrate	Sand		
UTM	14 Q 0378546 2144674				

Site	1.2	Date	21.1.17	Time	15:18
Stream order	2nd	Treatment	X	Control	
Wetted Width	0.7 m	Bankfull Width	2.3 m	Sample Reach	13.8 m
# of Subsamples	5	Elevation	2498 m	Slope	2-5°
Depth	0.02 m	Temperature	11 °C	Velocity	0.25 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	65%	Dominant Vegetation	Coniferous/Desiduous		
Dominant Substrate	Gravel	Secondary Substrate	Sand / Small Stones		
UTM	14 Q 0378464 2144833				

Site	1.3	Date	21.1.17	Time	16:07
Stream order	2nd	Treatment	X	Control	
Wetted Width	0.6 m	Bankfull Width	2.6 m	Sample Reach	15.2 m
# of Subsamples	5	Elevation	2532 m	Slope	2-5°
Depth	0.025 m	Temperature	11 °C	Velocity	0.25 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	70%	Dominant Vegetation	Coniferous		
Dominant Substrate	Gravel	Secondary Substrate	Sand		
UTM	14 Q 0378368 2144833				

Site 2

Site	2.1	Date	22.1.17	Time	15:55
Stream order	2nd	Treatment	X	Control	
Wetted Width	0.8 m	Bankfull Width	3.6 m	Sample Reach	21.6 m
# of Subsamples	5	Elevation	2634 m	Slope	2-5°
Depth	0.06 m	Temperature	11 °C	Velocity	0.2 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	85%	Dominant Vegetation	Coniferous		
Dominant Substrate	Gravel	Secondary Substrate	Sand		
UTM	14 Q 0376719 2145163				

Site	2.2	Date	22.1.17	Time	16:31
Stream order	2nd	Treatment	X	Control	
Wetted Width	0.9 m	Bankfull Width	2.6 m	Sample Reach	15.2 m
# of Subsamples	5	Elevation	2642 m	Slope	2-5°
Depth	0.07 m	Temperature	10 °C	Velocity	0.25 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	80%	Dominant Vegetation	Coniferous		
Dominant Substrate	Gravel	Secondary Substrate	Sand		
UTM	14 Q 0376692 2145162				

Site	2.3	Date	22.1.17	Time	17:15
Stream order	2nd	Treatment	X	Control	
Wetted Width	0.6 m	Bankfull Width	2.1 m	Sample Reach	12.6 m
# of Subsamples	5	Elevation	2647 m	Slope	2-5°
Depth	0.04 m	Temperature	10 °C	Velocity	0.25 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	65%	Dominant Vegetation	Coniferous		
Dominant Substrate	Gravel	Secondary Substrate	Sand		
UTM	14 Q 0376626 2145181				

Site 3

Site	3.1	Date	24.1.17	Time	12:05
Stream order	2nd	Treatment	X	Control	
Wetted Width	1.3 m	Bankfull Width	3.8 m	Sample Reach	22.8 m
# of Subsamples	5	Elevation	2682 m	Slope	2-5°
Depth	0.08 m	Temperature	12 °C	Velocity	0.5 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	50%	Dominant Vegetation	Coniferous		
Dominant Substrate	Sand	Secondary Substrate	Small Stones		
UTM	14 Q 0377678 2147778				

Site	3.2	Date	24.1.17	Time	12:42
Stream order	2nd	Treatment	X	Control	
Wetted Width	1.9 m	Bankfull Width	5.5 m	Sample Reach	33 m
# of Subsamples	5	Elevation	2693 m	Slope	2-5°
Depth	0.06 m	Temperature	13 °C	Velocity	0.6 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	50%	Dominant Vegetation	Coniferous		
Dominant Substrate	Sand	Secondary Substrate	Gravel		
UTM	14 Q 0377601 2147802				

Site	3.3	Date	24.1.17	Time	13:15
Stream order	2nd	Treatment	X	Control	
Wetted Width	2.2 m	Bankfull Width	4.7 m	Sample Reach	28.2 m
# of Subsamples	5	Elevation	2716 m	Slope	2-5°
Depth	0.05 m	Temperature	13 °C	Velocity	0.6 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	55%	Dominant Vegetation	Coniferous		
Dominant Substrate	Sand	Secondary Substrate	Gravel		
UTM	14 Q 0377598 2147977				

Site 4

Site	4.1	Date	23.1.17	Time	15:57
Stream order	2nd	Treatment		Control	X
Wetted Width	0.9 m	Bankfull Width	2.5 m	Sample Reach	15 m
# of Subsamples	5	Elevation	2686 m	Slope	2-5°
Depth	0.07 m	Temperature	10 °C	Velocity	0.35 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	70%	Dominant Vegetation	Coniferous		
Dominant Substrate	Small Stones	Secondary Substrate	Gravel		
UTM	14 Q 0372425 2150445				

Site	4.2	Date	23.1.17	Time	16:25
Stream order	2nd	Treatment		Control	X
Wetted Width	1.5 m	Bankfull Width	2.5 m	Sample Reach	15 m
# of Subsamples	5	Elevation	2679 m	Slope	2-5°
Depth	0.05 m	Temperature	10 °C	Velocity	0.65 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	50%	Dominant Vegetation	Coniferous		
Dominant Substrate	Small Stones	Secondary Substrate	Gravel		
UTM	14 Q 0372435 2150422				

Site	4.3	Date	23.1.17	Time	17:01
Stream order	2nd	Treatment		Control	X
Wetted Width	1 m	Bankfull Width	3 m	Sample Reach	18 m
# of Subsamples	5	Elevation	2679 m	Slope	2-5°
Depth	0.07 m	Temperature	11 °C	Velocity	0.8 m/sec
Riffle	X	Run	X	Pool	X
Canopy Cover	50%	Dominant Vegetation	Coniferous		
Dominant Substrate	Small Stones	Secondary Substrate	Gravel		
UTM	14 Q 0372436 2150412				

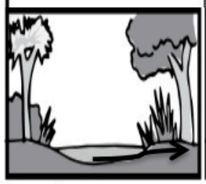
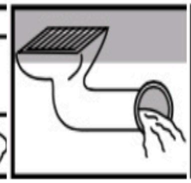
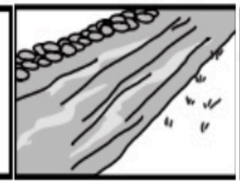
APPENDIX B - PHYSICAL SURVEY FORM

This appendix contains an educational stream survey form designed to encourage dialogue while taking simple measurements. The sponsors requested this as part of a future planned educational module. It is also intended to begin in the collection of background data that might be helpful in identifying future restoration projects.

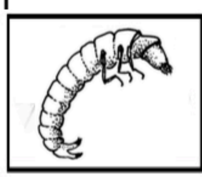
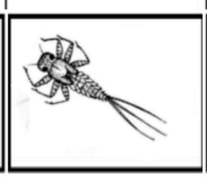
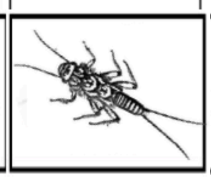
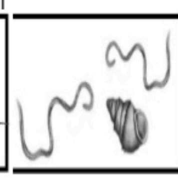
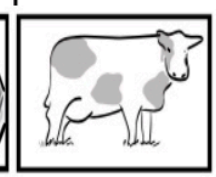
Images and layout are adapted from the Greater Wellington Regional Council Stream Health Assessment Worksheet (Greater Wellington Regional Council n.d.). Basic stream parameters adapted from CABIN protocol (CABIN 2014) and BC Streamkeepers Handbook (BC Streamkeepers 2000).

Hoja de Trabajo de Evaluación de Flujos

Fecha: ___________

Alteraciones Antropogénicas (Presente/No Presente)							
Hidrológico					Físico		
Equipo de Bombeo - Funcional	Equipo de Bombeo - No Funcional	Alcantarillas (<100 m río arriba)	Infraestructura de aguas pluviales	Basura en Flujo de Corriente	Alteración del Canal de Corriente (Enderezamiento)	Caminos	Presa o Barrera
							

Nombre del Muestreador		Orden de Flujo		Velocidad de la Corriente (m/s)	
Nombre del Río		Elevación (m)		Ancho Húmedo (m)	
Ciudad más Cercana		Cuesta Abajo		Ancho de Banco (m)	
Localización GPS (UTM)		Temperatura (C)		Profundidad Promedio (m)	

Indicadores Biológicos de la Salud de la Corriente							
Stream Invertebrates				Algas		Animales	Zona Ribereña
Caddisfly Detectado (S/N)	Mayfly Detectado (S/N)	Stonefly Detectado (S/N)	Principalmente Gusanos y Caracoles (S/N)	Algas Detectado (S/N)	Cobertura de Algas (0-100%)	Animales Domésticos en Corriente (S/N)	Cubierta de Árbol (0-100%)
							

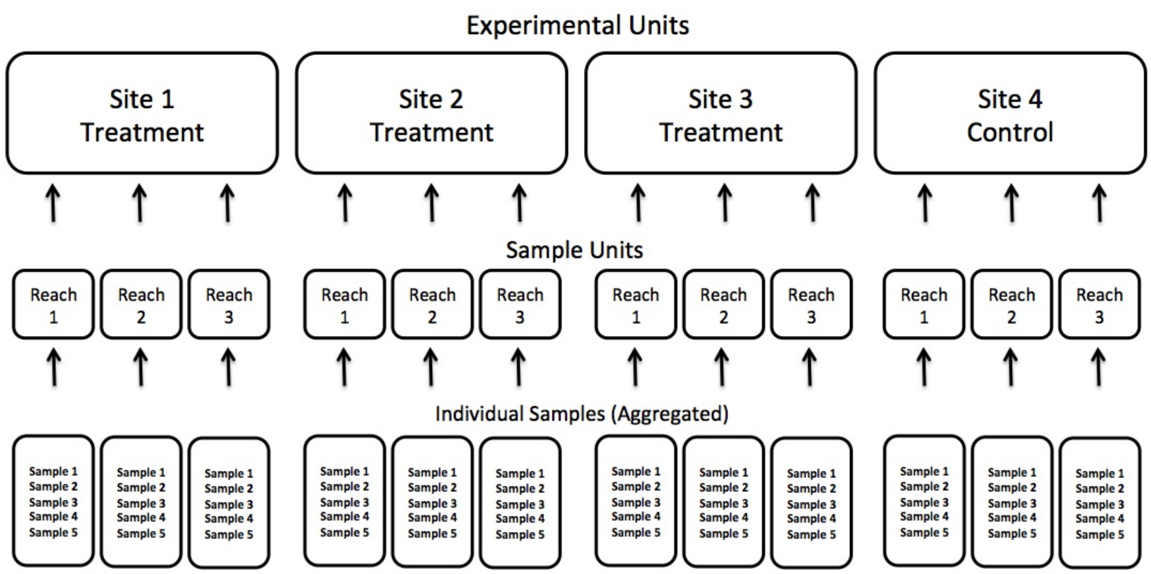
APPENDIX C - STATISTICAL DATA

This appendix is intended to provide a more detailed version of the statistical analysis presented in the study. Included here are the rationales for statistical design choices, the complete data set from the invertebrate study, and all calculated values from the statistical analysis.

Site and Sample Information

I sampled in four separate streams. These streams are the four experimental units included in this study. These include: 1) three treatment sites with anthropogenic alterations (Site 1, Site 2, and Site 3) and 2) one control site (Site 4). A visual representation of the sampling design can be seen in the figure below.

I divided each experimental unit into separate stream reaches, with three sampling units per stream. Each sampling unit had 5 sample elements. Each of the 5 sample elements was an individual in-stream sample that I collected in each sample unit (i.e., each stream reach). I used the number of sampling units (i.e., n = 3) as the sample size for the analyses.

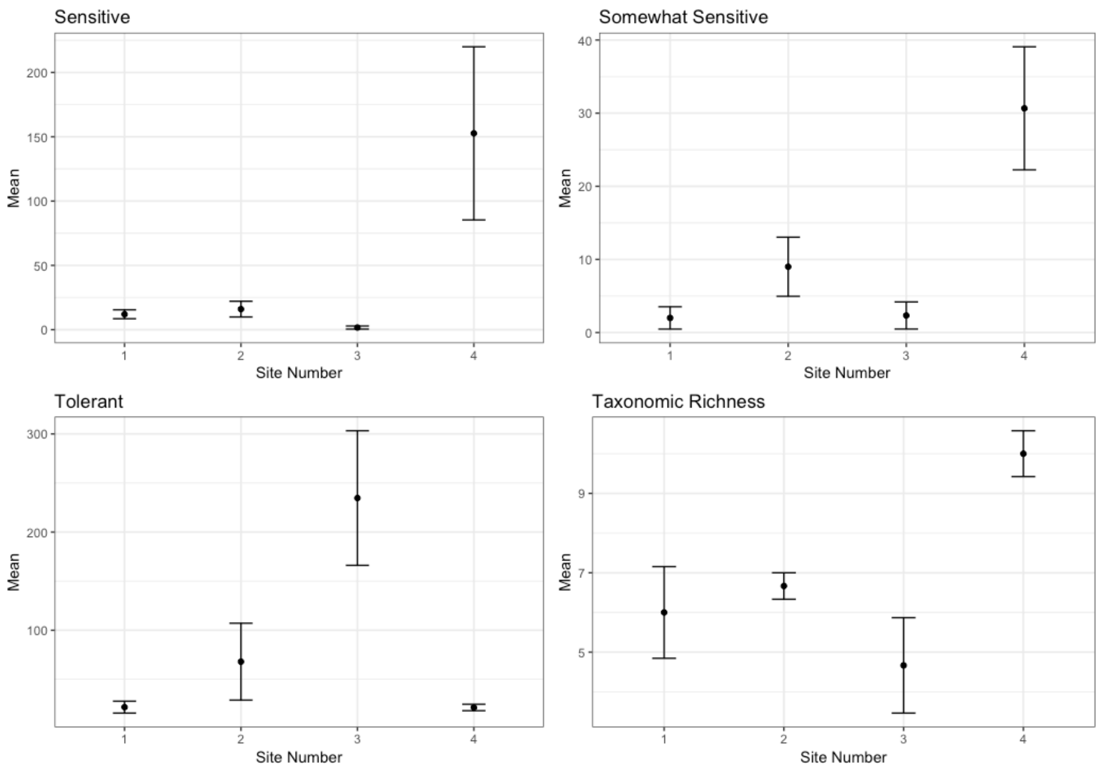


Mean and Standard Error of the Mean

I calculated the mean for each water quality sensitivity group and for taxonomic richness within each experimental unit. I calculated the mean using the values observed in the three sampling units within each stream. The mean values for these parameters were used to draw inferences about the abundance and richness in each sampled stream.

Standard error of the mean is an inferential statistical measure that indicates the uncertainty around the estimate of a mean measurement. I chose to measure the standard error of the mean because I am interested in the mean of the population from which the sample comes in each experimental unit. In other words, I am interested in the mean taxonomic richness of invertebrates and the mean abundance of invertebrates from each water quality sensitivity group for each of the sampled streams.

Mean and Standard Error of the Mean for abundance of benthic invertebrates of differing water quality sensitivity (sensitive, somewhat sensitive, tolerant), and taxonomic richness in stream sites is presented in the following figure.



Statistical Design

I used a One-Way ANOVA to test the hypothesis that there are no significant differences among the means of the four streams.

There are three assumptions that should be met for the use of ANOVA.

1 - Independence both within and among sample groups.

This is a part of the study design. I met this condition by having a minimum of 50 meters among sample sites, sampling downstream sites first to avoid disturbance, and having separate streams (independent replicates) for each experimental unit.

2 – Normality in the distribution of the data.

I used histograms and ‘normal QQ plots for residuals’ to determine if the data was normally distributed. Results showed that the data was not normally distributed.

The ANOVA can still be used if this condition is not met because it has been shown to be robust enough to handle non-normal data.

3 – The populations should have homogeneous variances (standard deviation).

I used Levene's test to determine if the differences in variance in stream sites were significant for each variable. The tests showed a P-value higher that .05 for each variable, meaning that there is no significant difference among the variance of each parameter and that this condition is met by the data.

One-way ANOVA

The ANOVA statistical test is used to compare the variance among means. The P value that is generated by the test gives the confidence interval by which the null hypothesis can be accepted or rejected. It is common to use a 95% confidence interval to make this determination. A P value below .05 means that this condition has been met.

Null hypothesis: There is no difference among the means observed in the different streams.

Alternative hypothesis: At least one sample mean is not equal to the others.

I ran an analysis of variance (ANOVA) for each measured parameter. Generated P values show that I can reject my null hypothesis with a 95% confidence interval for all observed parameters. I can now accept my alternative hypothesis with the same confidence interval for all observed parameters. Results are presented in the table below.

Parameter		Degrees of Freedom	sum square error	mean squared error	F value	Pr (>F)
Mean Abundance	Site 1-4	3	46196	15398.5	4.482	0.03988
Sensitivite	Residuals	8	27485	3435.7		

Parameter		Degrees of Freedom	sum square error	mean squared error	F value	Pr (>F)
Mean Abundance	Site 1-4	3	1640.67	546.89	7.8501	0.00908
Somewhat Sensitivite	Residuals	8	557.33	69.67		

Parameter		Degrees of Freedom	sum square error	mean squared error	F value	Pr (>F)
Mean Abundance	Site 1-4	3	92237	30746	6.5291	0.01524
Tolerant	Residuals	8	37672	4709		

Parameter		Degrees of Freedom	sum square error	mean squared error	F value	Pr (>F)
Mean	Site 1-4	3	46.333	15.4444	6.3908	0.01616
Taxonomic Richness	Residuals	8	19.333	2.4167		

Tukey HSD (Tukey Honest Significant Differences)

In a one-way ANOVA test, a significant P value means that some of the group means are different but does not tell us which ones. A post hoc analysis can be used to perform a multiple pairwise-comparison and indicate which values are significantly different from each other among pairs of sample sites.

I used the Tukey HSD test to determine if the mean differences among pairs of sample sites are significantly different for each measured parameter. I chose this test because the purpose of the study is to determine if there is a difference in taxonomic richness and relative abundance among the means of my treatment sites and my control site. I also used the test to determine if the treatment sites are significantly different from each other. The Tukey HSD tests the difference between specific pairs within the data set and generates an adjusted P value for the significance of this difference. The following table presents the generated values for these tests among the four sampled sites for each measured parameter.

Parameter	Site Comparison	P. adj
Mean Abundance	2-1	0.9997721
Sensitive	3-1	0.9961507
	4-1	0.0724791
	3-2	0.9899493
	4-2	0.0815637
	4-3	0.0534374

Parameter	Site Comparison	P. adj
Mean Abundance	2-1	0.8404125
Tolerant	3-1	0.0217763
	4-1	0.9999999
	3-2	0.0689433
	4-2	0.8376591
	4-3	0.0216007

Parameter	Site Comparison	P. adj
Mean Abundance	2-1	0.739297
Somewhat Sensitive	3-1	0.9999542
	4-1	0.0126578
	3-2	0.7653547
	4-2	0.0516522
	4-3	0.0135021

Parameter	Site Comparison	P. adj
Mean	2-1	0.9505655
Taxonomic Richness	3-1	0.726663
	4-1	0.0537224
	3-2	0.4418424
	4-2	0.1126935
	4-3	0.0127346

Treatment – Control Comparisons

Determination of the degree of difference among control and treatment site for measured parameters is a key reason for the current study. The results generated several values of interest for the comparison among control and treatment sites. The differences for the abundance of ‘sensitive’ group invertebrates are significant with a 90% confidence interval (adj. P value between .05 and .1). The differences for the abundance of ‘somewhat sensitive’ group invertebrates are significant using a 95% confidence interval in two cases and a 90% confidence interval in the remaining case. The differences for the abundance of ‘tolerant’ group invertebrates are only significant in one case using a 95% confidence interval. The differences for the taxonomic richness were significant in one case using a 95% confidence interval and one case using a 90% confidence interval. A 95% confidence interval is commonly used as a standard for significance. The failure to meet the 95% confidence level in several cases is likely a result of low sample size.

Treatment Site Comparisons

The differences among treatment sites were not statistically significant in all cases for all measured parameters with one exception. This result was expected and suggests a broad similarity across the treatment sites for taxonomic richness and relative abundance of benthic invertebrates with different water quality sensitivity levels. The one exception was the difference between site 3 and site 1 which was significant using a 95% confidence interval. This is likely due to the huge amount of ‘tolerant’ group midges in the samples at site 3.

Type 1 and 2 Errors

Type 1 Error – The incorrect rejection of a true null hypothesis

> This error is more or less likely to occur depending on the confidence interval used. It is common to use a 95% confidence interval to accept or reject a null hypothesis. This still leaves a 5% chance of a Type 1 error if the null hypothesis is rejected with 95% confidence.

Type 2 Error – The failure to reject a false null hypothesis

> The possibility of this error exists if we accept the null hypothesis based on the results of several of the Tukey HSD pairs. As indicated above, several of the cases meet a 90% confidence level but would not reject the null hypothesis if we adhere to the standards of statistical orthodoxy (95%).

This is not to say that the observed results are not indicative of real differences among the sites. The ‘significance’ of a finding can be measured in other ways than a P value. I would suggest that weighing the measured confidence intervals qualitatively in the context of the study itself as well as the existing knowledge about ecological effects of human alterations is a better way to evaluate the significance of the findings than a yes/no decision based on an orthodox 95% figure.

APPENDIX D - CONAGUA WATER QUALITY STANDARDS – STATE OF MEXICO

The following tables are sourced from current water quality discharge standards used by Conagua in the State of Mexico (Conagua 2010). They are provided for reference only for further water quality measurement information.

Characteristic	Permissable Limit mg/L
Tin	0.2
Arsenic	0.05
Barium	0.7
Cadmium	0.005
Cyanides	0.07
Free Residual Chlorine	0.2-1.5
Chlorides	250
Copper	2
Total Chrome	0.05
Total Hardness (CaCO3)	500
Phenols or Phenolic Compounds	0.3
Iron	0.3
Fluorides	1.5
Benzene	10
Ethylbenzene	300
Toluene	700
Xylene	500
Manganese	0.15
Mercury	0.001
Nitrates	10
Nitrites	1
Ammoniacal Nitrogen	0.5
pH	6.5-8.5
Aldrin/Dieldrin	0.03
Chlordane (Isomer Total)	0.2
DDT (Isomer Total)	1
Gamma-HCH (Lindane)	2
Hexachlorobenzene	1
Heptachlor and Heptachlor Epoxide	0.03
Methoxychlor	20
2,4 - D	30
Lead	0.01
Sodium	200
Total Dissolved Solids	1000
Sulfates	400
Methylene-Blue Active Substances (MBAS)	0.5
Total Trihalomethanes	0.2
Free Residual Iodine	0.2-0.5
Zinc	5
Total Coliform Organisms	2 MPN/100 ml 2 CFU/100 ml
Fecal Coliform Organisms	0 MPN/100 ml 0 CFU/100 ml (undetectable)

APPENDIX E – WATER USE AND INDIGENOUS RIGHTS IN MEXICO CITY: PUBLIC, PRIVATE, AND COMMUNITY APPROACHES TO WATER MANAGEMENT

PROLOGUE

In 2004, a group of women armed with hand-made wooden guns descended on the Los Berros Water Treatment Plant in the mountains West of Mexico City. The women were members of the Zapatista Army of Mazahua Women in Defense of Water, and they had come to occupy the facility. The guns were a symbolic expression of a deep anger rooted in decades of exclusion from participating in the management of local water resources.

The Mazahua women, members of the largest indigenous group in Mexico, peacefully occupied the plant for fifteen days in a standoff with local and regional authorities. In order to make their demands heard, the women shut down the water supply bound for Mexico City. This occupation was in response to the flooding of Mazahua agricultural fields by CONAGUA, the Mexican Water Authority (Oswald Spring 2011).

The historical roots of this conflict come from a long history of exploitation by colonial and national governments. In 1972 the federal authorities began to appropriate water resources in valleys adjacent to Mexico City that were the historical lands of the Mazahua and other indigenous groups. This diversion and consumption of water resources continued for decades with no consultation or compensation. Despite seeing their environment degraded and their resources siphoned off to support urban growth, these communities lacked basic infrastructure such as tap water, drainage, and sewage facilities (Oswald Spring 2011). The women decided to take matters into their own hands.

The negotiation process that ended the 2004 standoff was successful in securing promises of water facilities and infrastructure for indigenous villages, the rehabilitation of logging roads and impacted rivers, the protection of local water bodies, and reforestation initiatives to improve water capture. Despite these concessions, the conflict continues to unfold. Broken promises and the continued appropriation of regional water resources make a solution difficult (Oswald Spring 2011).

Failures to address the needs of water users are not uncommon in the continuing challenge of water management in the region surrounding Mexico City. Water ownership, management, and provision in Mexico are complicated by the interests and needs of diverse stakeholders. These include local users from various socio-economic groups, federal, state, and municipal governments, private corporations, and international development and finance organizations. Many problems come from a lack of coordination and the diffusion of responsibility between these actors. The conflict highlights the need for new solutions that can address the historical patterns of inequality and injustice that characterize water rights in Mexico.

INTRODUCTION

This report will explore the current debate on water access and provision in Mexico City and the surrounding region by focusing on local resistance. Most current research focuses on the issue of public or private provision of water and the respective merits or drawbacks of each (Budds and McGranahan 2003; Pierce 2012; Wilder and Romero Lankao 2006). The case of the Mazahua protests shows the historical failures of both of these methods to serve the needs of marginalized communities. The protests also emphasize the need for alternative conceptions of water management that are more democratic, transparent, and connected to the communities that rely on this precious resource.

An outburst of conflict by rural indigenous communities over water rights highlights the complicated nature of water provision in Mexico. The Mazahua people have continuously seen their traditional lands and resources eroded. In colonial times, it was in the name of “civilization”, in the twentieth century it was in the name of “development”. More recently, private companies have purchased communal lands and water from the state and federal governments, often without consultation or participation from rural communities. Today the Mazahua share their rivers, streams, and springs with the ever-growing demands of Mexico City (Salcedo 2015).

What can we learn through the ongoing battles for indigenous rights centered on water access in and around Mexico City? The complicated nature of this conflict raises several questions. What are the historical circumstances that led to the action, and where does this struggle fit into the discourse on development and prospects for sustainability? In order to explore these questions we must first situate the issue in a regional and global context. The actions of indigenous protesters are part of a larger conflict over the access and provision of water in Mexico City and the surrounding regions. This conflict, in turn, is shaped by the larger processes of international development that have influenced Mexico’s approach to water management. By exploring the history of the issue, we will be able to see the current conflict as the outcome of specific forces and interests in the past. We will then move to the specific historical conditions that set the backdrop for the conflict.

Focusing on Mexico specifically, I will explore the complicated nature of the interests and strategies employed by varying groups and stakeholders. These stakeholders include international development and financial organizations, corporations, government, protesters, indigenous groups, marginalized communities, and women. The successes and failures of public and private provision will be examined. I will then return to the battle for water rights in the Villa de Allende in order to shed some light on current directions and potential alternatives to state regulation or the deregulated privatization of water resources.

Global Transitions in Water Rights and Management

The fight of the indigenous Mazahua people of Mexico for water rights is part of a larger pattern of protest and resistance over the economic, social, and environmental aspects of water management. This struggle takes place at a variety of scales and with diverse actors. At one level, struggles erupt in local communities faced with privatization of water resources previously held as communal property. At another level, an international coalition of NGOs, public sector unions, scientists, academics and indigenous groups participate or protest at summits and conferences held by the United Nations and other development agencies. Often this same coalition is joined by anti-globalization activists and marginalized populations to stage protests at trade summits around the world. International negotiations on water resources are continually contested and large protests are common (Bakker 2007). A shared goal is the inclusion of local populations in the decision-making processes that determine the fate of the most vital resource of all: water.

Since 1992, developing nations worldwide have implemented a variety of policies aimed at the deregulation and privatization of infrastructure and resources previously managed by the state. These “neo-liberal” reforms have sparked a fierce global debate. Water ownership, provision, and management have been central to this discussion. Supporters argue that privatization can increase efficiency and accountability in water management. Criticisms include the argument that water is essential to life and not a “good” to be managed, the incompatibility of corporate values (i.e. profit) with the values of equality and human decency, and the fencing off of “the commons” by private interests.

These criticisms have occasionally reached a fever pitch, causing a reversal of the process of privatization and deregulation. Legal challenges in Buenos Aires and conflicts such as the “water war” in Cochabamba, Bolivia that led to the reversal of privatization initiatives show that public pressure can be effective in a fight for fair and just provision of water (Schouten and Schwartz 2007).

Water and land are central concerns of indigenous movements across Mexico. The Zapatista movement, a revolutionary group that rose against the state in the 1990s, has joined water defense campaigns in several Mexican states. Some of these movements have attained some success, but many promises made remain unfulfilled (Salcedo 2015). The protests of the Mazahua women in Mexico State are a local expression of this broad pattern of resistance.

Despite the almost universal presence of public disapproval to these types of water reforms in the developing world, successful resistance remains rare. There has been considerable resistance to neo-liberal reforms of water management in the past two decades throughout the developing world, including large-scale protests in Africa and Latin America. These are mostly the result of the continuing inability of neo-liberal policies of water privatization to improve water quality and access for poor and marginalized communities. Twenty years after the shift in focus to “economic” style water management, 884 million people remain without access to a safe and sustainable water source, with 2.6 billion lacking access to improved sanitation. This is the cause of very high levels of disease, suffering, and mortality worldwide and is a serious limit to development objectives (Mirosa and Harris 2012).

We will turn now to looking at the history of water provision in a development context. By looking at the history of water management, both public and private, we can begin to see some of the successes and limitations of these two alternatives approaches.

Despite some shifts between public and private provision over the past two centuries, the twentieth century saw water being almost universally treated a public good with near total control being taken by the state. But in the past three decades, experiments with opening water resources to free-market principles have occurred in the developing world, mainly in Latin America (Romero Lankao 2011).

The developed countries implemented and reached almost full provision of water and sanitation services by the beginning of the 20th century. This was all done using a model of public provision. By the 1970s, the significant lack of progress in water provision in the developing world became a focus for development agencies. In the 1980’s huge investments were made in infrastructure worldwide. Unfortunately, it soon became clear that infrastructure expansion alone would not be able to provide equitable access for all (Mirosa and Harris 2012). A consensus began to emerge that despite the success of public provision models in the developed countries, private sector participation might help to solve the implementation problems of the developing world.

This perspective can be tied directly to neo-liberal free market policies and the aggressive promotion of reforms and structural adjustment policies by international financial institutions. These policies are often seen by critics as a means of pursuing the interests and economic profits of donor countries in the developed world. Indeed, much of the global investment in water resources from the 1990s onwards was by multinational companies based in developed nations such as France and the United States (Budds and McGranahan 2003). Water privatization has been quite profitable.

The World Bank's 1992 policy on Water Management focused almost exclusively on the economic value of water and the transfer of water resources to the private sector. Policies that implemented this vision were pushed across the developing world as conditions for investments, loans, and debt relief (Wilder and Romero Lankao 2006).

A critical moment came in 1992 in Dublin with the creation of four general principles for water management, the "Dublin Principles". These emerged from preparatory discussion for the United Nations 1992 Rio Earth Summit. The four "Dublin principles" were declared in 1992 (Darnault 2008). They are as follows:

1. Fresh water is a finite and vulnerable resource, essential to life, development and the environment.
2. Water development and management should be based on a participatory approach, involving users, planners, and policy-makers at all levels
3. Women play a central part in the provision, management, and safeguarding of water
4. Water has an economic value in all its competing uses and should be recognized as an economic good

The fourth of these principles would signal a massive change from previous policies of subsidized public water provision. It established that water should be managed as an "economic good", a principle that would widely be interpreted as meaning that water should be provided by private companies and paid for by consumers. This principle was a result of the emerging neoliberal paradigm in development and resulted in a worldwide shift towards water privatization (Mirosa and Harris 2012). This commodification was accompanied by increased pressure from international development agencies such as the World Bank to implement water privatization initiatives.

In 2003 the World's Water and Environmental Ministers drafted a declaration in the face of growing water scarcity. This declaration stated that the commercialization of water resources was the best response to growing scarcity. This resulted in the inclusion of a large number of private corporations in development planning at the international scale (Bakker 2007).

2003 forums in Kyoto co-organized by the Global Water Partnership and the World Water Council reached a consensus, despite serious public opposition and protest. This consensus included new support for private sector financing, new mechanisms for private sector water supply management, and the failure to refer to water as a human right (Bakker 2007).

The 2003 Kyoto declaration is the embodiment of an increasingly dominant philosophy often called "liberal" or "market" environmentalism. It refers to a method of resource regulation that aims to use market-based solutions to solve environmental problems. The strategy focuses on economic growth and attempts to integrate environmental conservation into the neoliberal focus on growth, deregulation, and privatization. Environmental goods are framed as economic goods in order to subject them to the claimed efficiencies of the market (Bakker 2007).

Public services are often slow in providing access and prone to inefficiency and corruption. Still, the replacement of these services with private sector actors remains controversial (Budds and McGranahan 2003). Despite being widely promoted and implemented in the Global south in the 1990s, water privatization has not achieved the scale or benefits anticipated by international development agencies (Budds and McGranahan 2003). Between 5-10% of the world's population now depends on privatized water supply (Pierce 2012).

Public sector involvement has been justified a number of ways. These include the 'natural monopoly' characteristics of water, the cultural importance as a non-substitutable resource, its political and territorial importance, conflicts between stakeholders and users, and cross-boundary water requirements. Additionally the health and hygiene implications of inadequate coverage and the failure of private providers to extend services to poor communities have been used as arguments for state control (Bakker 2003).

Proponents of market environmentalism argue that water is a scarce resource and that market mechanisms will ensure it is distributed effectively and efficiently. They argue that pricing water at its full environmental and economic cost will ensure it is allocated to its highest value costs and be managed profitably by companies who are accountable to their customers (Bakker 2007). Opponents of this view argue that water is not a commercial resource but is a non-substitutable resource necessary for human life. They often call for water to be recognized as a human right. This view, they argue, places a responsibility on the state for provision and makes private sector involvement inappropriate (Bakker 2007).

One source of continuous criticism is the incompatibility of ideas of economic profit with the fact that water is needed for life and basic well-being. The focus on efficiency in development programs promoting privatization often obscure or ignore the fact that profit is the goal of private providers (Mirosa and Harris 2012).

Privatization and deregulation policies have been shown to be successful at improving provision to higher-value urban water users, hydroelectricity generation, and industrial users. This is perhaps not surprising when we look at the profits possible from provision to these consumers. However, the reforms have continuously failed to address the needs of poor, marginalized communities or the needs of the environment (Wilder and Romero Lankao 2006). Under the right circumstance, private providers may be able to improve efficiency and improve water and sanitation services. But they can also direct resources towards areas that are comparatively well off, create new regulatory concerns, and prioritize profit over other social or environmental concerns (Budds and McGranahan 2003).

We will now turn to the history of water management in Mexico in order to see how these global shifts in water management and provision have been implemented there. Mexico was one of the largest implementers of water privatization in the 1990s, pushed aggressively by development agencies and international financial organizations. We will look at the successes and failures of privatization initiatives in Mexico City before turning to the current situation there and the search for alternative models that may better serve the needs of all water users.

Historical Patterns of Water Management and Development in Mexico

Mexico City is constructed on reclaimed land that has been drained over the past few hundred years. Historically, the entire valley was a large lake and a series of connected wetlands. Settlement in the region has required the diversion and drainage of large areas of the basin. The main challenge for the past 500 years has been in finding ways to drain the Basin of Mexico and protect against seasonal flooding. By the start of the 20th century this had mainly succeeded but by the 1950s a new problem began to emerge, that of water scarcity (Hernandez and Cruz-Medina 2011). Historical efforts to drain the Valley of Mexico for urban expansion over the past 300 years have resulted in water scarcity, pollution, water conflicts, health issues, and environmental problems. These burdens have been disproportionately shouldered by poor and vulnerable populations (Oswald Spring 2011).

Historical drainage in the Basin of Mexico means that water must be pumped from hundreds of meters underground or from adjacent water basins. Getting water up to Mexico City (at 2400m elevation) requires visionary engineering and huge investments (Salcedo 2015). Groundwater exploitation in Mexico has been steadily escalating since 1847. This has resulted in the continuous drawdown of the aquifer as consumption overtook natural recharge rates. Ground water extraction is also causing subsidence of the entire metropolitan area, sinking an average of 7 cm a year. This causes damage to infrastructure, housing, and other investments (Romero Lankao 2011).

Well drilling escalated throughout the 20th century with aquifers being tapped in adjacent water basins (Hernandez and Cruz-Medina 2011). The main focus of water management since the 1950s has been to transfer the Basin of Mexico's problems to adjacent areas. This means the extraction of huge amounts of surface and groundwater from the surrounding regions. This is done through two connected inter-basin systems: the Lerma and the Cutzamala (Hernandez and Cruz-Medina 2011). This extraction is one of the root causes of environmental damage in the region.

The strategies of water management have changed a lot over the past 50 years in Mexico City. Until the early 1990s, Mexico had one of the strongest systems of state control in virtually all sectors of the economy and civil society. The changes that led to a dismantling of this strong interventionist system have caused large changes in the water sector and can be seen in the transformation of water, agricultural, and environmental legislation since 1992 (Wilder and Romero Lankao 2006).

Mexico radically transformed its urban, agricultural, and environmental framework in the early 1990s, concurrent with the adoption of the North American Free Trade Agreement (NAFTA) in 1994. Investments in government water agencies and water infrastructure have decreased dramatically since this time. Many of these changes were done under immense pressure from the World Bank and international development agencies, which were strongly pushing for the implementation of neoliberal reforms across the developing world (Wilder and Romero Lankao 2006). Since 1994, 27 hydraulic concessions have been given out to 16 corporations. This has effectively privatized millions of cubic meters of previously public water on 15 major rivers in 10 states (Acedo 2015).

Water reform strategies began in the late 1980s in Federal District of Mexico City. By 1993 water administration had been privatized in a short and closed bidding process with little public participation or transparency. Four companies (with strong transnational ties) were given concessions to be the private administrators of water in the Federal District (Wilder and Romero Lankao 2006). The implementation of neoliberal water reforms in the 1990s in Mexico was driven by multilateral financial institutions (the World Bank and others) with the support of bilateral development agencies. These reforms were undertaken even in the face of considerable resistance and public opposition (Budds and McGranahan 2003).

The implementation of the National Water Law in Mexico in 1992 decentralized water management from the federal to the state and municipal level. This opened the door for the privatization of municipal provision. These changes, as well as changes to environmental protection laws, were conditions of $350 million loan from the World Bank (Wilder and Romero Lankao 2006). Mexico city cut public expenditures through the sale of public utilities, cutting water subsidies, and laying off thousands of public sector employees. Almost all publicly owned enterprises were sold to the private sector. National water bureaucracies shrunk dramatically and investment in infrastructure decreased. This was accompanied by a reduction in environmental and labor regulations (Romero Lankao 2011).

The National Water Commission (CONAGUA) was created to manage the fundamental elements of regulation and management and interstate water transportation. Several smaller organizations were tasked with regulation and sanitation. These organizations quickly granted service contracts to a number of private companies strongly affiliated with transnational corporate firms (Romero Lankao 2011). This was done with little or no public consultation and despite considerable opposition from various stakeholders, including indigenous groups with claims on water resources.

The changes affected rural and indigenous communities surrounding Mexico City as well. In 1992, article 27 of the Mexican constitution was amended to permit the titling and privatization of publicly owned water resources across the country. These resources had previously only been permitted to be owned collectively by *ejidos*, communally managed collectives (Romero Lankao 2011). In Mexico, community organizations manage the older and smaller water distribution systems while the larger systems have been transferred to organizations set up by the government. These organizations have made moves to privatize much of the infrastructure and supply management (Ahlers and Zwarteveen 2009). Privatization policies in Mexico have also led to the large-scale transfer of locally controlled land and water assets to the private sector. This has been particularly true in the case of lands controlled by *ejidos* (communally managed) in rural and poor regions (Wilder and Romero Lankao 2006).

Mexico's neoliberal reform strategy has the decentralized governance of water resources as a central focus. This shift began in 1992 and has been dramatically transformative by shifting critical state functions to municipalities, user associations, and private corporations (Wilder and Romero Lankao 2006). The implementation of neoliberal reforms in water management takes two specific forms. The first is privatization, referring to the reorganization of water allocation, with resources that were formerly publicly owned being made available for private ownership. The second is commercialization, the introduction of market mechanisms and economic incentives to guide effective distribution. In Mexico, privatization was applied to reorganizing ownership, and commercialization was fully implemented (Ahlers and Zwarteveen 2009). Commercialization sees water as an economic good and turns water users into individual consumers rather than a collective of citizens (Bakker 2007). Both of these processes continue to occur at municipal, state, and federal levels throughout Mexico City and the surrounding regions.

International development agencies, funding organizations, and national governments in Latin America have claimed repeatedly that decentralization strategies are critical to water reform. They argue that it results in improved efficiency, provision, and allocation of water resources. The World Bank maintains that privatization leads to improved accountability, empowerment for local communities, and better management of resources. These conceptions all focus on water as an "economic good" and measure the outcomes with this perspective in mind (Wilder and Romero Lankao 2006).

The private provision of water services has failed to achieve the benefits and scale hoped for by proponents of neoliberal reform policies in the 1990s. Although private companies and government officials viewed many privatization projects as successful, public reaction has been far more contradictory. There has been extensive criticism from academics as well as poor and marginalized communities (Tortajada 2006). Privatization in Mexico City has succeeded in improving metering, billing, and customer inventories, as well as increasing revenues. The economic focus of these gains demonstrates the priorities of private water providers. Significant improvements have not been made in improving provision to underserved areas or improving environmental conditions (Wilder and Romero Lankao 2006). The overexploitation of aquifers and the contamination of groundwater remain unaddressed. Disagreements exist within the literature as to the effectiveness of privatization measures in Mexico to improve efficiency of distribution, often using the same evidence to arrive at different conclusions. This efficiency is framed in economic terms and often ignores the related social and environmental aspects of water systems (Pierce 2012).

Many of the shortcomings of privatization initiatives have been blamed on local, state, and federal governance. These resulted in failures of network expansion and contract negotiations. The lack of coordination between the Federal District and the State of Mexico concerning the supply in the Basin of Mexico created additional problems (Pierce 2012). Despite these shortcomings, the push for privatization in water provision and management continues today. The commitment to privatizing water resource was reaffirmed by municipal decision in Mexico City in 2010 (Romero Lankao 2011). We will now to turn to the current state of water provision in Mexico City and the surrounding regions.

Water Ownership, Management, and Provision in Mexico

Mexico City is the second most densely populated city in the world. This population is still increasing, putting additional pressure on scarce water resources. (Oswald Spring 2011).

With over 22 million water users in the metropolitan area, Mexico City is on the verge of a water crisis. The current issues include overexploited aquifers, environmental degradation, land subsidence, lack of water access in many parts of the city, and a lack of equity in the provision of water and sanitation. Current challenges include addressing ecological needs for water, increasing water demand for energy generation, increasing demand for irrigation, and the uncertainties surrounding climate change and population growth (Mirosa and Harris 2012).

Both state-led and privatized water management in Mexico City have externalized the most pressing issues of water provision to surrounding areas. The severe environmental consequences of Mexico City's huge demand for water are transferred to the Lerma and Cutzamala basins (Romero Lankao 2011). Mexico City actively seeks to expand its water supply through the acquisition of *ejido* lands that are communally owned and managed. Over 30% of its current supply comes from water imported from outside the valley of Mexico (Wilder and Romero Lankao 2006).

Many immigrants from poor rural regions arrived in Mexico City in the 1950s. They settled largely in the slums of Netzahualcoyotl and Chalco, areas adjacent to large open sewage canals. Flood events repeatedly expose these areas to disease and compromise local water supplies. The lack of investment and maintenance of infrastructure further threatens water quantity and quality. These areas have continued to be underserved and neglected under neo-liberal reforms (Oswald Spring 2011). Also, household water provision in the poorest areas overwhelmingly falls on women. Women travel large distances to secure water from depots, trucks, or access points (Salcedo 2015).

A result of the privatization of water provision in Mexico City has been the creation of a two-tiered system with one tier having full access and another having irregular access and/or less reliable service. Only 68% of water users in Mexico City have full 24 hour access to water (Romero Lankao 2011). The decentralization of water management has also resulted in a diffusion of responsibility. The larger regional and societal problems become too large for individual private actors to address so they often are ignored. This includes mainly environmental and social issues resulting from current unsustainable water practices (Romero Lankao 2010).

The urban poor who are not provided with any water service at all are estimated to be around 5% of the population. Private water trucks provision these and other underserved areas and costs are around 500 percent more than domestic consumers with municipal service (Tortajada 2006). This means that the poorest and most vulnerable populations are paying the most for water. Contamination and disease from flooding is a huge risk in Mexico City. Less than 4% of sewage is treated, with large amounts of untreated water being discharged in adjacent rural areas. Inadequate infrastructure often results in floods that carry untreated wastewater into urban areas (Romero Lankao 2011).

Water quality and quantity generally deteriorates from West to East in Mexico City. This is due to proximity to the Cutzamala system and changes in elevation. It also matches changes in socio-economic geography with many of the wealthiest suburbs located in the West and the poorest slums in the eastern edges of the city (Salcedo 2015). Groundwater sources in these poorest areas are especially contaminated with toxic contaminants, a legacy of unplanned and unsustainable development in the twentieth century.

Groundwater resources are unsustainable in the long term. Groundwater extraction is currently exceeding recharge levels by 173%. This unsustainable use of groundwater is an impending time bomb for a continually growing population. The seven most overexploited aquifers in Mexico are part of this system (Oswald Spring 2011). Subsidence due to groundwater extraction now exceeds 7 cm a year. Mexico City is literally sinking into the lakebed it once occupied. Underground distribution pipes feel continuous pressure. They are estimated to leak over 40% of drinking water before delivery (Grillo 2009). Current projections suggest that within 40 years, groundwater extraction will be completely unfeasible. This is currently the source of almost 70% of Mexico City's water (Salcedo 2015). What options will remain for Mexico City if this resource is depleted?

A shift towards private sector involvement in water has been accompanied by the massive growth of the bottled water market. This use of previously public resource is particularly contested and criticized. Transnational bottling companies are the usual beneficiary of these uses (Bakker 2003). Mexico is currently the world's second largest consumer of bottled water (Tortajada 2006). Water supplies in underserved areas are augmented by private for-profit actors such as water venders and bottled water companies. These result in cost-per-unit prices far exceeding municipal rates (Bakker 2003). Also, Private water providers in the most underserved areas are often under threat of violence. Hijackings of water trucks are common. Water depots have also been attacked and invaded in times of water shortage (Salcedo 2015). This desperation demonstrates the extreme dimensions of the current crisis and the need for an alternative conception of water management.

Article 4 of the Mexican Constitution states that “Everyone has the right to access, provision, and sanitation of water for personal and domestic consumption as sufficient, safe, acceptable, and affordable. The State guarantees this right” (Acedo 2015). A centerpiece of current conflicts over water is the paradox inherent in classifying water as both a human right and an economic good. If water and sanitation are rights, this would imply the necessity of their provision regardless of ability to pay (Romero Lankao 2011).

Water is a critical need worldwide for consumption and sanitation. Over 1 billion people lack access to safe drinking water, and over 2 billion lack access to proper sanitation (Schouten and Schwartz 2007). In megacities like Mexico City, water quantity and quality are subject to the threats of a number of complex urban and regional processes. These include population growth, land use change, unsustainable agricultural practices, deforestation, ecosystem destruction, erosion, lack of planning and oversight, political conflicts, private interests, and the impacts of climate change (Oswald Spring 2011).

Water management in Mexico City is further complicated by the political complexities of water administration. Federal, state, and municipal authorities are responsible for different parts of water provision. This is further complicated by the fact that the Federal government is controlled by the conservative PAN party, the state governments of Hidalgo and Mexico by the moderate PRI party, and the government of Mexico City by the leftist PRD party (Oswald Spring 2011).

The ruling PRI party and its allies in Mexico attempted to make several reforms to the Water Act in 2015. This attempt was aggressively blocked by a broad coalition of concerned citizens, organizations, indigenous groups, academics, environmental and social activists, and scientists. Reasons for the opposition include further privatization measures, attempts to facilitate diversion and displacement of water resources, reducing protection from contaminants, promoting water use for fracking oil, and restricting scientific and social monitoring. Additionally, the bill was criticized for treating water as an economic good and ignoring cultural, social, and environmental factors (Acedo 2015). As of 2015, continuous pressure is coming from federal government to further increase privatization. Due to public protests and anger, the bill is currently on hold (Salcedo 2015).

The conflicts around water in Mexico City are numerous. Government and large businesses continuously expand engineering projects, upsetting conservationists and indigenous groups. Congress and NGO groups are battling over the continuing privatization of water resources. Water shortages, floods, and unequal distribution create social tensions within Mexico City (Salcedo 2015). The success of grassroots mobilization in 2015 has temporarily prevented the further privatization of national water resources. The proposed measures would have given formal rights to private corporations to further control public water resources in Mexico (Acedo 2015).

The result of privatization in Mexico seems to be a channel for capital accumulation by private entities as well as a way for the state to legitimately transfer the burden of water management to non-state institutions. It has not led to improvements in equity or a more sustainable use of the resource. The cultural and environmental values of water have been largely ignored by this system (Wilder and Romero Lankao 2006).

Water supply transformation is merely one aspect of a larger process that is institutional, socio-economic, and technical. It aims to make non-market forces respond to the demands of capital, redistribute power among local elites, the dismantling of the water “commons”, and the increasing influence of urban elites into rural resources (Bakker 2003). The concerns of citizens at these processes were amplified by the complete lack of transparency in water contract negotiations. This directed much of the criticism at individual (often state) actors (Pierce 2012). This process extends far beyond Mexico City to the rural areas that mitigate the demands of Mexico City’s water crisis.

Water privatization occurs through many channels. These include temporary transfers, permanent sales of water rights, water rights purchased through land acquisition, and long term well rentals. Often, these methods are used to privatize water rights from extremely poor rural communities or indigenous groups. Rural *ejido* communities in many cases already faced unequal access to water resources before the implementation of neoliberal reforms. Reforms in 1992 made communal lands increasingly vulnerable to exploitation by the private sector. Increased volatility to market fluctuations in crop prices under neo-liberal economic reforms have contributed to the sale of water rights by rural communities (Wilder and Romero Lankao 2006).

What does this water crisis mean for rural and indigenous communities in the surrounding region? We will now return to the Mazahua people in the Villa de Allende region of Mexico

State. These indigenous “water warriors” are fighting for a locally controlled alternative to the water management strategies of the past few decades. They see the consequences of these policies on their traditional lands and their protest is rooted in very real concerns about the sustainability of the water their community depends on.

After Spanish conquest the patterns of human pressure on Mazahua ecosystems began to grow. New settlements were established to support gold and silver mines in the area and increasing amounts of forest land were cleared for agriculture, domestic animals, and construction materials (Farfán, Casas, Ibarra-Manríquez, and Pérez-Negrón 2007). The 20th Century saw the greatest amount of environmental change in the region due to population growth, agricultural expansion, illegal logging, and construction of new settlements (Farfán et al. 2007).

This environmental change directly affects the Mazahua and other local indigenous groups. 345000 Mazahua people live in Mexico in the border regions between the states of Mexico and Michoacan. Other local indigenous groups include the Matlatzinca, Otomi, Nahua, and Purhupecha. The Mazahua economy is mainly agricultural, producing maize, beans, wheat, barley, potatoes, and livestock. Gathering of local plants compliments the economy by providing food, medicine, and tradable goods (Farfán et al. 2007).

Mexico is one of the greatest reservoirs of traditional ecological knowledge in the world because of its natural and cultural diversity. Ethnobotanical studies have identified over 5000 useful plant species with patterns of traditional use by over 58 indigenous ethnic groups (Farfán et al. 2007). A 2007 study of indigenous plant use in the Mazahua village of Francisco Serrato in Michoacan (less than 30 km from Attesi) found 213 useful plant species and 31 species of edible mushrooms. Over 75% of these occur only in wild areas (Farfán et al. 2007). The continued environmental degradation associated with water extraction has put this economy in turmoil.

The construction of the Cutzamala system beginning in the 1970s brought environmental, social, and economic damage to many small communities in the region. After decades without compensation the Mazahua began to lobby on the municipal, state, and federal levels (Araujo et al. 2011). The Mazahua Front for Sustainable Development of Cutzamala is an indigenous organization created to preserve the environment affected by the creation of a regional hydro-electric system that simultaneously extracts water for Mexico

City. The Chilesdo dam in Villa de Allende collects water from the Malacatepec river in the Mazahua region (Araujo et al. 2011).

In 2004 the Mazahua women took the lead in the fight for justice and called themselves the Zapatista Army of Mazahua Women for Water Defense. The Mazahua have continuously applied pressure and fought for a dialogue with federal and state agents (Araujo et al. 2011). The protests succeeded in the implementation of drinking water systems in 16 communities previously without water infrastructure. It also succeeded in empowering and revitalizing the community. Women attested in testimonials that the movement led to positive changes in gender and family relations at home (Araujo et al. 2011).

The Mazahua women have stated that sustainable development is a real goal but that the local community must define it or else it is meaningless and will be unable to deal with the realities of the rural experience (Araujo et al. 2011). The success of the fight for water rights has led to a revitalized call for equity. This includes access to bilingual education, additional schools and hospitals, the return of appropriated land, and compensation for damaged lands due to the construction of the Cutzamala system (Araujo et al. 2011). The transition from focusing on water issues to confronting larger issues of sustainable development demonstrates the transformational potential of community organization. This will be explored further in the next section, which focuses on alternative pathways to water provision and management.

Alternative Pathways of Water Provision

The neo-liberal water governance reforms of the past few decades have continually failed to address the challenge of extending access to some segments of the population. This often includes vulnerable, underserved, and marginalized populations (Mirosa and Harris 2012). The result has been a continuous resistance both locally and internationally to deregulation and privatization.

Relatively robust community management and control mechanisms already exist in many parts of the world and in Mexico in particular. These are still an alternative option for water management despite the recent push for privatized control (Bakker 2007). *Ejido* communal control of water resources has been done sustainably for over a century in many rural areas.

The inability of many countries in the developing world to provide water and sanitation access to their citizens is often cited as a reason for private sector partnerships. However, evidence suggests that the reasons are less to do with the lack of “market efficiency” as they are a result of a history of indebtedness and historically rooted patterns of dependency that reduce the availability of investment resources (Romero Lankao 2011). Additionally, international monetary organizations have put severe pressure on Mexico to reduce public sector investments as a strategy of fiscal discipline.

The idea that privatization is a form of “decentralizing” water resource control is severely criticized by scholars who argue that it is simply a way of re-centralizing water management in the hands of national markets and powerful global economic interests. Indeed, evidence from Mexico suggests that the result of privatization has been consolidated control of water resources and capital accumulation by private entities. There is little evidence of promised improvements in efficiency and provision (Wilder and Romero Lankao 2006). The transformation of community control to corporate control of resources has led some critics to classify the changes in water policy as a “transformation”, rather than a mere “privatization”. The nature of these changes makes the barriers to fundamental change more complex and difficult to navigate (Bakker 2003).

Some international efforts have attempted to counter the economic focus of development agencies. In response to the Dublin principles, the P7 Declaration in 2000 focused on “water democracy”. This was the decentralized, community based, democratic water management inspired by social, economic, and environmental values (Bakker 2007). It is this model that represents a true alternative to state-led or privatized water management and one that may be possible in Mexico.

The establishment of the Latin American Water Tribunal demonstrates the effectiveness of pressure being used to address water rights issues, even without the support of formal legal systems. Established in 1998 and expanded to all of Latin America in 1995, the tribunal has been successful in advancing the causes of marginalized and underserved communities across Latin America using the language of human rights. The tribunal declares that “water is a fundamental right, inherent to life and human dignity” (Mirosa and Harris 2012).

Critiques of neoliberal reforms argue that the privatization of water supply systems is an act of dispossession with a variety of negative consequences. It is often equated to a “top-down" approach to globalization imposed on the developing world by powerful institutions, private interests, and entrenched global power structures. The argument maintains that that introducing the logic of the market into water debates (i.e. profit motives) is incompatible with the human right to water (Bakker 2007).

Conceptions of water as an "economic good" clash with viewpoints that see water as a "free" good provided by nature, with traditional, religious, and cultural values associated with water, and with environmental conceptions of water as a part of natural ecosystems (Wilder and Romero Lankao 2006). Current strategies that base water rights in the idea of a collective "commons" aim to counter the top-down centralizing tendencies of current approaches and replace them with a local and community based management (Mirosa and Harris 2012).

The United Nations approved a resolution in 2010 in support of the human right to water. The human right to water focuses on goals such as water access, provision, attention to vulnerable and marginalized communities, and equity (Mirosa and Harris 2012). However, many critics have suggested that this approach does not go far enough to address the failures of the privatization policies of the past few decades. Specifically, it remains silent on issues of water provision and who is responsible for it.

Many thinkers have pointed out the failures of formal declarations to actually deliver water access to poor and marginalized communities. International declarations often focus on promotion, ignoring the implementation regime and lack of enforcement capacity (Mirosa and Harris 2012). "Human rights" in many ways are individualistic, anthropocentric, state-centric, and potentially compatible with private sector water management. Because of this, the are limited in their ability to correct the past failures of water management to address the limitation of state or private models of water provision (Bakker 2007).

Despite these problems, rights based arguments are one possible method of addressing the injustices of historical resource loss. The UN Declaration on the Rights of Indigenous People declares that indigenous groups have the rights to their historical lands and resources. This includes water rights, as well as traditions and heritage. It also states that indigenous people have the rights to determine and develop strategies for the management and development of their lands (Mohamed 2007). The content of the declaration is in direct opposition to the past and current actions of federal and state authorities. The power imbalance between marginalized rural communities and the authorities of Mexico City create continuous issues for a resolution of this issue.

Feminist critiques of neoliberal water management place politics and power at the center of the debate. Local water struggles must be linked to larger trends in history and economics. Water has important cultural and spiritual associations and these are tied very much to place. Because of this, private companies or the state often misunderstand and mismanage local resources (Bakker 2007). Additionally more recognition must be given to the way discourse frames and gives meaning to struggle (Ahlers and Zwarteveen 2009). The ways water issues in the region are discussed and framed make the concerns of indigenous communities seem marginal at best. Alternatives to decentralization and privatization should be explored and some solutions may come by looking more closely at historical indigenous patterns of water management, community management models, and the successes and failures of public and private models.

Some solutions may come at the municipal level. Both public and private providers have failed to provide adequate water and sanitation to marginalized and poor areas, leaving large segments of urban and rural vulnerable and underserved (Budds and McGranahan 2003). Megacities require an integrated and directed water management strategy that should include rainwater harvesting, equity based subsidies, maintenance of infrastructure, restoration of ecosystems, and broad urban planning reform. Private water providers are particularly ill-suited for this type of institutional change (Oswald Spring 2011).

Climatic changes and severe discrepancies in water availability and access make the equitable provision of water in Mexico critical for a sustainable future (Wilder and Romero Lankao 2006). The lack of awareness among citizens as to the true severity and risks of overexploitation requires a transformation in government policy and public engagement. This transformation must involve an integrated and just water policy that includes ecological restoration, reforestation, and educational initiatives aimed at reducing consumption (Oswald Spring 2011). This is a political, cultural, and environmental challenge.

Access to water is rarely treated as a political issue. The Millennium Development Goals never explicitly mention the political dimensions of water access. The failure to mention the political aspects of water provision is likely due to the neo-liberal focus on water as an economic good. The United Nations has worked with international financial institutions to promote deregulation and privatization of water resources in the developing world (Schouten and Schwartz 2007).

The processes of climate change are likely to exacerbate the global struggle for water resources. The processes of climate change highlight key struggles such as the struggle for limited access, allocation, and the struggle between alternative conceptions of development (Gupta and Lebel 2010). Problems of water distribution have two faces. The first is the access to the resource. The second is the allocation of resources, risks, burdens, and responsibilities for distribution problems. Addressing these problems requires access to social processes. These can be legitimate processes such as law or science, or can be processes of social movements and protest (Gupta and Lebel 2010).

Instead of reacting to the failures of state-led or neoliberal policies, new alternatives must focus on situating water management challenges within the larger socio-cultural context, and ultimately within the fluid cycles of the environment. This also opens up the possibility of a conception that includes people, plants, and animals, and the ecological cycles that sustain us.

Two responses have emerged to the growing amount of private sector involvement in water supply management. The first is the emergence of anti-privatization campaigns based on the idea of water as a human right. The second is the promotion of alternative water governance models (Bakker 2007).

The anti-privatization movement has increasingly mobilized around the idea of human rights. This rights based approach has been helpful to highlight some of the fundamental concerns about private sector involvement in water management. However, the claims have no explicit legal backing in broad international treaties. A number of prominent NGOs have been pushing for a unanimous declaration. The declaration of a “right to water” still faces a number of issues such as lack of clear responsibility for provision, lack of capacity for implementation, and potential for trans-boundary conflicts (Bakker 2007). But does a rights based approach necessarily preclude private sector involvement? Since 2004, private sector elements have endorsed the human right to water and maintained that the private sector could still be involved in fulfilling that requirement.

Alter-globalization activists reject the rights based argument and claim that it only reinforces the public/private binary and ignores other options for effective management. They argue that the models of state or market control are both expressions of corporatist models that exclude communities, collective decision, and vulnerable communities (Bakker 2007).

Alter-globalization activists have increasingly turned to alternative concepts of property rights with a focus on the “commons”. This approach focuses on a number of unique characteristics of water. Water is a flowing resource and is essential to human and ecosystem health. It cannot be substituted and is integrated into communities and ecosystems through its natural cycling. Because of this, collective management by communities is necessary. Water management has a long history of both market and state failures. This as often been used to justify community management (Bakker 2007).

Disrupting the public/private binary and opening the possibility for alternative decentralized and community-based management strategies enable the visualization of a water management system equipped to deal with the failures of public and private systems. By rooting management in the local area of distribution and use, social and environmental concerns become the explicit concern of water managers (Bakker 2007).

Economic suggestions to solving the problems of water management in the basin of Mexico focus primarily on correcting inefficiencies in supply and demand. This includes increasing consumer costs or tariffs to adequately match true costs of extraction and provision, and artificially recharging aquifers. Nether of these solutions addresses the needs of many communities currently underserved by current models (Hernandez and Cruz-Medina 2011). The most progressive strategies use a twofold tactic. This includes the reform of state governance and the proliferation of alternative local models of resource management. These community led initiatives often share one aspect of the neo-liberal agenda, decentralization. This is a method that can lead to greater community control of resources (Bakker 2007).

Alternative methods to water resources management have been proposed to correct the shortcomings of neo-liberal reforms. One example of this is the Water Poverty Index (WPI). It uses a five-part index to weigh resources, access, capacity, use, and environmental impacts. The interest in alternative methods to assess decision making around water management is a promising direction for future research and application (Darnault 2008).

Integrated water management systems aligned with the principles of sustainable development (Bruntland 1987) would consider the functioning of aquatic ecosystems and the limits of natural regeneration. These would be factored into social and cultural needs, which in turn would factor into economic considerations. This nested approach acknowledges the dependence that human systems have on our environment. A truly sustainable model would take ecosystem resilience and stability as a primary goal. Unfortunately, environmental and social concerns are usually subsidiary to economic concerns in water management decisions (Darnault 2008). Private sector involvement has heightened many of the barriers to integrating more fair and equitable distribution of water resources. More integrated and accountable policies and measures are required to address these concerns, whether publicly or privately provided (Romero Lankao 2011).

Conclusions

Despite protest, criticism, and lack of proven success, water governance is subject to a continuous and ongoing privatization and deregulation. New forms of privatization, marketization, and commercialization are being pushed forward all over the world. These policies rarely take into account an assessment of historical performance or take full account of the social, cultural, and environmental consequences that these changes will create (Mirosa and Harris 2012). In fact these processes often contribute to the processes of environmental and cultural degradation around the world.

Successfully confronting these challenges is a difficult and complex issue. Solutions must happen at a variety of scales in order to create lasting changes. A return to water governance focused on deep sustainability is necessary to create a future where this resource can be used and protected for future generations. Changes to water systems to promote rainwater collection, protect water source from pollution, and reduce the diversion and pumping of water resources can help to stabilize some of the worst environmental effects. This is the part of the solution that can come from reform at the municipal level.

Cultural changes can also paly a part in creating a more just and sustainable system. Community Water management in the context of a reconnection to the land can create an ethic of responsible stewardship that could be very powerful in rural areas. Rights based arguments can be effective in the fight to secure historical rights to lands and resources held by indigenous populations. These rights can in turn be used to develop alternative management strategies that focus on the needs of local populations instead of disconnected private interests.

Political pressure like the P7 Declaration and the Latin American Water Tribunal can be effective at tackling the issue from an international scale. The UN Declarations of Rights for Water and the Rights of Indigenous People can be used as effective tools to apply political pressure for change. Protests and resistance, both local and global, have proven effective in the past and are also a critical piece of the fight for lasting change.

Current mainstream solutions to the provision and fair distribution of water are very focused on economic and technical issues. Without a broader change in the pattern of human settlement, power structures, social equity, and resource allocation, such strategies are unlikely to create a truly just or equitable system of water governance (Oswald Spring 2011). By integrating the needs and desires of the entire human community, important steps can be taken in this direction. This will require a transformation at the institutional level. When people are left out of the equation and profit is paramount, equality and justice are forgotten.

WORKS CITED – APPENDIX E

Acedo, A. (2015). Acedo - Grassroots Movement Blocks Water Privatization in Mexico - 2015 - Truthout.pdf. Retrieved March 19, 2017, from

Ahlers, R., and Zwarteveen, M. (2009). The water question in feminism: water control and gender inequities in a neo-liberal era. *Gender, Place and Culture*, *16*(4), 409–426. https://doi.org/10.1080/09663690903003926

Araujo, A., Acevedo, G., Lorenzo, O., and Romero, I. (2011). Zapatista Army of Mazahua Women in Defence of Water in the Cutzamala Region: Testimonies. *Development*, *54*(4), 499–504. https://doi.org/10.1057/dev.2011.90

Bakker, K. (2003). Archipelagos and networks: urbanization and water privatization in the South. *The Geographical Journal*, *169*(4), 328–341.

Bakker, K. (2007). The “commons” versus the “commodity”: Alter-globalization, anti-privatization and the human right to water in the global south. *Antipode*, *39*(3), 430–455.

Bruntland, G. H. (1987). *Report of the World Commission on Environment and Development: Our Common Future*. United Nations. Retrieved from http://www.ask-force.org/web/Sustainability/Brundtland-Our-Common-Future-1987-2008.pdf

Budds, J., and McGranahan, G. (2003). Are the debates on water privatization missing the point? Experiences from Africa, Asia and Latin America. *Environment and Urbanization*, *15*(2), 87–114. https://doi.org/10.1177/095624780301500222

Darnault, C. J. (2008). Sustainable development and integrated management of water resources. *Overexploitation and Contamination of Shared Groundwater Resources*, 309–324.

Farfán, B., Casas, A., Ibarra-Manríquez, G., and Pérez-Negrón, E. (2007). Mazahua ethnobotany and subsistence in the monarch butterfly biosphere reserve, Mexico. *Economic Botany*, *61*(2), 173–191.

Grillo, I. (2009). Grillo - Dry Taps in Mexico City A Water Crisis Gets Worse - TIME.pdf. Time.

Gupta, J., and Lebel, L. (2010). Access and allocation in earth system governance: water and climate change compared. *International Environmental Agreements: Politics, Law and Economics*, *10*(4), 377–395. https://doi.org/10.1007/s10784-010-9139-1

Hernandez, S., and Cruz-Medina, M. (2011). Sustainable Management of Domestic Water Residues and Diminution of Discharges Into Municipal Collectors in Mexico. *Theoretical and Empirical Researches in Urban Management*, *6*(2).

Mirosa, O., and Harris, L. M. (2012). Human Right to Water: Contemporary Challenges and Contours of a Global Debate. *Antipode*, *44*(3), 932–949. https://doi.org/10.1111/j.1467-8330.2011.00929.x

Mohamed, S. (2007). Introductory Note to the United Nations Declaration on the Rights of Indigenous Peoples and Cal v. Attorney General, Supreme Court of Belize. *International Legal Materials*, *46*(6), 1008–1049.

Oswald Spring, Ú. (2011). Aquatic systems and water security in the Metropolitan Valley of Mexico City. *Current Opinion in Environmental Sustainability*, *3*(6), 497–505. https://doi.org/10.1016/j.cosust.2011.11.002

Pierce, G. (2012). The Political Economy of Water Service Privatization in Mexico City, 1994–2011. *International Journal of Water Resources Development*, *28*(4), 675–691. https://doi.org/10.1080/07900627.2012.685126

Romero Lankao, P. (2010). Water in Mexico City: what will climate change bring to its history of water-related hazards and vulnerabilities? *Environment and Urbanization*, *22*(1), 157–178. https://doi.org/10.1177/0956247809362636

Romero Lankao, P. (2011). Missing the multiple dimensions of water? Neoliberal modernization in Mexico City and Buenos Aires. *Policy and Society*, *30*(4), 267–283. https://doi.org/10.1016/j.polsoc.2011.10.007

Salcedo, A. (2015, November 12). Mexico City's water crisis – from source to sewer. *The Guardian*. Retrieved from https://www.theguardian.com/cities/2015/nov/12/mexico-city-water-crisis-source-sewer

Schouten, M., and Schwartz, K. (2007). Water as a political good: implications for investments. *International Environmental Agreements: Politics, Law and Economics*, *6*(4), 407–421. https://doi.org/10.1007/s10784-006-9013-3

Tortajada, C. (2006). Water management in Mexico City metropolitan area. *Water Resources Development*, *22*(2), 353–376.

Wilder, M., and Romero Lankao, P. (2006). Paradoxes of Decentralization: Water Reform and Social Implications in Mexico. *World Development*, *34*(11), 1977–1995. https://doi.org/10.1016/j.worlddev.2005.11.026

APPENDIX F – STATE OF MEXICO MUNICIPAL DATA: VILLA DE ALLENDE, MEXICO

(Municipal Geographical Information Handbook of the United Mexican States, 2009)

Prontuario de información geográfica municipal de los Estados Unidos Mexicanos

Villa de Allende, México
Clave geoestadística 15111

2009

Ubicación geográfica

Coordenadas	Entre los paralelos 19° 17’ y 19° 30’ de latitud norte; los meridianos 99° 60’ y 100° 15’ de longitud oeste; altitud entre 1 900 y 3 600 m.
Colindancias	Colinda al norte con el Estado de Michoacán de Ocampo y los municipios de San José del Rincón y Villa Victoria; al este con los municipios de Villa Victoria y Amanalco; al sur con los municipios de Amanalco y Donato Guerra, al oeste con el municipio de Donato Guerra y el Estado de Michoacán de Ocampo.
Otros datos	Ocupa el 1.38% de la superficie del Estado. Cuenta con 71 localidades y una población total de 41 938 habitantes http://mapserver.inegi.org.mx/mgn2k/; 6 de julio de 2009.

Fisiografía

Provincia	Eje Neovolcánico (99.69%) y Sierra Madre del Sur (0.31%)
Subprovincia	Mil Cumbres (91.58%), Lagos y Volcanes de Anáhuac (8.11%) y Depresión del Balsas (0.31%)
Sistema de topoformas	Sierra compleja (48.93%), Lomerío de basalto con mesetas (42.64%), Lomerío de basalto (7.8%), Valle de laderas tendidas (0.31%) y Sierra alta compleja con cañadas (0.32%)

Clima

Rango de temperatura	10 – 18°C
Rango de precipitación	1 000 – 1 200 mm
Clima	Templado subhúmedo con lluvias en verano, de mayor humedad (88.78%) y semifrío subhúmedo con lluvias en verano, de mayor humedad (11.22%)

Geología

Periodo	Neógeno (67.38%), Cuaternario (29.50%) y No disponible (0.86%)
Roca	Ígnea extrusiva: toba ácida (38.27%), basalto (24.51%) y andesita (22.28%) Sedimentaria: brecha sedimentaria (6.83%) Metamórfica: metamórfica (0.86%) Suelo: aluvial (3.08%) y residual (1.91%)
Sitio de interés	No disponible

Edafología

Suelo dominante	Andosol (78.29%) y Luvisol (19.45%)

Hidrografía

Región hidrológica	Balsas (100%)
Cuenca	R. Cutzamala (100%)
Subcuenca	R. Tilostoc (96.61%) y R. Zitácuaro (3.39%)
Corriente de agua	Perennes: Tilastoc y Salitre Intermitentes: Guadalupe y Tilastoc
Cuerpo de agua	Perennes (0.6%): Laguna Verde y Laguna Seca Intermitente:

Uso del suelo y vegetación

Uso del suelo	Agricultura (58.34%) y zona urbana (1.66%)
Vegetación	Bosque (39.03%) y pastizal (0.37%)

Uso potencial de la tierra

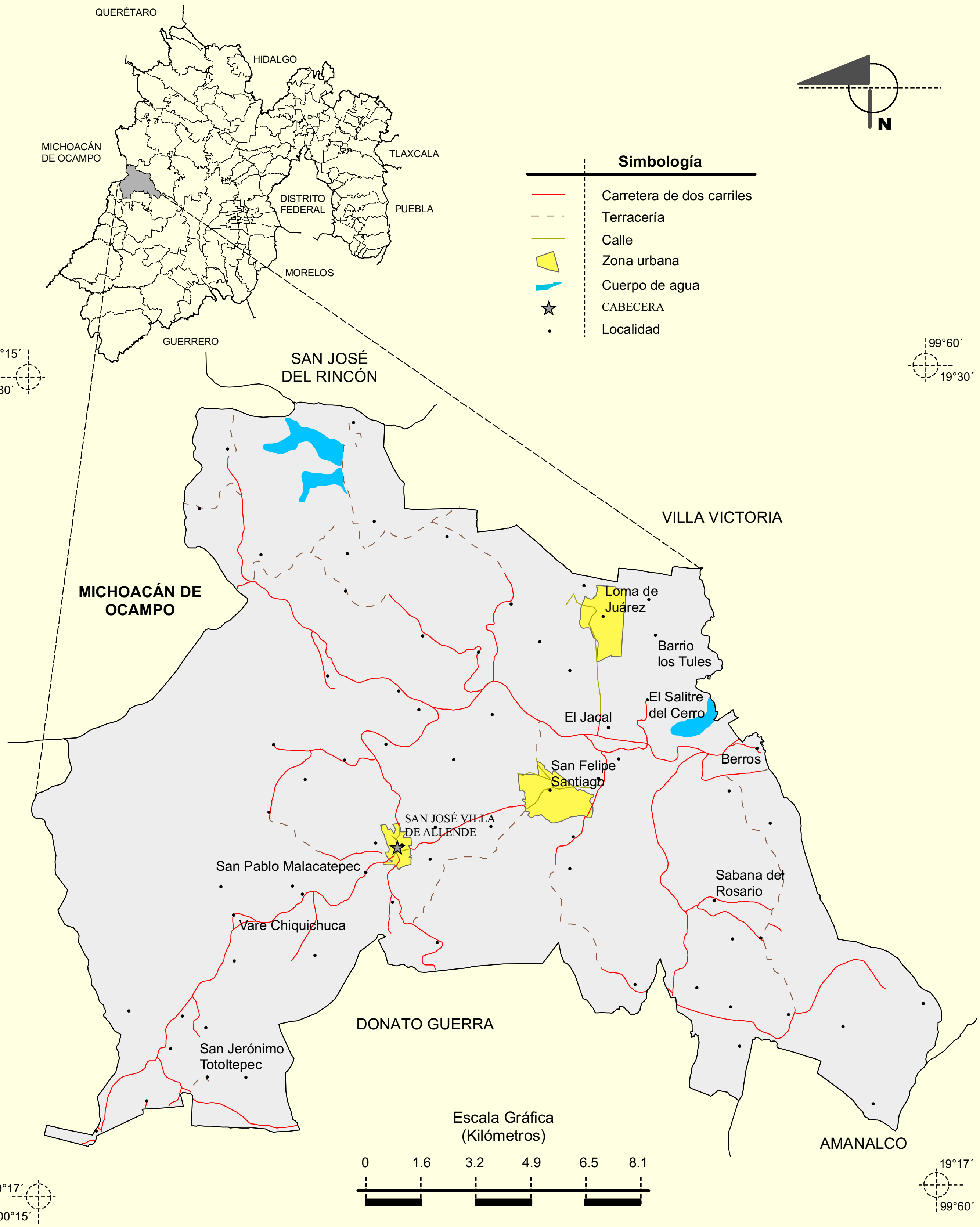
Agrícola	Para la agricultura mecanizada continua (56.47%) Para la agricultura manual estacional (26.96%) Para la agricultura manual continua (5.93%) Para la agricultura mecanizada estacional (4.83%) Para la agricultura de tracción animal continua (3.55%) No apta para la agricultura (2.26%)
Pecuario	Para el desarrollo de praderas cultivadas (64.85%) Para el aprovechamiento de la vegetación natural diferente del pastizal (26.96%) Para el desarrollo de praderas cultivadas con tracción animal (5.93%) No apta para uso pecuario (2.26%)

Zona urbana

Las zonas urbanas están creciendo sobre suelos y rocas ígneas extrusivas del Cuaternario, en lomeríos y sierras; sobre áreas donde originalmente había suelos denominados Andosol y Luvisol; tienen clima templado subhúmedo con lluvias en verano, de mayor humedad, y están creciendo sobre terrenos previamente ocupados por agricultura y bosques.

Prontuario de información geográfica municipal de los Estados Unidos Mexicanos
Villa de Allende, México.

Localidades e Infraestructura para el Transporte



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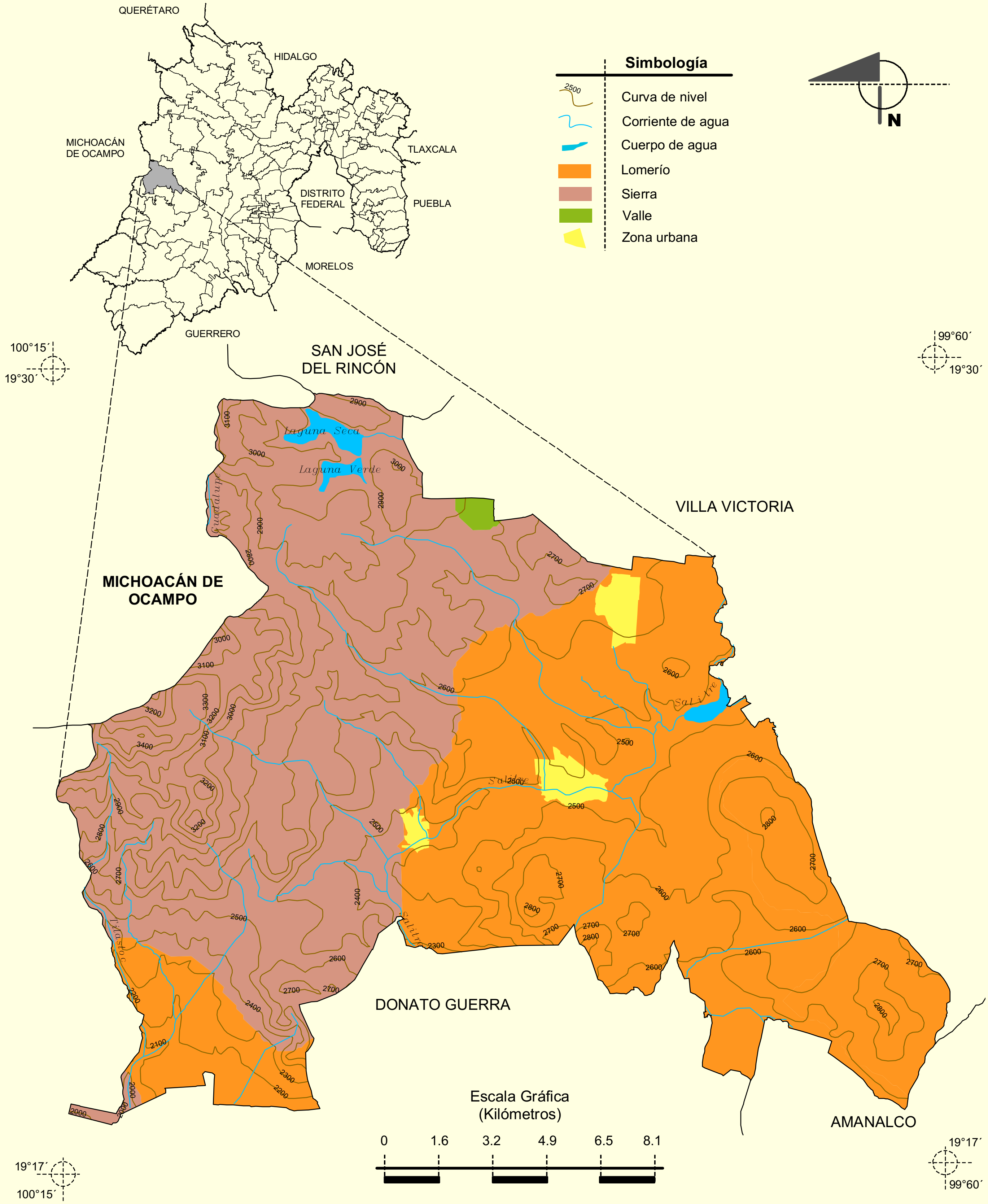

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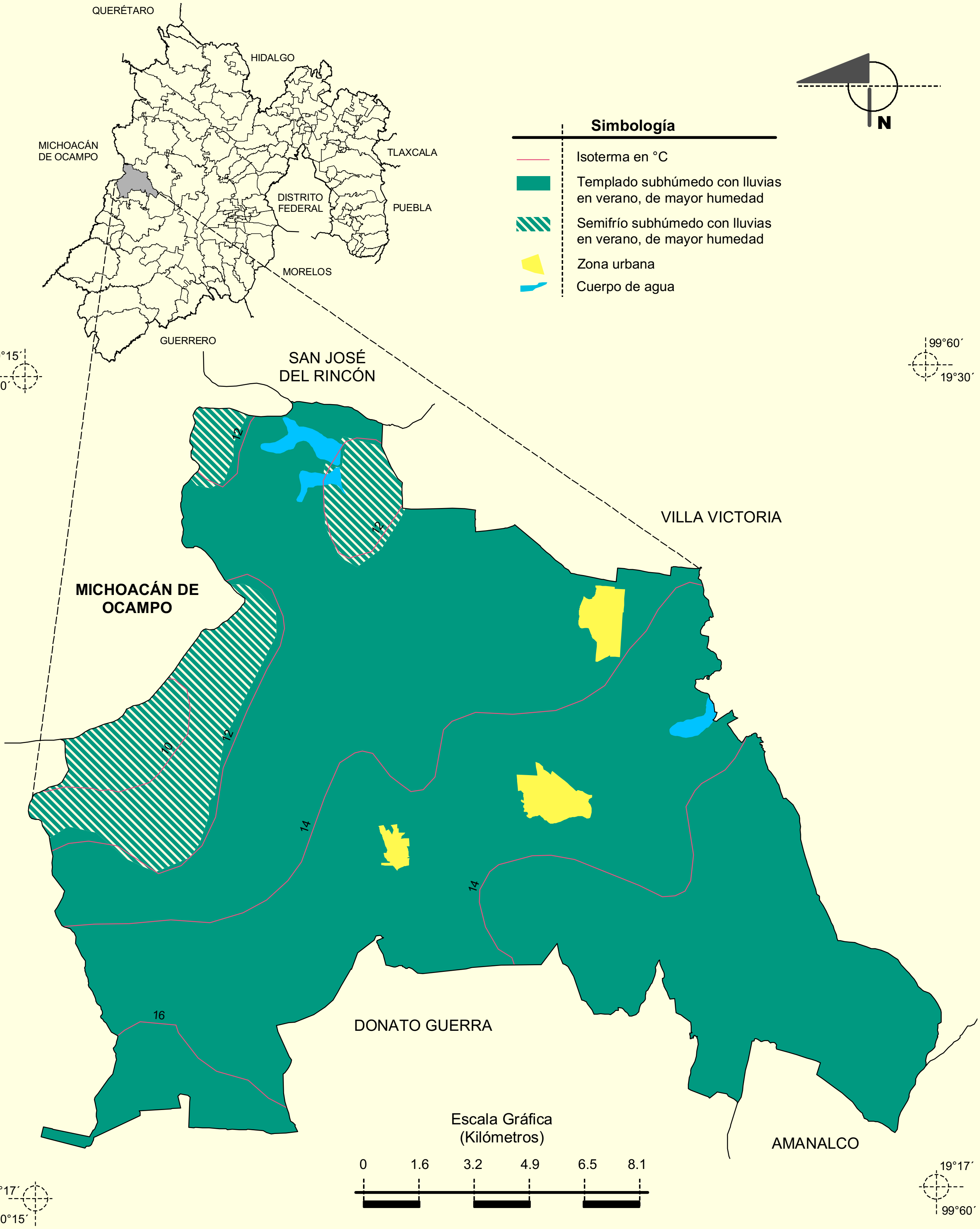
INEGI. Información Topográfica Digital Escala 1:250 000 serie III.
INEGI-CONAGUA. 2007. Mapa de la Red Hidrográfica Digital de México escala 1:250 000.

Climas



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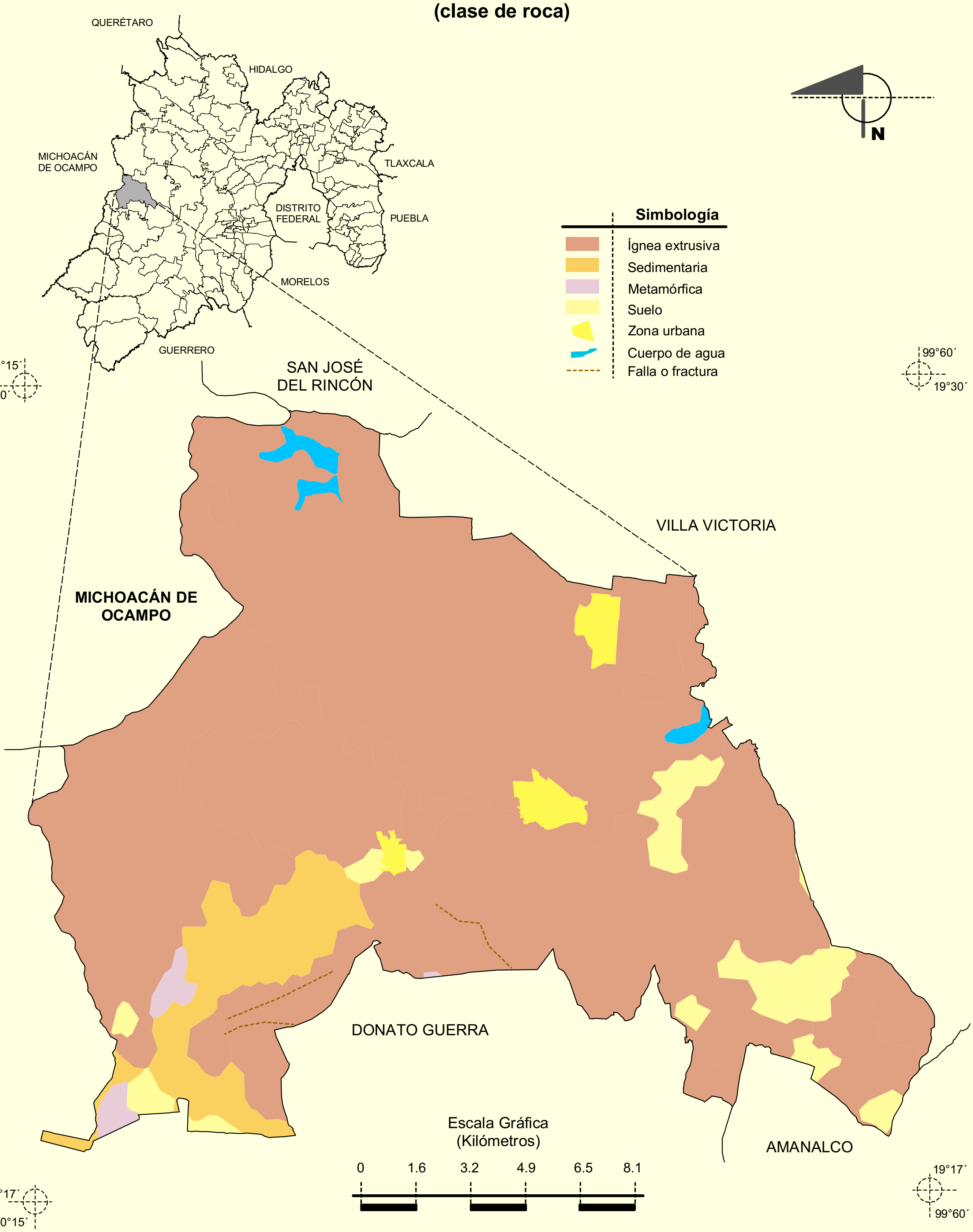
INEGI. Información Topográfica Digital Escala 1:250 000 serie III.

Prontuario de información geográfica municipal de los Estados Unidos Mexicanos
Villa de Allende, México.

Geología
(clase de roca)



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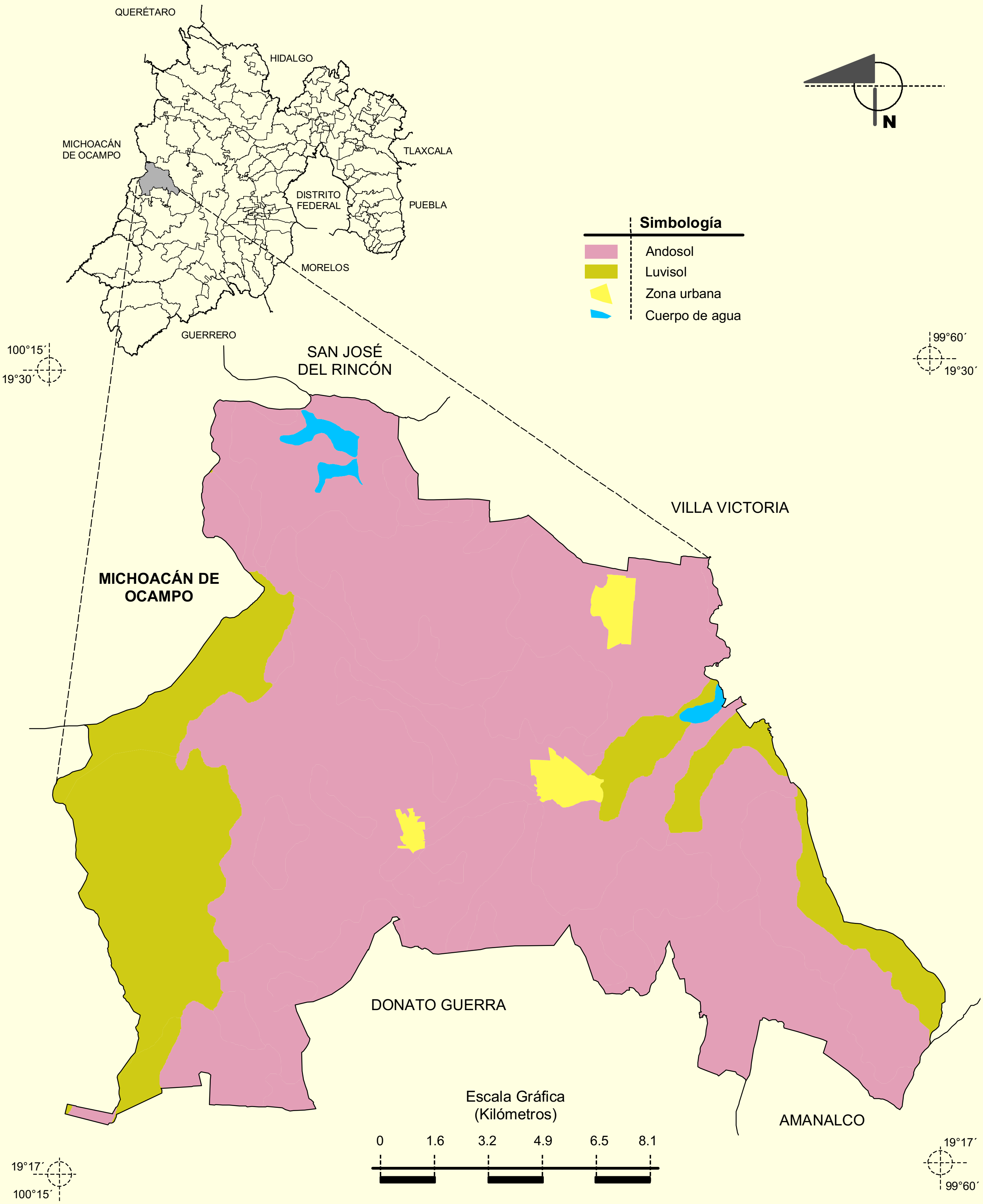
Villa de Allende, México.

Suelos Dominantes



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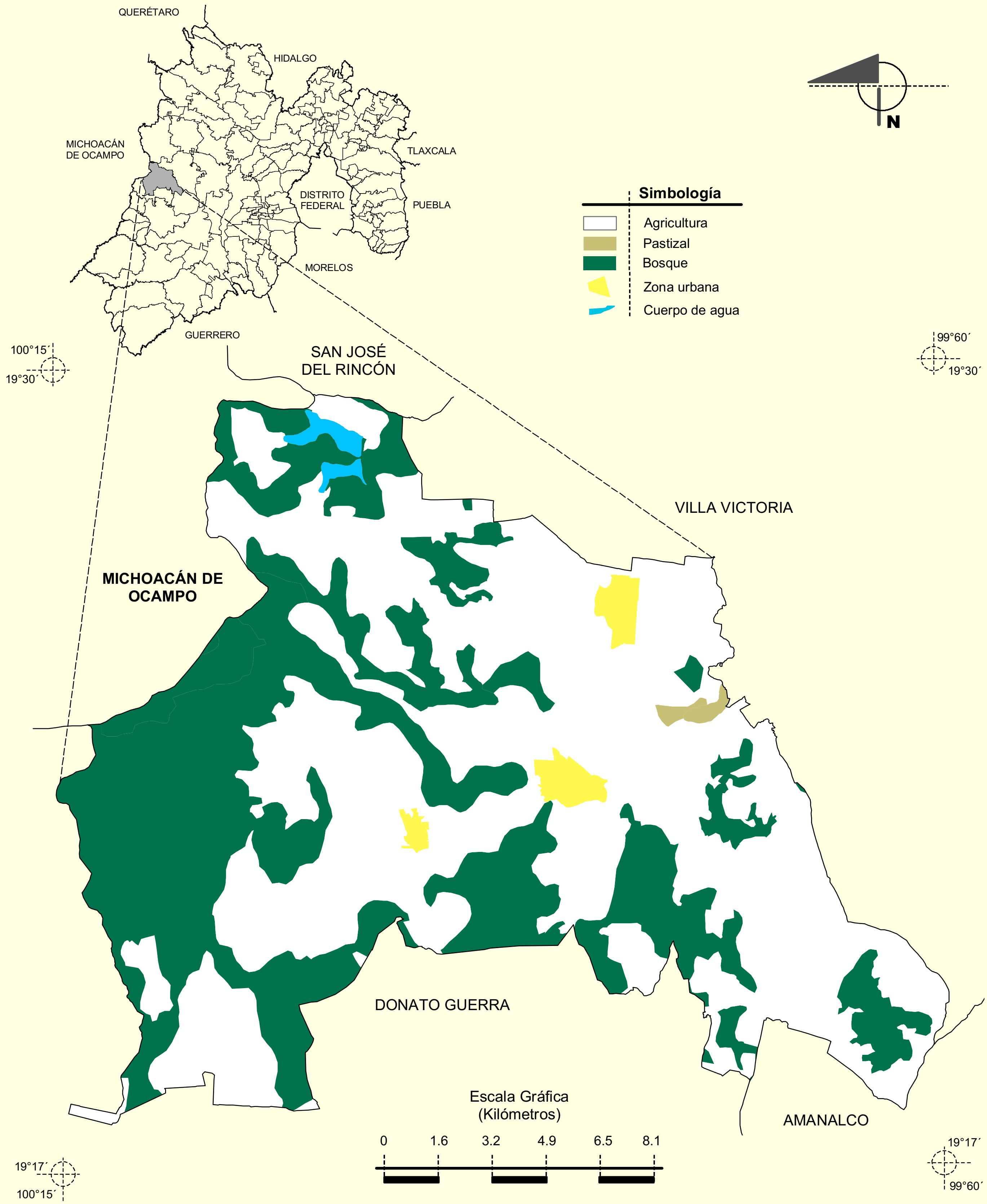
INEGI. Conjunto de Datos Vectorial Edafológico, Escala 1:250 000, Serie II (Continuo Nacional).
INEGI. Información Topográfica Digital Escala 1:250 000, serie III.

Uso del Suelo y Vegetación



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