2020

THE OVEREXPLOITATION OF THE VALLE DE QUERÉTARO AQUIFER AND ITS IMPACT IN SMALL PERI-URBAN COMMUNITIES, QUERÉTARO, MÉXICO

Kelsey Kirkland
Michigan Technological University, kakirkla@mtu.edu

THE OVEREXPLOITATION OF THE VALLE DE QUERÉTARO AQUIFER AND ITS IMPACT IN SMALL PERI-URBAN COMMUNITIES, QUERÉTARO, MÉXICO

By

Kelsey A. Kirkland

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Geological Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2020

This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Geological Engineering.

Department of Geological and Mining Engineering and Sciences

Report Advisor:	*John S. Gierke*
Committee Member:	*Kari Henquinet*
Committee Member:	*Rudiger Escobar Wolf*
Department Chair:	*Aleksey Smirnov*

Table of Contents

List of Figures

List of Tables

Acknowledgements

First, I would like to thank Peace Corps and Michigan Tech for allowing me to pursue my long-time dream of serving as a volunteer while simultaneously completing a master's degree.

I would also like to thank my advisor, John Gierke for all of his support and guidance in this process. This report would not have been possible without his valuable feedback and encouragement. Thank you to Blair Orr and Kari Henquinet for preparing me to be a culturally sensitive volunteer and for giving me the skills necessary to manage my expectations and have a productive service.

Many thanks to Ingeniero Humberto Uehara for sharing valuable technical information necessary in the completion of this report and to Dr. Amilcar González de Cosío Frías for believing in my work.

Mil gracias a la familia Galván por su cariño y apoyo infinito, a mi Mamá anfitriona Aurora, a mis hermanos Gilberto y Alejandro, y a mi amiga Vero por la generosidad, el amor y la guía que me han dado durante toda mi estadía en México.

Special thanks to my Dad for his valuable feedback and help throughout the writing process. Thank you to my Mom, Dad, and Lizzy for loving and supporting me, and thank you to my best friend Kyeti for always being there for me no matter the distance.

Abstract

The Valle de Querétaro Aquifer is the only viable local water source satisfying the domestic, agricultural, and industrial water needs of the Querétaro Valley. Severe depletion of the groundwater source has had significant consequences throughout the region, especially in the peri-urban communities of Santo Niño de Praga, Tlacote el Bajo, and La Palma. Historically, residents depended on aquifer-fed freshwater springs (known as Los Tajos) to meet their basic and productive needs. Spring production ceased between 10 and 15 ago and investigating the causes formed the basis of this research.

Analysis of available qualitative and quantitative data was used to identify the environmental and anthropogenic factors that have contributed to changes in the aquifer over time. A groundwater budget analysis was used to determine which hydrological components have had the most significant impact on groundwater availability.

Evaluation of available data indicates that several factors have contributed to a severe depletion of the aquifer over time. Modification of the land surface and a mountainous landscape hydrology have impacted recharge potential in the region. Over-extraction to meet the water demand of the growing urban population and sustain the agricultural and manufacturing industries have contributed to a severe depletion of the Valle de Querétaro Aquifer. The groundwater budget analysis quantitatively confirms that groundwater extraction and recharge are the hydrological components that have had the greatest impact on groundwater availability. Extraction rates have exceeded recharge rates for decades, resulting in a consistent groundwater deficit and a corresponding drop in the water table across the aquifer. Ultimately, a drastically lowered water table over time due to over-extraction and limited recharge ultimately caused flow cessation in Los Tajos.

1 Introduction

1.1 Motivation

Motivation for research on the Valle de Querétaro Aquifer and Los Tajos developed while the author was serving as a Peace Corps Environmental Education Volunteer in the central state of Querétaro, México. The author was assigned to Santo Niño de Praga, a small peri-urban community of approximately 500 inhabitants, located roughly 16 kilometers from the capital city of Santiago de Querétaro (see Figure 1). Changes in weather patterns throughout México have significantly impacted agricultural production, conservation of biodiversity, and the availability and quality of natural resources. Environmental Education Volunteers in México work to promote environmental awareness and conservation of natural resources through education and sustainable practices. The author's primary assignment was to work with local youth and promote environmental awareness and appreciation, while also helping them develop the skills necessary to adapt to and mitigate the effects of a changing climate. During her 1.5-year service as a Volunteer, the author experienced water shortages during the dry-season, and as a result made water conservation a priority both in her teaching curriculum as well as in her day-to-day life.

1.2 Objective

Depletion of the Valle de Querétaro Aquifer has had significant consequences throughout the region, especially in the small peri-urban communities. Historically, the communities of Santo Niño de Praga, Tlacote el Bajo, and La Palma depended on freshwater springs (known locally as Los Tajos) that were supplied by groundwater flow. According to informal interviews with residents, spring flow ceased between 10 and 15 years ago. The objective of this report is to determine the causes for reduced spring flow in Los Tajos through:

(1) Synthesis of quantitative and qualitative data to determine the environmental and anthropogenic factors that have contributed to changes in the Valle de Querétaro Aquifer over time.

(2) A groundwater budget analysis to quantitatively identify which hydrological components have had the greatest impact on groundwater availability.

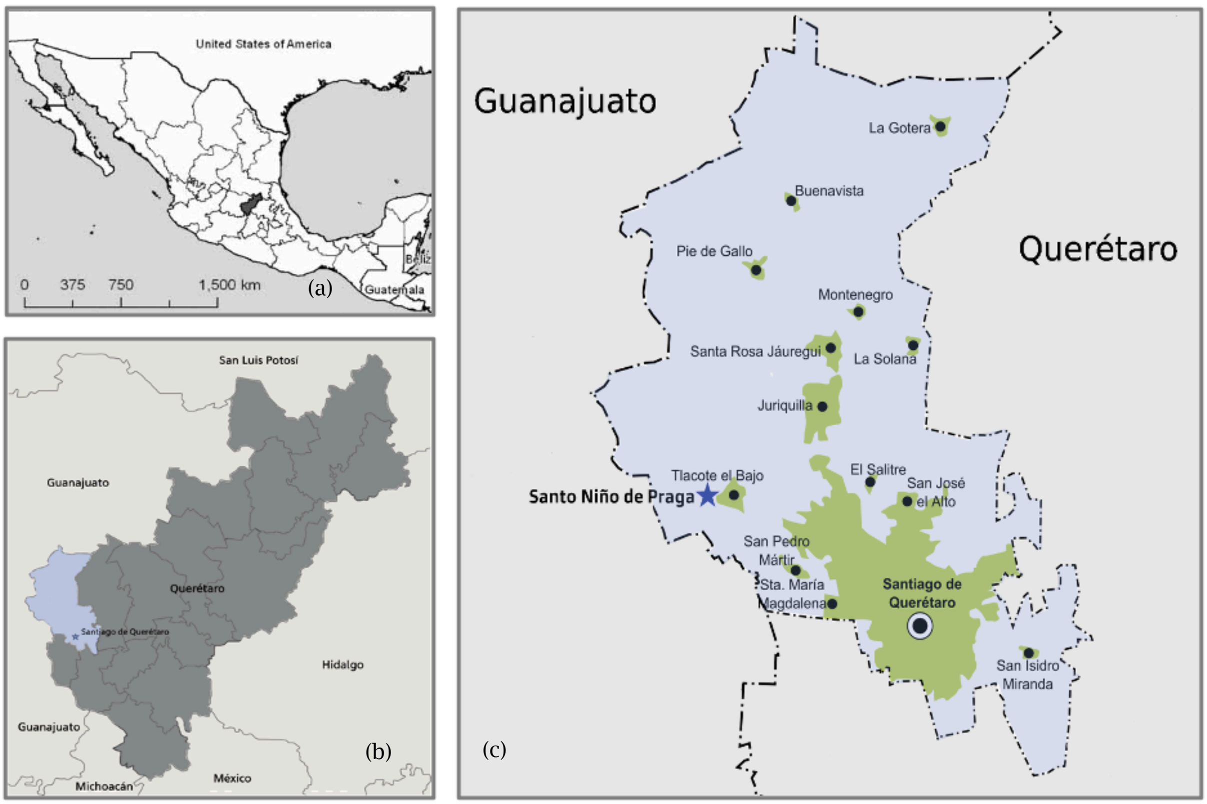


Figure 1 Location map of Santo Niño de Praga, Querétaro, México ((a) reproduced from Mesa et al. Water Policy Vol 18, Issue 6, pp 1473-1489 (2016) with permission from the copyright holders, IWA Publishing, (b) adapted from Wikipedia Commons (2010) & (c) adapted from Battroid (2010)).

2 The Querétaro Valley

Groundwater is an essential resource for addressing global water needs and serves as the primary source of water for more than 70% of México's 120 million inhabitants (Instituto Nacional de Estadística, Geografía e Informática [INEGI], 2015). Central México is experiencing one of the most severe aquifer depletion cases in the world, as the largest populations and industries continue to depend almost exclusively on the resource (Castellazzi et al., 2016; Chaussard et al., 2014; Pacheco-Martínez et al., 2013). This chapter discusses the environmental and anthropogenic factors that have impacted the Valle de Querétaro Aquifer over time and gives background information on the freshwater spring site Los Tajos.

2.1 Environmental Factors

2.1.1 Geology

The Querétaro Valley is an extensive rectangular basin that trends north-south with terrain that ranges in elevation from approximately 1,800 to 2,400 meters above sea level. A collapse caused by normal-fault failures that occurred "almost symmetrically and equidistantly" (CONAGUA, 2015) along a north-south orientation produced the Querétaro Valley graben (see Figure 2). Simultaneous fault failures trending east-west delineated the graben effectively enclosing it on all sides by areas of higher topographic relief (CONAGUA, 2015; Ochoa-González et al., 2018). The high concentration of normal faults throughout the Valley has produced a highly compartmentalized aquifer, influencing the local and regional flow dynamics (Carreón-Freyre et al., 2005; Ochoa-González et al., 2015).

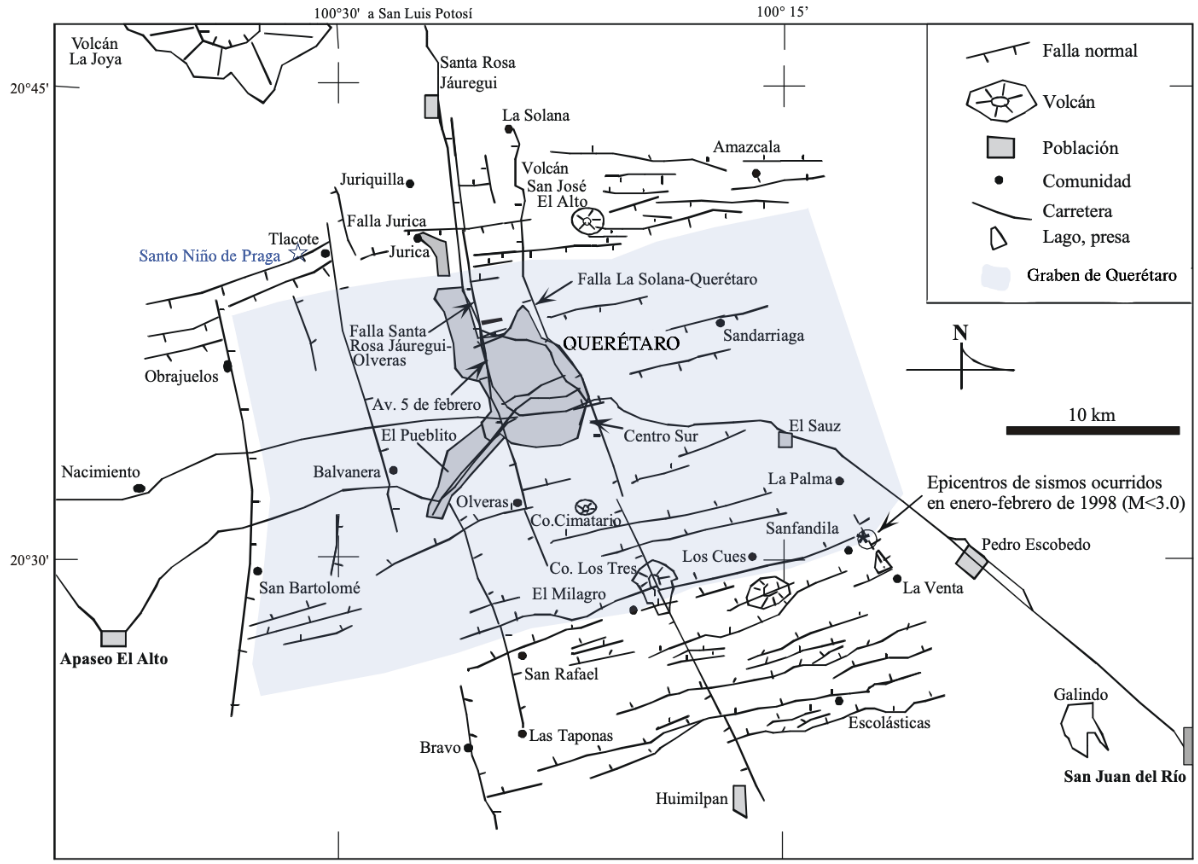


Figure 2 Map depicting the Querétaro Valley fault system and the Querétaro Valley graben (adapted from Aguirre-Díaz et al. (2012)).

The regional stratigraphy results from a complex geologic history including episodes of volcanism, faulting, and intermittent periods of sedimentation (Cortés Silva et al., 2012). As a result, the aquifer is composed of an accumulation of heterogeneous materials including; alluvial deposits, marine sediments, lava flows, and lake volcaniclastics (see Figure 3). The aquifer is capped by impermeable clays and underlain by Quaternary and Upper Tertiary alluvial formations (primarily conglomerate and sandstone) of high permeability. Below the alluvial formations, basaltic and andesitic lava flows are repeated with variable porosity and fracturing, and interbedded with pyroclastic and lacustrine deposits (Neri Flores et al., 2019; Ochoa-González et al., 2015; Ochoa-Gonzalez et al., 2018; SUEZ, 2019). The surrounding areas of higher topographical relief are comprised of volcanics (basalts, andesites, and tuffs) from the Miocene and Oligocene epochs (SUEZ, 2019).

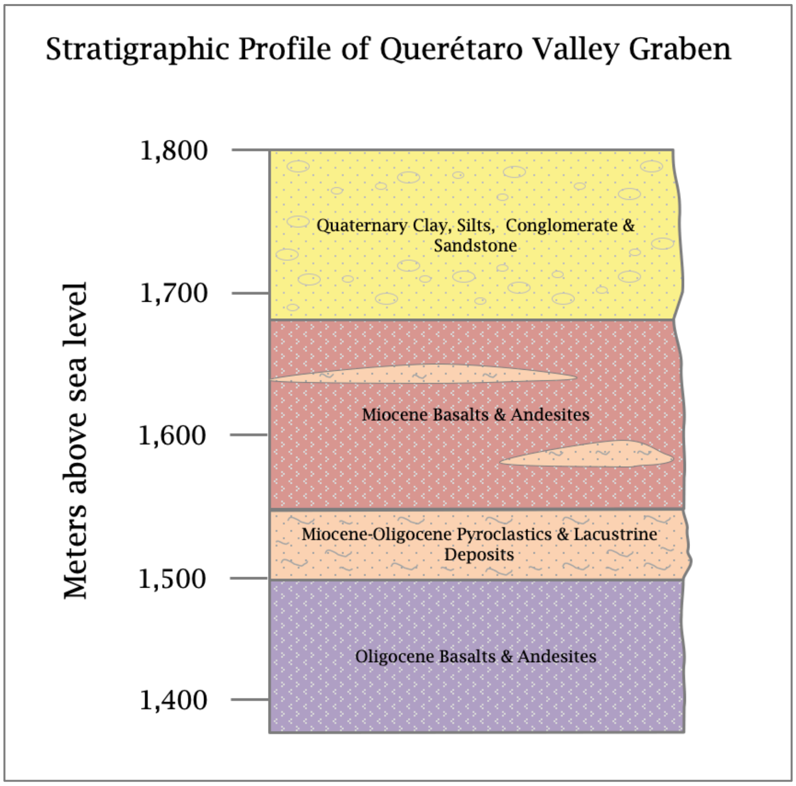


Figure 3 Stratigraphic profile of the upper 400 meters of the Valle De Querétaro Graben (data adapted from SUEZ (2019)).

2.1.2 Climate & Precipitation

The Querétaro Valley is categorized as having a semi-arid temperate climate, with an average annual temperature of 17 ˚C and the hottest months between May and August (CONAGUA, 2015). The region also experiences a distinct rainy season with average annual rainfall between 540 and 570 mm, concentrated in the months of June-August (CONAGUA, 2015; Soria et al., 2020; SUEZ, 2019).

2.1.3 Surface Waters

All waters from the Querétaro Valley discharge into the Lerma-Chapala River Basin, which provides water to the largest populations and most concentrated industrial and agricultural operations in México (CONAGUA, 2012). The main channel in the Querétaro Valley drainage basin is the Querétaro River, and its primary tributaries are the El Pueblito and Arenal Rivers (CONAGUA, 2015; Villa Alvarado et al., 2014). The headwaters of the Querétaro River are located in the Sierra Gorda (the central-western mountainous region of the state) and flow southwest until entering the lower elevations of the Valley. The river then flows westerly, passing through the city of Querétaro, and on to Las Adjuntas (the outlet point where the Querétaro River merges with its tributaries), before finally crossing the state boundary into Guanajuato (CONAGUA, 2015) (see Figure 4).

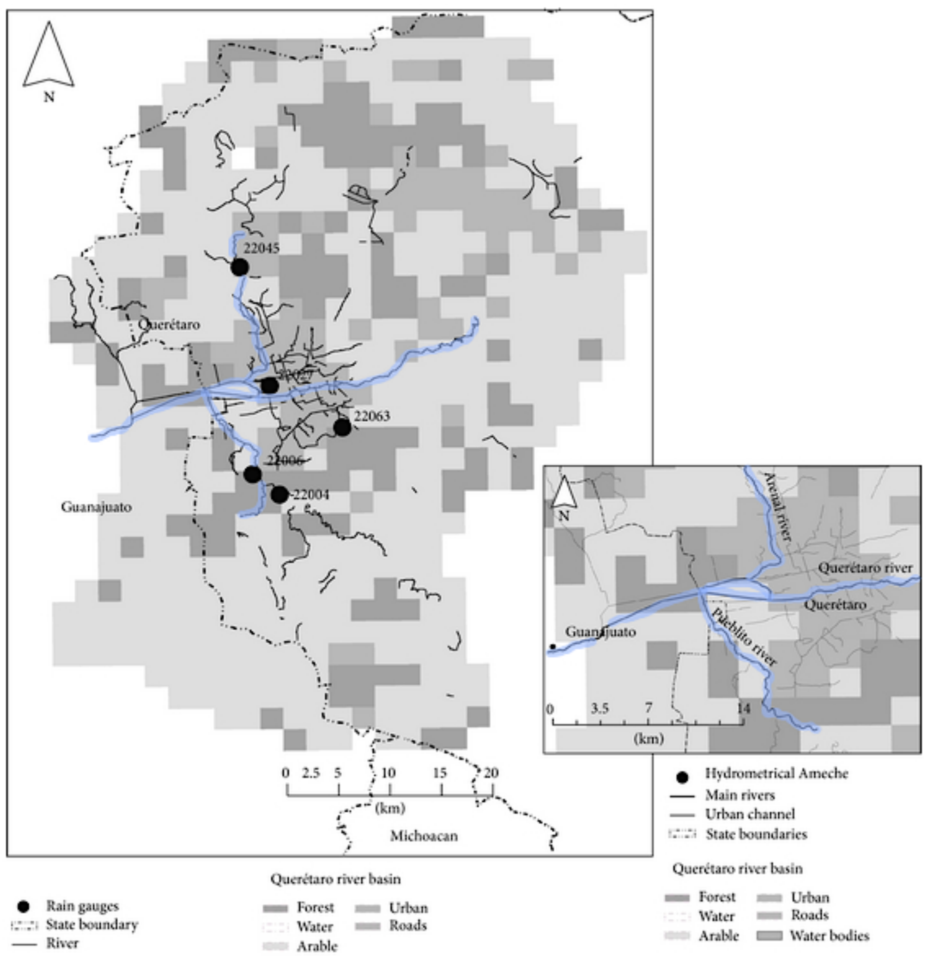


Figure 4 Location map of the Querétaro River and its two primary tributaries, the El Pueblito and Arenal Rivers (adapted from Villa Alvarado et al. (2014)).

2.1.4 Groundwater

The Valle de Querétaro Aquifer is located in the southwestern quadrant of the central Mexican state of Querétaro (20° 35' 34.8" N, 100° 23' 31.6" W) and encompasses an area of approximately 484 km^2 (see Figure 5) (de la Llata Gómez, 2003). The Querétaro Valley depends on groundwater supplied by the Valle de Querétaro Aquifer for nearly all of its domestic, industrial, and agrarian needs (Ochoa-González et al., 2018; SUEZ, 2019).

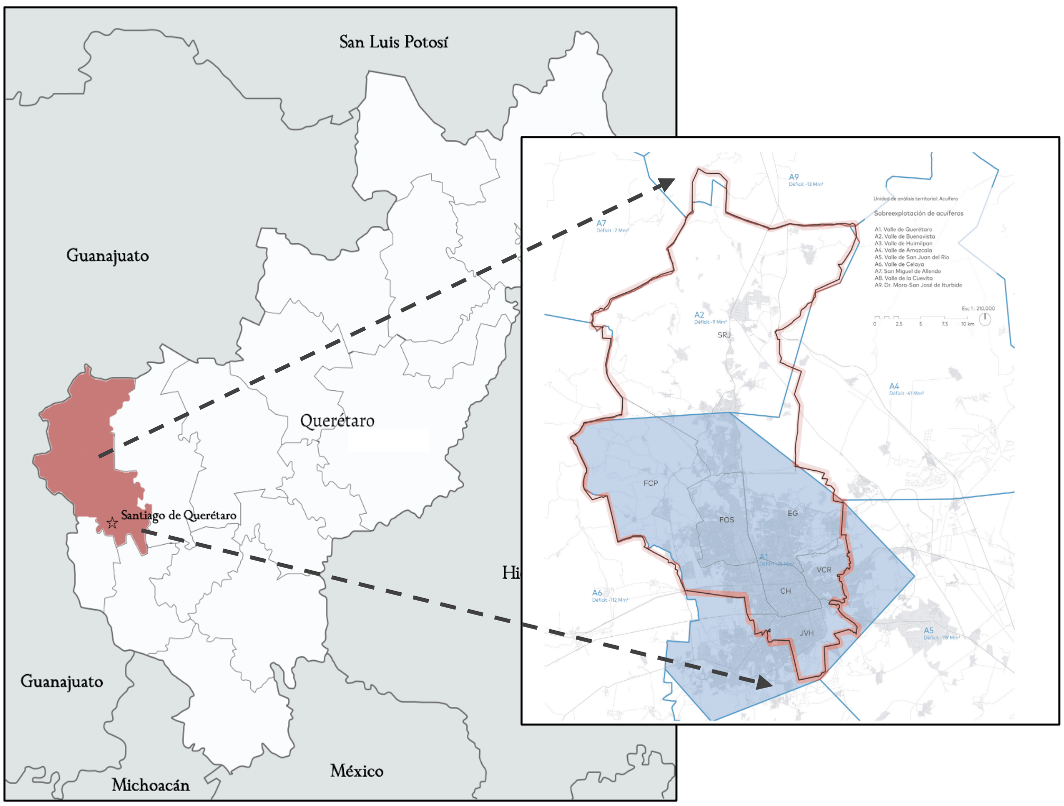


Figure 5 Location map of the Valle de Querétaro Aquifer delineated in blue (adapted from Wikipedia Commons (2010) & ONU-Habitat (2018)).

2.2 Anthropogenic Factors

2.2.1 Urbanization & Population Growth in the Querétaro Valley

The population of Querétaro in the 1700s was roughly 6,000 inhabitants and remained this size until the 1920s, when it reached an estimated 30,000 people (see Figure 6) (González-Sosa et al., 2013).

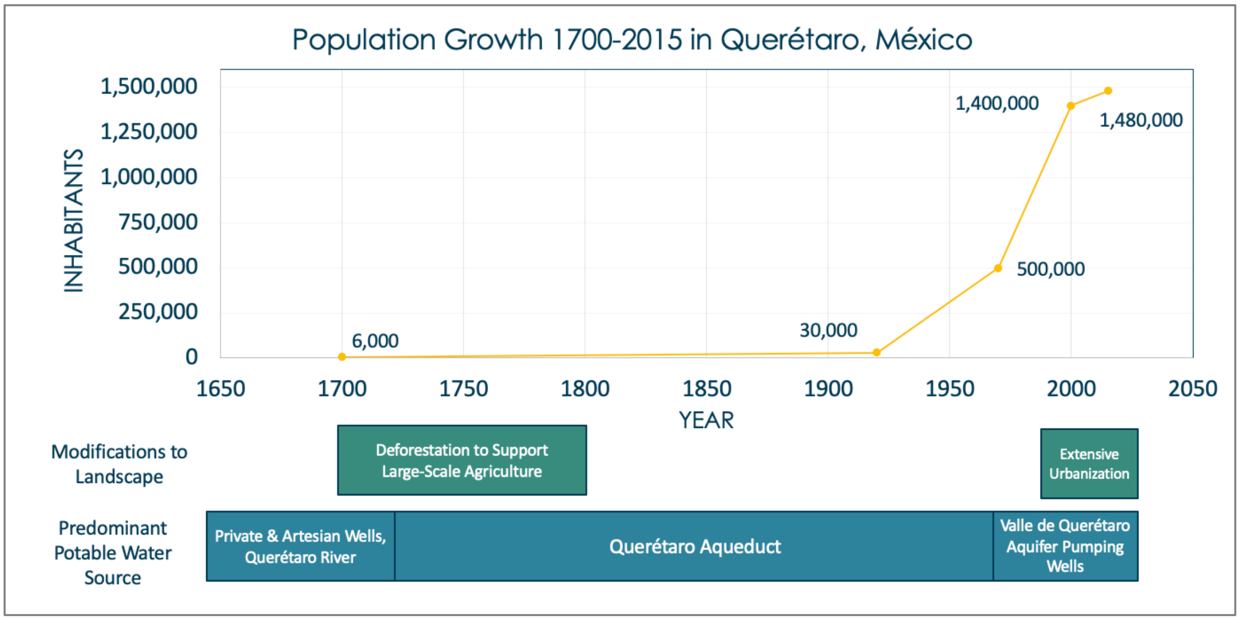


Figure 6 Population growth in the Querétaro Valley (1700-2015) with simultaneous changes to the landscape and the predominant source of potable water (1700-2020).

During the 1920s Mexican Revolution, Querétaro was established as the temporary capital of México. Populations shifted from surrounding rural areas to metropolitan areas, transforming the city into a thriving agricultural, industrial, and cultural center (González-Sosa et al., 2013; History.com Editors, 2018). Persistent migration of individuals in search of better living, working, and educational opportunities over the last 50 years has continued to drive rapid population growth in the greater metropolitan area (Cortés Silva et al., 2012). In 1970 the population of Querétaro reached approximately 500,000 inhabitants, and by the year 2000, the population had grown to nearly

1,400,000 (de la Llata Gómez, 2003). In 2015, the greater metropolitan area of Querétaro reported nearly 1,480,000 inhabitants (see Figure 6) (INEGI, 2017). The metropolitan area of Querétaro has expanded to include the three major municipalities of Corregidora, El Marqués, and Huimilpan (see Figure 7b) (INEGI, 2005; Mesa et al., 2016). Rapid population growth and urban development in the region (see Figure 7a) have resulted in an increased demand and extraction of groundwater from the Valle de Querétaro Aquifer (Soria et al., 2020).

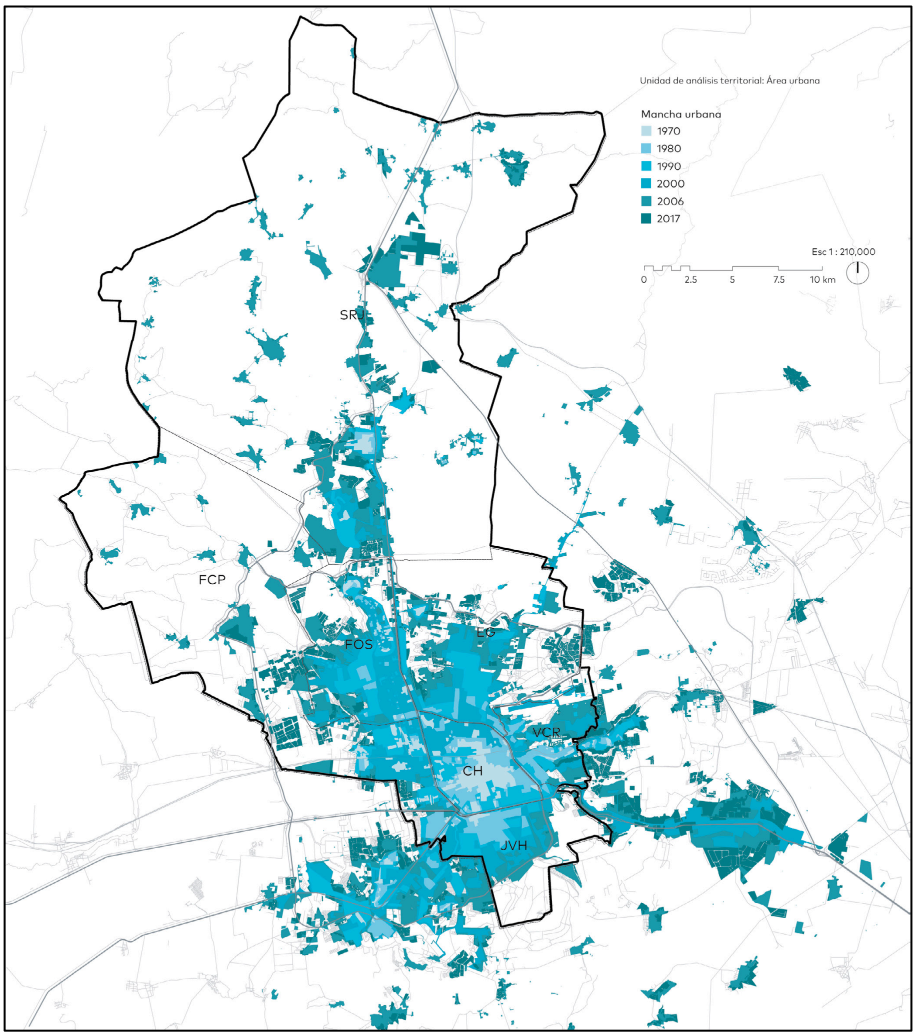


Figure 7a Map of the greater metropolitan area of Querétaro from 1970 to 2017 and the corresponding change in urban footprint over time (adapted from ONU-Habitat (2018)).

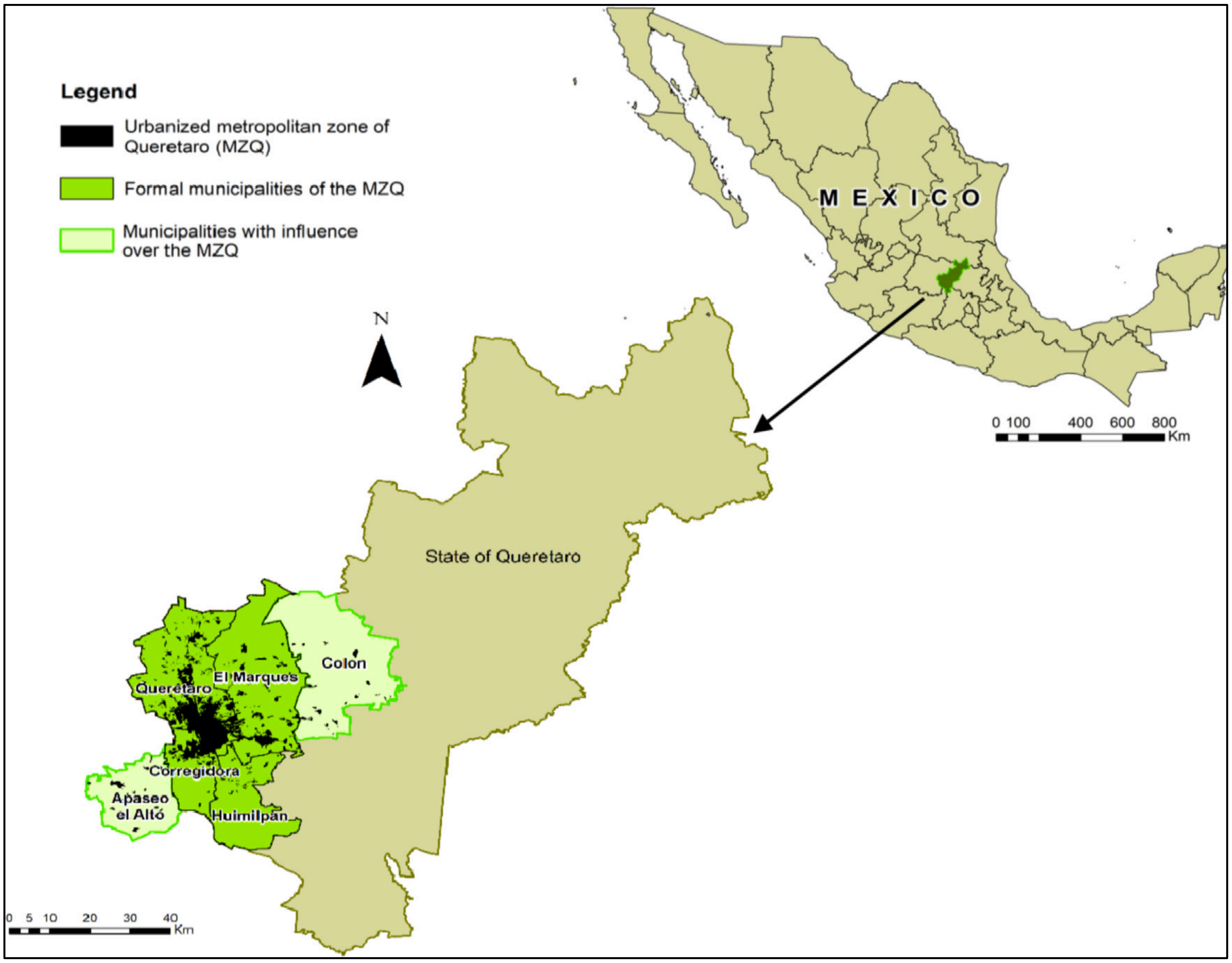


Figure 7b Regional map of the state of Querétaro highlighting the four municipalities with the highest population density (adapted from Soria et al. (2020)).

2.2.2 Land-Use Changes

Land-use and land-cover types determine important soil parameters, including permeability, porosity, hydraulic conductivity, evapotranspiration, infiltration, and recharge rates. They also control how water and contaminants move through a system. Urban development and the conversion of lands for agricultural use often involves deforestation or the removal of natural riparian vegetation (U.S. Geological Survey [USGS], 2016). Removal of vegetation and increased use of impervious materials significantly impact hydrological processes by increasing runoff rates and soil erosion, and decreasing evapotranspiration, infiltration, and recharge (González-Sosa et al., 2013; USGS, 2016).

The Querétaro Valley is encompassed by areas of higher topography, which historically were populated by temperate oak forests and deciduous tropical woodlands. Matorral vegetation (mesquite trees and woody-thorned shrubs) covered the low-lying areas (de la Llata Gómez, 2003). Intensive deforestation during the 1700s (see Figure 6) drastically transformed the vegetative landscape. The geography of the Querétaro Valley has allowed for an increase in population density as well as substantial agro-industrial development, altering its land-cover characteristics and impacting the availability and quality of water resources (Gonzalez-Sosa et al., 2013).

2.2.3 Human Impact on Surface Waters

In the Querétaro Valley, freshwater was initially acquired from surface water sources such as hand-dug wells, artesian wells, trenches, or directly from the Querétaro River (de la Llata Gómez, 2003; Suárez Cortéz, 1998). Consumption and use of contaminated surface waters eventually resulted in widespread health problems. The Querétaro River was highly polluted by domestic washing, textile production, disposal of tannery wastes, and regular discharges of agricultural and anthropogenic effluents (Suárez Cortéz, 1998). The need for access to potable water instigated the construction of the Querétaro Aqueduct in the 1720s (see Figure 6). The completed Aqueduct channeled artesian water to various locations throughout the city center and allowed for the separation of clean water from wastewater.

While the construction of the aqueduct improved public health overall, it accentuated environmental issues by allowing the Querétaro River to become the destination for all generated wastes. Socio-economic conflicts also emerged as wealthy residents (who lived in the city center) had unrestricted access to potable water, whereas impoverished and indigenous populations had minimal access (Suárez Cortéz, 1998). A rise in gastrointestinal illnesses in the 1940s initiated drilling of the first modern pumping wells in Querétaro (de la Llata Gómez, 2003) and eventually a transition to exclusive use of groundwater was made in the early 1970s (see Figure 6).

At present, the Querétaro River and its tributaries continue to experience high levels of contamination making them unsuitable alternatives for potable water (Comité Técnico de Aguas Subterráneas del Acuífero del Valle de Querétaro [CTASAVQ], 2002; Cortés Silva et al., 2012). In 2019, the Querétaro River Hydrological Restoration and Sanitation Program, led by Dr. Eusebio Ventura Ramos, identified 48 critical points of contamination along the Querétaro River. Contamination in the most important regional waterways is a result of residential dumping/littering combined with continual domestic, industrial, and agricultural discharges into its open waters (see Figure 8) (Alcalá, 2019).

Figure 8 Photograph of present-day contamination of the Querétaro River (Photo Credit: M. Martinez (2019)).

Water quality continues to deteriorate due to a lack of infrastructure for managing wastes. The city of Querétaro has 19 sewage treatment facilities that treat roughly 20-30% of wastewater, leaving the untreated 70-80% to be discharged directly into open waterways (Navarro et al., 2004; ONU-Habitat, 2018). In the neighboring Corregidora municipality, there are no wastewater treatment plants and all discharges flow directly into surface waters, creating numerous health hazards for residents and negatively impacting the environment. Authorities in the region have encouraged industries in the region to install on-site water treatment plants to meet current environmental regulations (Navarro et al., 2004). It is cheaper, however, to pay fines rather than install the necessary technology on-site, and due to a lack of environmental law enforcement, many do not comply.

2.2.4 Human Impact on Groundwater

2.2.4.1 Groundwater Use & Distribution

According to SUEZ (2019), 316 pumping wells are legally established within the limits of the Valle de Querétaro Aquifer. Of the 316 wells, 213 are active, and 103 are inactive. Of the active legal wells, 127 are allocated for domestic use, 46 for agricultural purposes, 37 for industrial use, and three were used for other purposes (see Figure 9).

The study conducted by SUEZ (2019) documents all legal extraction wells; however, it does not consider the thousands of illegal wells that are currently in operation throughout the region. The public agency *Comisión Estatal de Aguas* (CEA) is responsible for the regulation, distribution, and protection of water resources in México. "A common feature of this organization, like many others in Mexico, is secrecy and lack of transparency in public management of water resources" (Mesa et al., 2016). A report conducted by ONU-Habitat (2018) indicates that mismanagement by the CEA in Querétaro since 2003 has allowed an estimated "three thousand wells, many of them private and not legally registered, [to] draw water throughout the aquifer for industrial use" within the Querétaro municipality.

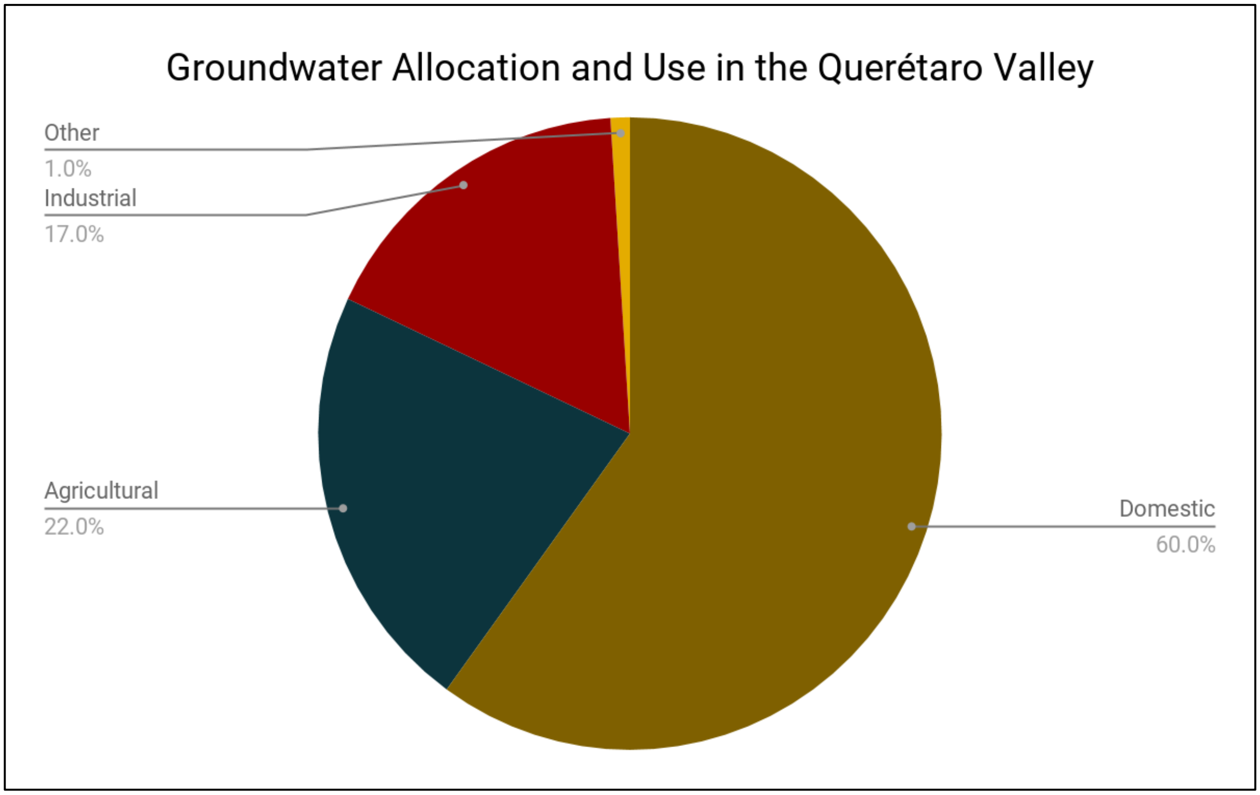


Figure 9 Pie chart depicting the allocation of groundwater in the Querétaro Valley (data adapted from SUEZ (2019)).

The extraction of groundwater by illegal wells is not reflected in the Figure above and therefore does not give an accurate depiction of groundwater use in the Querétaro Valley, nor does it account for the impact that the illegal wells have had on groundwater availability. Inefficient and leaky pipes that distribute water throughout the Querétaro Valley also accentuate water availability issues. According to Programa de las Naciones Unidas para el Desarrollo (PNUD) et al. (2011), nearly 60% of the water used in drip irrigation is lost to evaporation in Querétaro, indicating a highly ineffective system for conserving water in the agricultural zones. Additionally, ONU-Habitat (2018) reports that 33% of water distributed in the municipal water supply system is lost due to leaks.

2.2.4.2 Changes in Water Table Elevation Over Time

The water table is defined as the subsurface boundary between the unsaturated zone (where air and water fill the spaces between the sediments, rocks, and fractures) and the saturated zone (where groundwater completely fills the voids) (National Geographic Society, 2019). Researchers have referred to the saturated zones of the Valle de Querétaro Aquifer as the Upper and Main Aquifers (see Figure 10a). The water table elevation is influenced naturally by geology, topography, and precipitation fluctuations. The water table is influenced anthropogenically by groundwater extraction, irrigation/drainage systems, and modifications to the landscape (National Geographic Society, 2019; USGS, 2018a).

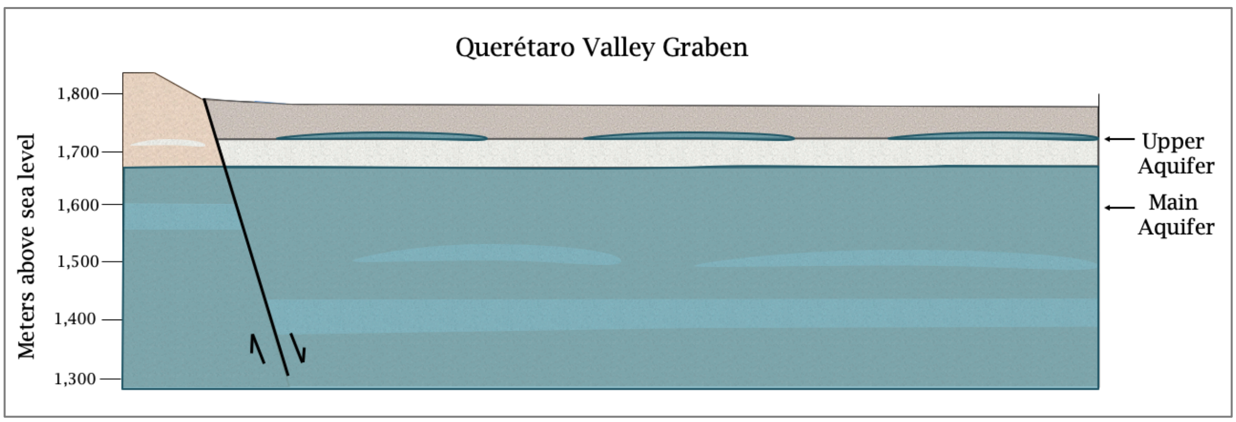


Figure 10a Schematic cross-section of Upper and Main Aquifers of the Querétaro Valley (data adapted from SUEZ (2019)).

Historical reports indicate that in the 1940s, the water table reached surface elevations (Cortés Silva et al., 2012; González-Sosa et al., 2013), but more extensive pumping of groundwater in the 1970s caused the water table to drop tens of meters (see Figure 10b) (Ochoa-González et al., 2018).

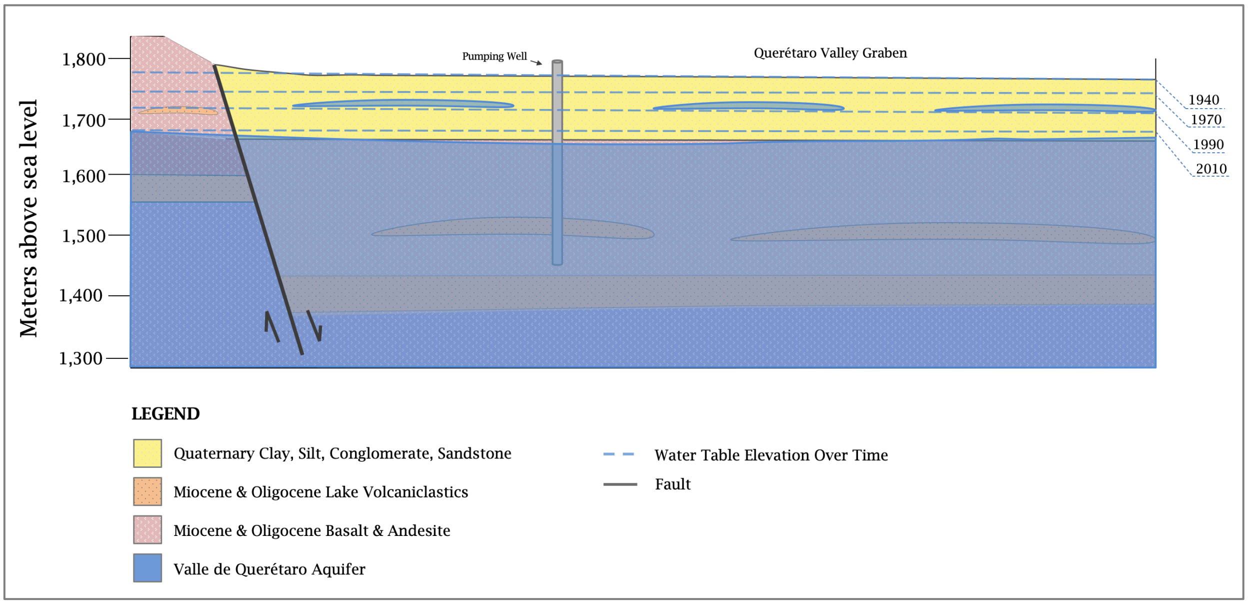


Figure 10b Schematic cross-section of change in water table elevation over time through various geologic units (data adapted from Cortés Silva et al. (2012); González-Sosa et al. (2013) & SUEZ (2019)).

The Upper Aquifer existed between 40 and 70 meters below the ground surface and served as the primary source of groundwater for the Querétaro Valley until it was exhausted in the 1990s (Ochoa-González et al., 2018; SUEZ, 2019). Following the depletion of the Upper Aquifer, pumping transitioned into the volcanic units of the Main Aquifer, composed of fissure basalts and andesitic lava flows with medium to high permeability (Carreón-Freyre et al., 2005; SUEZ, 2019). The water table dropped to between 120 and 140 meters below the ground surface by 2010, limiting the available water to pyroclastic and lacustrine geologic units that form the bottom of the Main Aquifer. The average well depth at present is between 150 and 180 meters below the surface (see Figure 10c) (SUEZ, 2019).

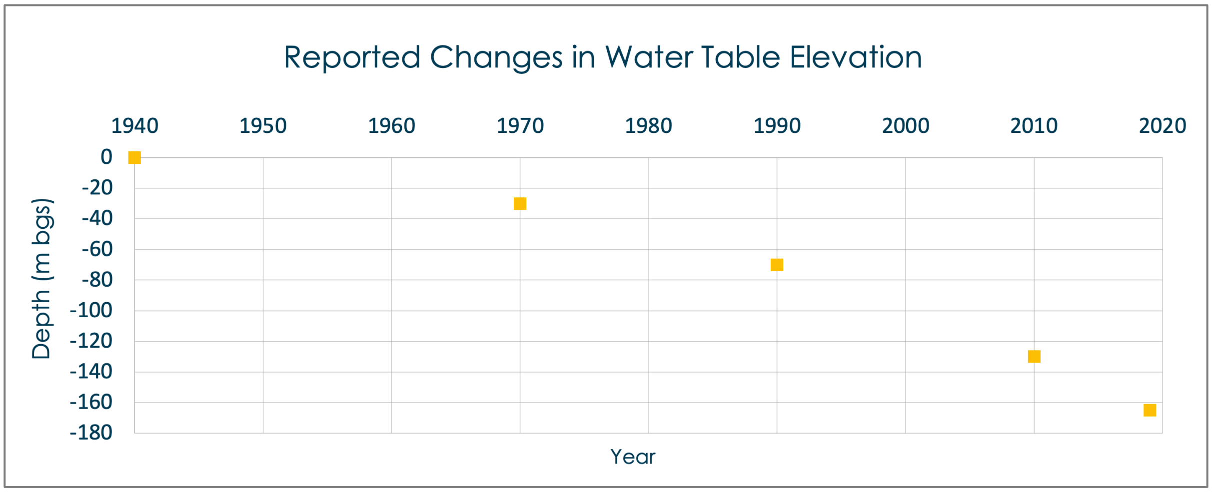
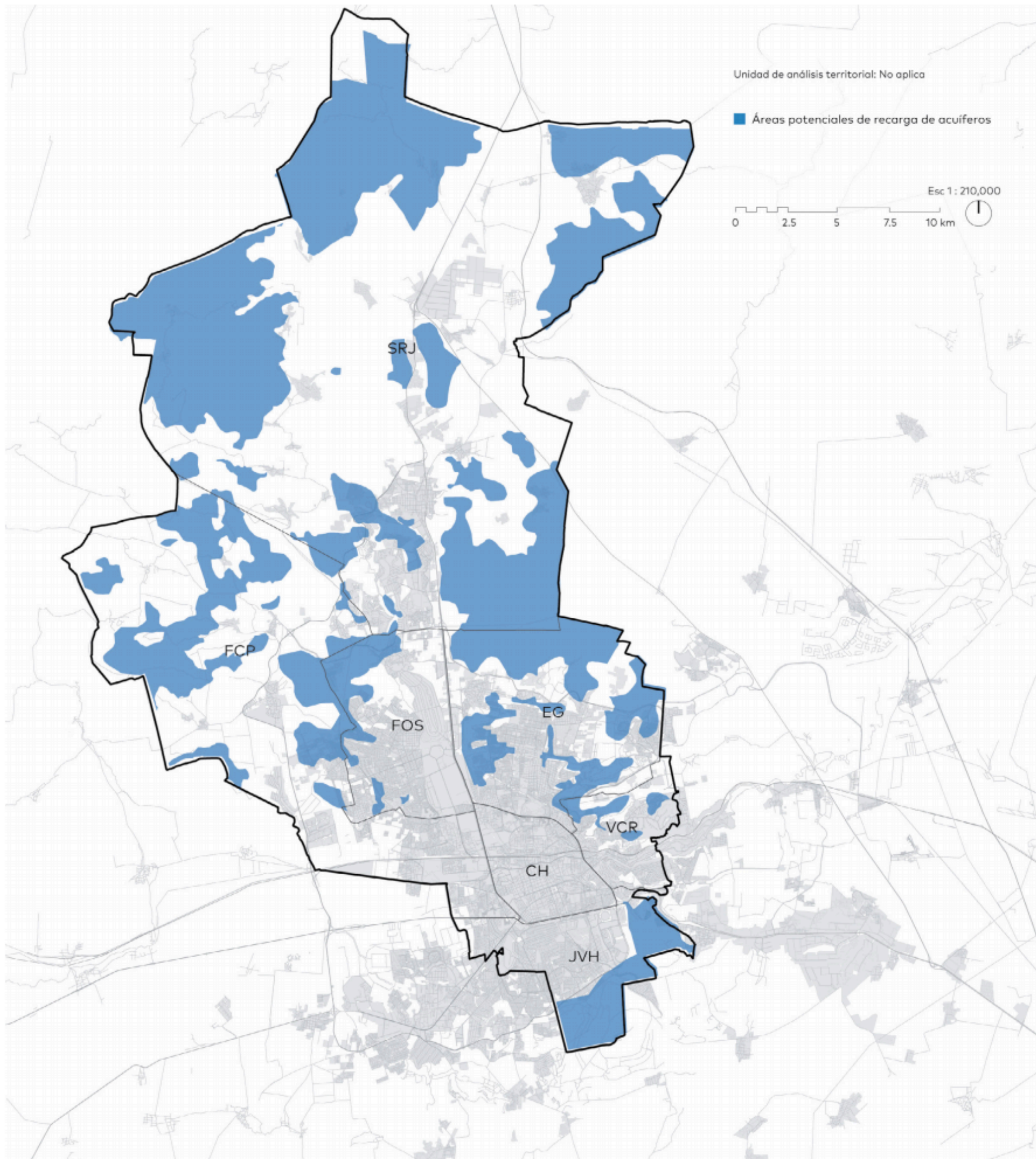


Figure 10c Graph depicting approximate change in water table elevation since 1940 (data adapted from Cortés Silva et al. (2012); González-Sosa et al. (2013) & SUEZ (2019)).

2.2.4.3 Recharge

The Valle de Querétaro Aquifer is recharged naturally from the infiltration of precipitation, groundwater flows from adjacent aquifers, and artificially from human activities (SUEZ, 2019). The Querétaro Valley recharge zones are concentrated in the vegetated areas of higher topographical relief that surround the Valley center (see Figure 11) (ONU-Habitat, 2018). During precipitation events, water infiltrates and flows vertically along fault planes and horizontally through porous volcanic rocks towards the lower elevation Valley center (due to gravity and hydraulic head differences) (Carreón-Freyre et al., 2005; SUEZ, 2019). Much of these important recharge zones have been or are currently being urbanized, affecting recharge potential. Increased use of impervious surfaces (*i.e.*, concrete, pavement, and roofing materials) results in increased surface runoff and erosion, and decreased infiltration and recharge to the Valle de Querétaro Aquifer.



Mapa 54 Alta permeabilidad y recarga potencial. Fuente: Elaboración ONU-Habitat con base en información de cartografía de INEGI 2010 y PMDU de Querétaro 2015.

Figure 11 Recharge zones highlighted in blue for the Valle de Querétaro Aquifer (adapted from ONU-Habitat (2018)).

2.3 Los Tajos

Springs are a natural source of water that form where groundwater meets the Earth's surface and flow is initiated (National Geographic Society, 2019; USGS, 2019). Historically, Los Tajos was a productive freshwater spring that supplied potable water to the small peri-urban communities of Santo Niño de Praga, Tlacote el Bajo, and La Palma (see Figure 12). An open tank made of tepetate (earthen) bricks was installed at the base of the springs so that residents could gather drinking water, bathe, or wash clothes (Gandler et al., 2010) (see Figure 13). Although most households in these communities were connected to the municipal water supply by the 1970s, many continued to supplement their water needs through continued use of Los Tajos spring water (Noguéz Dávila, 2012) (see Figure 14).

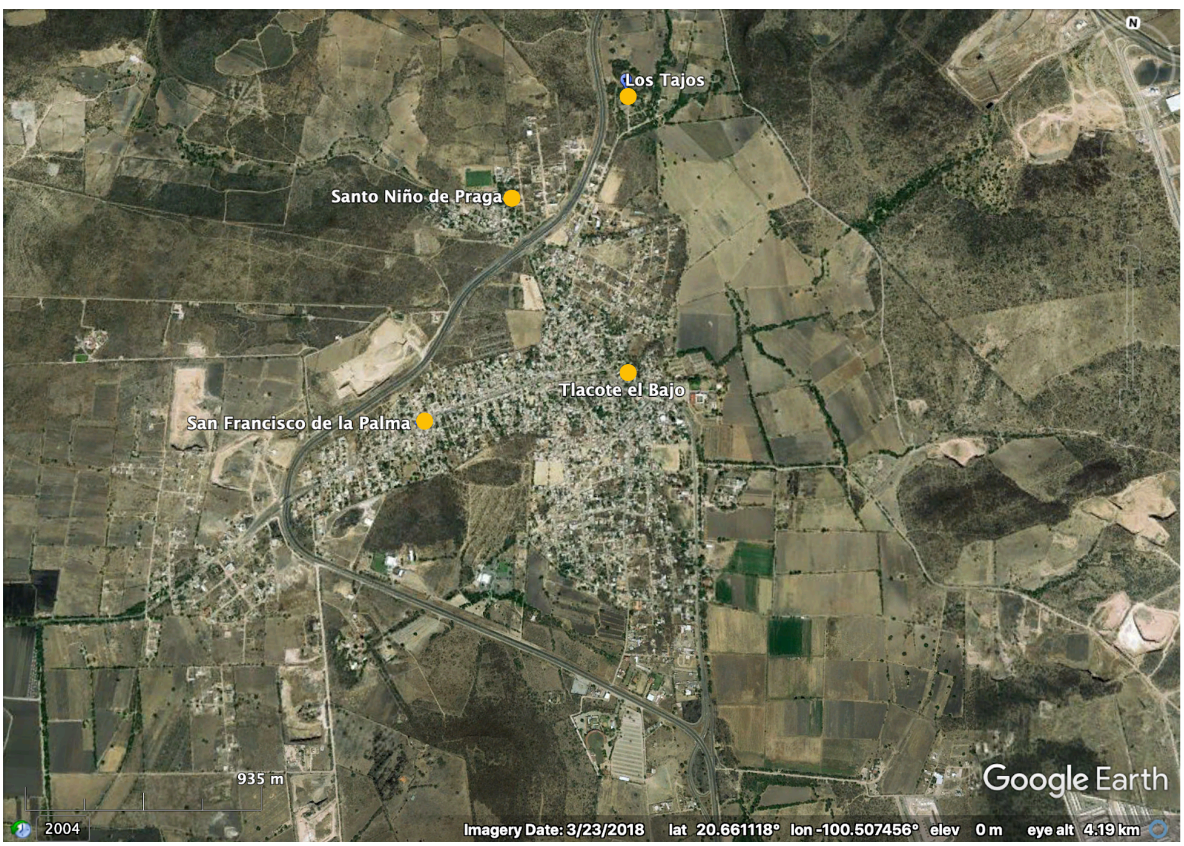


Figure 12 Location map of the freshwater spring Los Tajos and surrounding communities of Santo Niño de Praga, Tlacote el Bajo, and La Palma (Google Earth (2018)).

Figure 13 Photograph of the entrance to Los Tajos (Photo Credit: L. Noguéz Dávila (2007)).

Figure 14 Photograph of residents taking water from Los Tajos (Photo Credit: G. Andrade (1992) as cited in Noguéz Dávila (2012)).

The freshwater springs' high productivity prompted communal landholders in Tlacote to develop an ecotourism business. Construction began for a fish farming tank, a public pool, and a spa (Noguéz Dávila, 2012) (see Figures 15a & 15b). In the early 2000s, spring flows ceased, effectively terminating all planned projects (Noguéz Dávila, 2012). Locals excavated 30 meters below the surface in search of water (Noguéz Dávila, 2012), but according to recent hydrologic studies, the water table is now more than 150 meters below the surface (SUEZ, 2019). At present, residents of the three communities rely entirely on water supplied by the municipality to meet their household needs. The municipal supply is subject to regular water shut offs and residents are apprehensive of the water quality.

Figure 15a Photographs of proposed fish farming tanks that would have utilized channeled spring water from Los Tajos (Photo Credit: L. Noguéz Dávila (2007)).

Figure 15b Photograph of the constructed community pool that would have utilized channeled spring water from Los Tajos (Photo Credit: L. Noguéz Dávila (2007)).

2.3.1 Access to Municipal Water

Despite national goals to achieve universal access to potable water, many shortcomings and water-related inequities still remain in Querétaro (Estévez, 2019). Coverage is optimal in urban areas but more unevenly distributed in rural areas. (PNUD) et al. (2011) states:

> Access to water is a fundamental human right that is challenged by social inequalities, including economic status, race, sex, among others… Access to and management of water is controlled by those who maintain power and privilege in society. (p. 16)

In 2003, 53% of residents the urban and peri-urban zones of Querétaro had potable water service 17 to 24 hours a day; 42% had water available for 3 to 16 hours, while the remaining 5% only had access to the resource every third day (Perrusquía, 2003). In 2017, the CEA received the highest number of residential complaints regarding water shortages and shut offs (ONU-Habitat, 2018; Soria et al., 2020). In Querétaro, private companies control the price of water without consequence (Estévez, 2019). This greatly affects smaller peri-urban communities that typically have fewer economic resources, as companies have been known to raise water usage rates to 16 times more per cubic meter of water compared to urban residents that have been connected to the municipal water supply for years (Perrusquía, 2003). Because many residents want to avoid issues, they pay what they are charged, but some residents refuse to pay the high prices and have been known to break meters and use water illegally (Estévez, 2019).

During her Peace Corps service, there were periods where the author would not have running water for days at a time. Most households have a pila (open concrete water tank) to store water for when the water supply is shut off, however the water quality deteriorates with time and exposure, so the stored water is only used to water plants, wash clothes, or to clean. Bottled water is necessary for consumption. The author also knew of residents who illegally turned off water meters due to high prices leaving these lower-income households without access to water.

2.3.2 Water Quality Issues

Although nearly all water used comes from the Valle de Queretaro Aquifer, many residents still do not consider it safe for human consumption. Individual well sites within the metropolitan area of Querétaro showed high concentrations of total and fecal coliforms, which can cause severe gastrointestinal illnesses. At a different well site, concentrations of total dissolved solids were found to be well above the acceptable limit, a concern for consumers over the long term (Perrusquía, 2003; PNUD et al., 2011). A lack of consistent water quality monitoring by officials has allowed for bacterial and harmful metals/trace elements (arsenic, fluoride, nitrates, and manganese) to accumulate in the metropolitan water supply (Mesa et al., 2016; Perrusquía, 2003; PNUD et al., 2011). According to a report by ONU-Habitat (2018), extraction of groundwater at increasingly greater depths also significantly reduces water quality due to a higher concentration of sediments and heavy metals.

3 Methods

The Valle de Querétaro Aquifer and Los Tajos were selected for this research based on their proximity and relevance to the author's Peace Corps site. The author was unable to gather field measurements due to an unexpected evacuation and early termination of Peace Corps service as a result of the COVID-19 pandemic. Hydrological analyses were modified accordingly to focus on compiling and analyzing data from prior research. Qualitative and quantitative data obtained from available literature were used to determine the environmental and anthropogenic factors that have contributed to changes in the Valle de Querétaro Aquifer over time. A groundwater budget analysis was developed using reported quantitative data to identify which hydrological components have had the most significant impact on groundwater availability. The specific yield was calculated to confirm calculated changes in groundwater storage and the reported drop in water table elevation, based on the local geology. The Thornthwaite-Mather Water Budget was used to gain insight on the contributions of surface water hydrology components (*i.e.,* precipitation, temperature, evapotranspiration, and recharge) and environmental factors (*i.e.,* soil field capacity and root zone depth) on the hydrological system. Soil texture was classified to determine the soil composition of the Querétaro Valley and its impact on water movement over and through the subsurface.

3.1 Groundwater Budget

A water budget is a valuable tool used to quantitatively assess the contributions of relevant hydrological factors in a given system. A groundwater budget essentially analyzes the balance of inflows and outflows to determine groundwater availability and sustainability.

Inflows are the components that contribute to the system. Sources of inflows in the Valle de Querétaro Aquifer hydrological system include; natural vertical recharge from the infiltration of precipitation, natural horizontal flows into the aquifer from adjacent aquifers, and artificially induced recharge from various sources. Induced recharge is derived from leaks in the water or wastewater distribution systems, water losses at pumping well sites, agricultural irrigation, agricultural runoff, water used for livestock, and urban stormwater, irrigation, and runoff.

Outflows are the components of a water budget that are removed from the system. In the Valle de Querétaro Aquifer hydrological system, natural discharge and well extraction are the output components (see Figure 16). The extraction rate refers to the annual volume of water extracted by pumping wells. Natural discharge is water that leaves the system as groundwater flow. Groundwater storage is the amount of available water in an aquifer, with a negative change in groundwater storage indicating a deficit (Castellazzi et al., 2016).

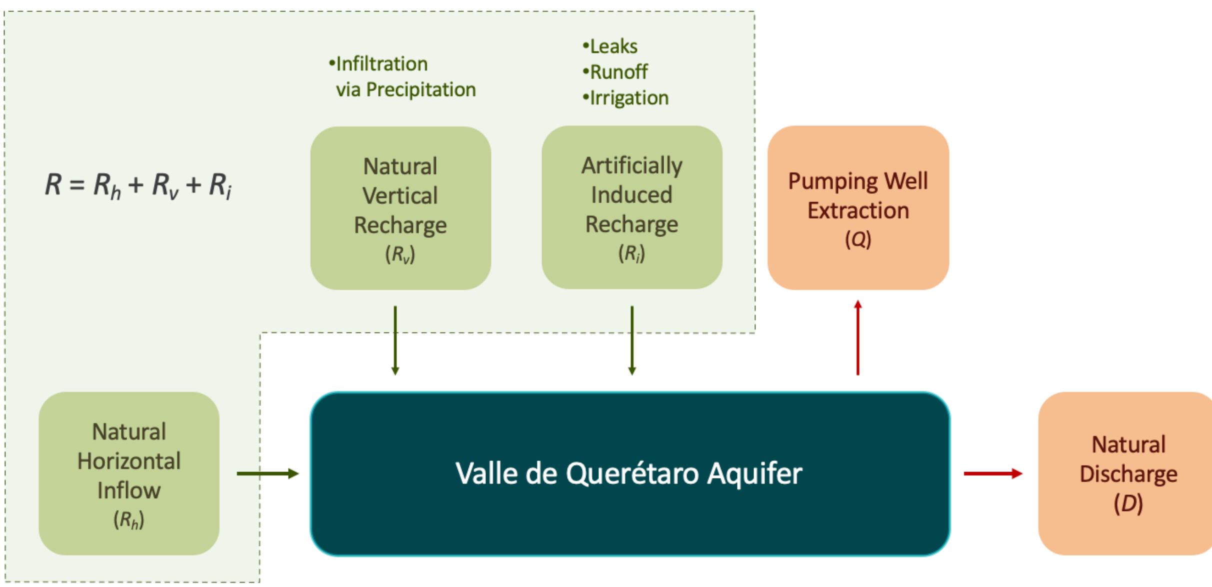


Figure 16 Schematic of the groundwater budget components and their contributions to the Valle de Querétaro hydrological balance. Inflows are depicted in green and outflows are depicted in orange.

The water budget components pertaining to the Valle de Querétaro Aquifer hydrological system can be expressed using the following equation:

$$\Delta GWS = (R_v + R_i + R_h) - (D + Q) \quad (1)$$

Where:

- ΔGWS = Change in groundwater storage
- R_v = Natural vertical recharge rate
- R_i = Artificially induced recharge rate
- R_h = Natural horizontal recharge rate
- D = Natural discharge rate from aquifer
- Q = Extraction rate by pumping wells

The change in groundwater storage in Equation (1) is equal to the difference between the summed value of the recharge rates and the sum of extraction by pumping wells and natural discharge from the aquifer. Equation (1) can be simplified by combining the contributions of each form of recharge, and would be expressed as:

$$\Delta GWS = R - (D + Q) \quad (2)$$

Where:

- ΔGWS = Change in groundwater storage
- R = Recharge rate
- D = Natural discharge rate from aquifer
- Q = Extraction rate by pumping wells

Despite being simplified, Equation (2) considers surface water parameters such as precipitation, evaporation, and runoff, although these components do not appear directly. The budget is calculated as a balance between groundwater inflows from recharge areas and outflows to discharge areas or pumping wells. The combined recharge value is derived by calculating the change in groundwater storage based on measured water table elevations and extraction rates. The main advantage of using the groundwater budget method is that evapotranspiration estimates are not required, and their related errors are not reported in the groundwater availability estimation (Castellazzi et al., 2016).

According to Castellassi et al. (2016), the limitations of using this simplified groundwater budget equation are the availability of "in situ measurements and the inaccuracies of pumping and recharge estimates." While Equation (2) does not provide insight into the temporal and spatial variations of an aquifer system, it is applicable to this research because the CNA and CEA most often utilize a simplified groundwater budget equation (Castellassi et al., 2016). Additionally, various published works pertaining to the Valle de Querétaro Aquifer, report values for a combined recharge rate, annual extraction rates, and natural discharge, making use of this equation most suitable for the Valle de Querétaro Aquifer groundwater budget.

3.2 Specific Yield

Specific yield is defined as the ratio of the volume of water drained by gravity to the total volume of porous rock (Harter, 2005). The specific yield assumes equilibrium conditions and an unconfined aquifer. The specific yield is used to determine water availability in an aquifer, per unit meter drop in the water table (Harter, 2005). Specific yield is unitless and is typically expressed as a percentage (Harter, 2005). To calculate specific yield, the equation defining it is rearranged as the following:

$$S_y = \frac{\Delta GWS}{A \cdot \Delta h} \quad (3)$$

Where:

S_y = Specific yield

ΔGWS = Average change in groundwater storage (average volume extracted)

A = Plan area of the aquifer

Δh = Water table elevation change

The specific yield is used in this report to confirm the calculated average change in groundwater storage and the change in water table elevation across the Valle de Querétaro Aquifer, based on the regional geology. The specific yield value was validated by comparing the calculated specific yield value to specific yield ranges found in *A Manual in Field Hydrogeology* (Sanders, 1998) and the corresponding rock and soil types.

3.3 Soil Texture Classification

A soil texture classification triangle is utilized to determine soil texture based on the percentages of clay, silt, and sand (see Figure 17). The soil texture type is defined where the three compositional lines intersect.

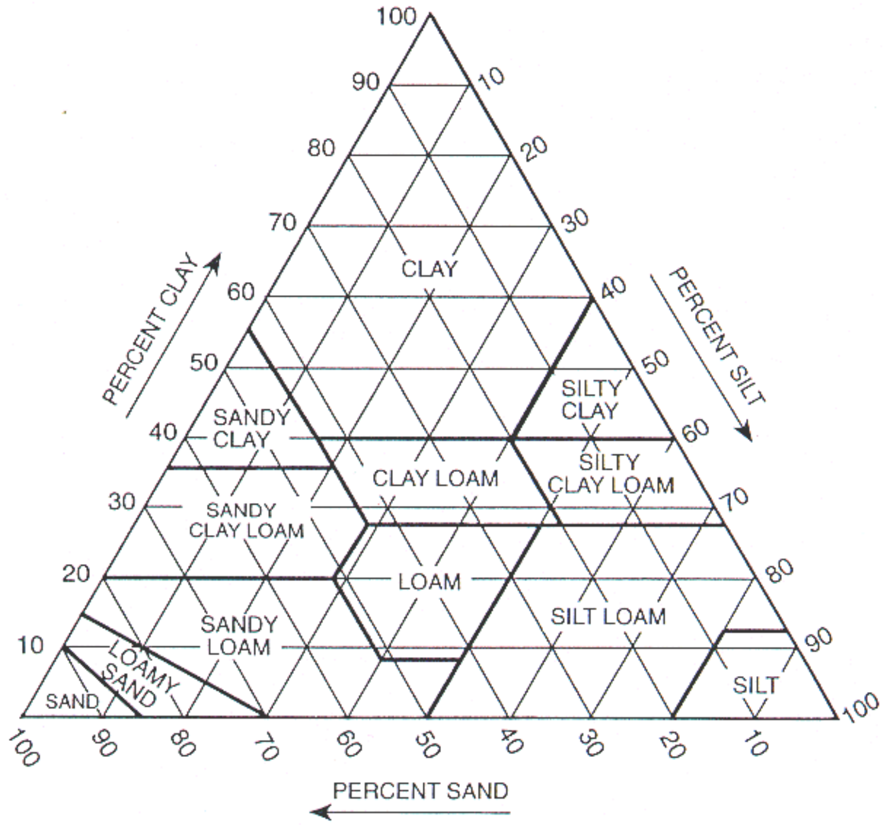


Figure 17 USDA Soil Texture Classification Triangle used to classify soil texture (adapted from Groenendyk et al. (2015)).

Soil texture classification is also used to gain a better understanding of the hydraulic parameters of the soil such as, water retention, porosity and permeability, infiltration rates, and recharge potential. In this report the soil texture classification triangle was used to determine the primary soil texture in the Querétaro Valley and evaluate how this texture may impact water movement over and through the subsurface and contribute to groundwater recharge. Values used for the soil texture classification were average compositional percentages obtained from Cortés Silva et al. (2012) that were determined based on 232 initial 2-kg samples of soil collected throughout the Querétaro Valley from 0 to 25-cm depth and an additional 74 samples that were collected later from different sites around the Valley.

4 Results & Discussion

4.1 Groundwater Budget Results

A groundwater budget analysis was used to identify which hydrological components have had the most significant impact on groundwater availability. A spreadsheet was used to compile reported quantitative data from various sources. Variability in the data results from differences in methodology or the reported values lacking an explanation of their derivation. The presented values represent the year when the report was published or the year preceding the publication, unless stated otherwise. Table 1 summarizes values for recharge (R), natural discharge (D), extraction (Q), and the calculated change in groundwater storage (ΔGWS) from the various sources. Average, minimum, and maximum annual values for each component are also presented.

Table 1 Equation (2) groundwater budget component values reported by various sources from 1996-2019. Highlighted values represent the minimum, maximum, and mean values for each component expressed in millions of cubic meters per year (Mm^3/yr).

Groundwater Budget Components: Valle de Querétaro Aquifer				
Data Source	**Recharge (R) (Mm^3/yr)** (Millions of m^3/yr)	**Natural Discharge (D) (Mm^3/yr)**	**Extraction by Wells (Q) (Mm^3/yr)**	**Change in Groundwater Storage (ΔGWS) (Mm^3/yr)**
*CEA (1999)	67.0	0.0	107.5	-40.5
**CEA (2011)	70.0	0.0	103.0	-33.0
*CNA (1999)	70.0	0.0	107.0	-37.0
*SEDESU (2002)	59.4	6.0	109.3	-55.9
SUEZ (2019)	77.6	0.0	77.6	0.0
ONU-Habitat (2018)	37.0	0.0	111.0	-74.0
Cortés Silva et al. (2012) [data from 1996]	70.0	0.0	103.0	-33.0
Cortés Silva et al. (2012) [data from 2000]	77.0	0.0	109.7	-32.7
DOF (2009)	70.0	0.0	109.7	-39.7
de la Llata Gómez (2003)	70.0	0.0	103.0	-33.0
Carrera-Hernandez et al. (2016) [data from 2010]	43.0	0.0	104.0	-61.0
Perrusquía (2003)	77.0	0.0	110.0	-33.0
CONAGUA, 2015 [data from 1996]	70.0	0.0	107.0	-37.0
CONAGUA, 2015 [data from 2014]	70.0	0.0	103.0	-33.0
CTASAVQ (2002)	77.0	0.0	110.0	-33.0
* as cited in de la Llata-Gómez (2003)				
** as cited in PNUD (2011)				
*** as cited in SUEZ (2019)				
MIN	**37.0**	**0.0**	**103.0**	**-74.0**
MAX	**77.0**	**6.0**	**111.0**	**-32.7**
MEAN	**66.2**	**0.4**	**106.9**	**-41.1**
	(R)	**(D)**	**(Q)**	**(ΔGWS)**

Based on the values presented in Table 1, recharge (*R*) contributes an average value of 66.2 Mm3/year to the groundwater budget. The natural discharge (*D*) component withdraws from groundwater storage an average of 0.4 Mm3/year and extraction by wells (*Q*) an average of 106.9 Mm3/year (see Figure 18). The components that have the most considerable impact on groundwater storage and thus groundwater availability are recharge and extraction, of which the extraction rate is much greater. Various reports established targets for natural discharge that should reach the main channel and provide baseflows to surface waters each year; however, as pumping wells extract nearly all groundwater flows, actual natural discharge flows are considered negligible (SUEZ, 2019) and as a result were excluded in the calculations. In addition, the Table also shows that the Valle de Querétaro Aquifer has had a negative change in groundwater storage for over 20 years with the exception of one report, SUEZ (2019), and indicates an annual average deficit in groundwater storage due to significantly higher extraction rates compared to recharge rates.

Valle de Querétaro Aquifer Component Averages Over Last 20 Years

Values in millions of cubic meters per year (Mm^3/year)

Change in Groundwater Storage = Recharge - [Natural Discharge + Extraction]

$$\Delta GWS = R - (D + Q)$$

$$-41.1 = 66.2 - (0.4 + 106.9)$$

Figure 18 Calculated averages of R, D, and Q components used to solve for the average ΔGWS.

4.2 Specific Yield Results

The change groundwater storage values presented in Table 1, the area of the Valle de Querétaro Aquifer (484 km^2), and reported drops in the water table were used to calculate the average specific yield for the Querétaro Valley (see Table 2). If there was no change in water table elevation value provided in the literature, the calculated average change in water table elevation (-3.1 m/yr) was used (see Table 3).

Table 2 Calculated average specific yield (S_y) value based on data reported by various sources from 1996-2019.

Specific Yield: Valle de Querétaro Aquifer				
Data Source	**Change in Groundwater Storage (ΔGWS) (m^3)**	**Area Valle de Querétaro Aquifer (A) (m^2)**	**Change in Water Table Elevation (Δh) (m)**	**Specific Yield (S_y)**
*CEA (1999)	-4.05E+07	4.84E+08	-3.1	2.70%
**CEA (2011)	-3.30E+07	4.84E+08	-3.1	2.20%
*CNA (1999)	-3.70E+07	4.84E+08	-3.1	2.47%
*SEDESU (2002)	-5.59E+07	4.84E+08	-3.1	3.73%
SUEZ (2019)	0.00E+00	4.84E+08	-3.0	0.00%
ONU-Habitat (2018)	-7.40E+07	4.84E+08	-3.1	4.93%
Cortés Silva et al. (2012) [data from 1996]	-3.70E+07	4.84E+08	-3.0	2.55%
Cortés Silva et al. (2012) [data from 2000]	-3.27E+07	4.84E+08	-3.0	2.25%
DOF (2009)	-3.97E+07	4.84E+08	-3.1	2.65%
de la Llata Gómez (2003)	-3.30E+07	4.84E+08	-3.1	2.20%
Carrera-Hernandez et al. (2016) [data from 2010]	-6.10E+07	4.84E+08	-2.5	5.04%
Perrusquía (2003)	-3.30E+07	4.84E+08	-2.7	2.53%
CONAGUA, 2015 [data from 1996]	-3.70E+07	4.84E+08	-3.1	2.47%
CONAGUA, 2015 [data from 2014]	-3.30E+07	4.84E+08	-3.1	2.20%
CTASAVQ (2002)	-3.30E+07	4.84E+08	-3.2	2.13%
* as cited in de la Llata-Gómez (2003)				
** as cited in PNUD (2011)				
*** as cited in SUEZ (2019)			**Average**	**2.9%**

Table 3 Water table drop values for the Valle de Querétaro Aquifer reported by various sources.

Data Source	Reported Change in Water Table Elevation (Δh) (m/yr)
SUEZ (2019)	-3.0
Mesa et al. (2016)	-3.1
Carrera-Hernández et al. (2016)	-2.5
CONAGUA (2015)	-3.1
González-Sosa et al. (2013)	-3.0
*Ortiz Villaseñor (2009)	-3.3
Cortés Silva et al. (2012)	-3.0
Carreón-Freyre et al. (2005)	-3.6
CTASAVQ (2002)	-3.2
Perrusquía (2003)	-2.7
*as cited in Cortés Silva et al. (2012)	
Average	**-3.1**

The average specific yield was calculated to be 2.9% which corresponds to clay and silt soil types and shale, sandstone, and non-karst limestone or dolomite lithographic units (Sanders, 1998). The ranges are consistent with the upper geological units found in the Querétaro Valley graben composed of clays and silts, as well as the alluvial deposits (*i.e.,* sandstone). The specific yield value that was calculated confirmed the reported changes in water table elevation and average change in groundwater storage over time to be reasonable, based on the geology of the Querétaro Valley graben.

4.3 Soil Texture Classification Results

Average percentages of clay, silt, and sand reported by Cortés Silva et al. (2012) (see Table 4) were used in conjunction with the USDA Soil Texture Classification Triangle (see Figure 19) to determine the prevalent soil texture in Querétaro Valley and its impact on water movement over and through the subsurface. Based on the given percentages, it was determined that a clayey soil texture dominates the Querétaro Valley. This result is consistent with the calculated specific yield value of 2.9% that is characteristic of clay soils and the geologic reports of a clay-rich uppermost layer in the Querétaro Valley graben. Clayey soil textures typically exhibit higher water retention, lower porosity and permeability, and slower infiltration rates (University of California Santa Cruz, 2005). Thus, the dominant soil type throughout the Querétaro Valley likely has a significant impact on the ability of water to infiltrate in the lower elevation areas of the Valley (based on the geology) and further limiting recharge potential in a recharge limited hydrological system.

Table 4. Reported soil parameter values from the Querétaro Valley. Mean percentages of clay, silt, and sand utilized are highlighted in green (data adapted from Cortés Silva et al. (2012)).

Soil Type	Clay (%)	Silt (%)	Sand (%)
Mean (%)	42.72	35.20	22.01

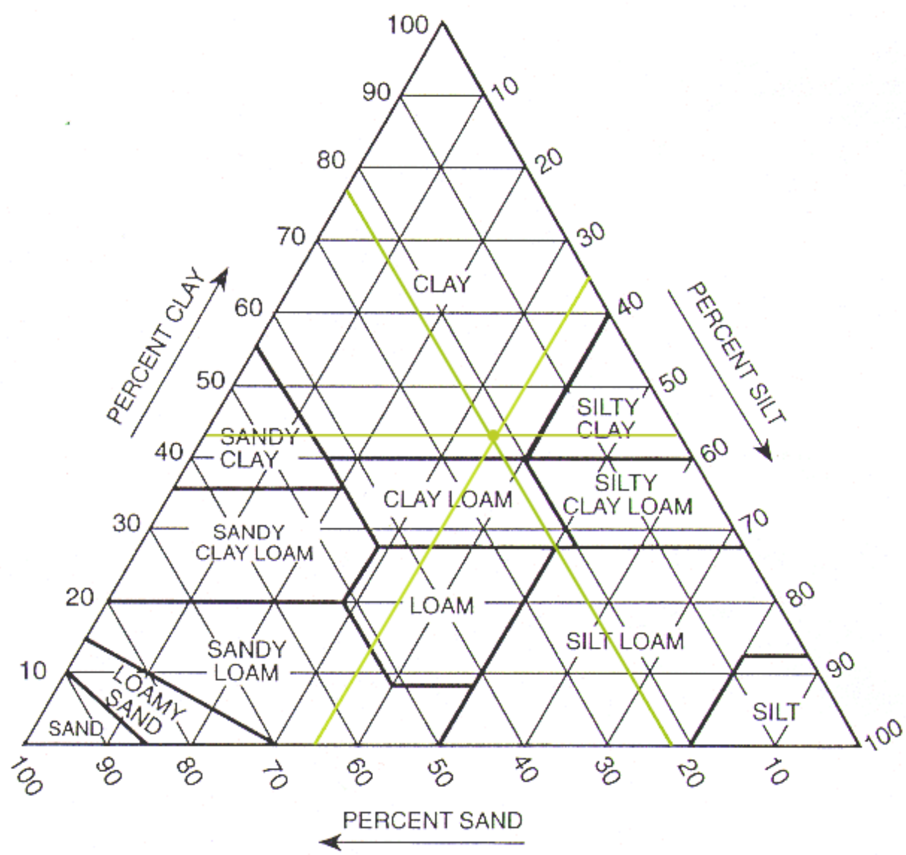


Figure 19 USDA Soil Texture Classification Triangle used to classify Querétaro Valley soil texture (adapted from Groenendyk et al. (2015)).

4.4 Discussion

For nearly 50 years, groundwater from the Valle de Querétaro Aquifer has been the only viable water source for residents and the manufacturing and agricultural industries established in the region. The overexploitation of groundwater due to over-allocation, mismanagement, unregulated use, and inefficient distribution systems have ultimately contributed to a severely depleted aquifer and drastically lowered water table. The sustainability and longevity of the Valle de Querétaro Aquifer depend upon responsible use, respect for the resource, and better overall management of regional water resources.

4.4.1 Human Impact on Water Resources

Population growth in the greater metropolitan area of Querétaro has led to an increase in groundwater demand, resulting in increased extraction rates and depletion of the aquifer to the point of exhaustion. The manufacturing and agricultural industries in the region require nearly 40% of the groundwater allocation and depend upon the resource for their sustainability, putting additional stress on the Valle de Querétaro Aquifer. Thousands of illegal wells throughout the Querétaro Valley extract groundwater, further accentuating limited groundwater availability.

Land-use changes associated with urbanization have altered the regional hydrology by increasing the use of impervious materials in development and by deforestation and the removal of natural vegetation. As a result, recharge rates have decreased and runoff rates have increased, leading to increased erosion, overland flow (*i.e.,* flooding events), and greater discharges of water from the Querétaro River at its outlet.

Due to the high levels of superficial contamination in the Querétaro Valley, no viable alternatives exist to supplement the groundwater supply. Residents are also apprehensive of groundwater quality due to a lack of consistent monitoring by the CEA and an overall lack of communication with the public regarding water quality.

Water scarcity concerns and the necessity for water in the Querétaro Valley instigated the construction of the Aqueduct System II in 2011, bringing in water from nearly 120 kilometers east of the city of Querétaro (Carrera-Hernández et al., 2016). The aqueduct was constructed to provide additional water to the greater metropolitan area of Querétaro in order to meet the water demands of the Querétaro Valley and aid in the recovery of the Valle de Querétaro Aquifer. Since its completion, the aqueduct has delivered a volume of 30 to 40 million cubic meters per year, allowing the pumping rate of the Valle de Querétaro Aquifer to decrease to roughly 65 million cubic meters per year (SUEZ, 2019). Contributions by the aqueduct have allowed for a minor recovery in the static level of the aquifer by reducing extraction rates and allowing recharge to accumulate. The combined volume of water produced by the aquifer and aqueductwill not be sufficient to meet the water demands of the metropolitan area beyond the year 2021 due to a continued increase in population density (Diario Oficial de la Federación, 2009). Based on the available literature, it is unclear what plans or strategies have been established to meet the future water needs of the region.

4.4.2 Hydrologic Implications

The physical geography and climate of a region determine the level of interaction between groundwater and surface water (USGS, 2016). The Querétaro Valley is made up of variable terrain with elevations ranging from roughly 1,800 to 2,400 meters above sea level and a semi-arid climate with limited annual rainfall. Variable amounts of precipitation and down slope water flow are characteristic of mountainous landscapes as described in USGS (2016) and have a significant impact on the recharge potential of a hydrological system, as well as the availability of groundwater. In a mountainous landscape, streamflow is primarily augmented by groundwater discharges during dry periods and by runoff during the rainy season. If rainfall intensity is such that it exceeds the infiltration capacity of the soil, or it is not able to infiltrate due to the presence of impervious surfaces, water will reach streams quickly by flowing downhill and over the surface to the main channel (USGS, 2016).

In most hydrologic systems, surface water and groundwater are interconnected and interdependent on one another. In a balanced system groundwater flows outlet into superficial bodies of water and in return, vertical and horizontal recharge augments the groundwater supply (USGS, 2018b). In an unbalanced system, where extraction of groundwater is so great that equilibrium cannot be achieved, a negative change in groundwater storage results, also known as a deficit (Alley et al., 2013; Castellazzi et al., 2016). The absence of surface waters is a direct result of the depletion of groundwater and a lowered water table. As surface waters attempt to compensate for the imbalance and reach an equilibrium state by infiltration, the result is often dried up lakes, rivers, streams (Alley et al., 2013; USGS, 2016). Freshwater springs are also affected by water table drops as springs form where the water table meets the ground surface, and if the water table is lowered and water does not reach the surface, flows will cease (see Appendix D, Figure D).

According to the Missouri Department of Natural Resources (2007), changes in water table elevation are greatest in recharge areas of higher topographical relief and show much less variation in the lower elevations which are typically groundwater discharge zones. Observations made by SUEZ (2019) explain that the lowest water table levels in the Querétaro Valley were concentrated in the areas of higher topographic relief on the Valley periphery with depths of nearly 180 meters below the ground surface, whereas readings collected in the central zone of the Valley showed ranges between 140 to 150 meters below the surface.

5 Potential Strategies for Future Resource Management

According to the United Nations Development Programme (2011), deteriorating environmental conditions often persist even with protective laws or achieved development goals due to the continued use of unsustainable practices. Progress on achieving environmental sustainability is often inadequate due to a lack of accountability and environmental priority, thus making education, capacity building, and improved governance critical in achieving sustainable practices.

There are numerous challenges regarding the implementation of improved water management and protection in Querétaro. Through Peace Corps service in Santo Niño de Praga, the author observed an absence of environmental education and education regarding the conservation natural resources, in both schools and communities. Inadequate enforcement of environmental regulations has allowed for the depletion and contamination of natural resources throughout México. Governmental entities such as SEMARNAT (Secretaría del Medio Ambiente y Recursos Naturales) that aim to protect natural resources, lack the funding and personnel to carry out the work. Agencies, such as the CEA, are not transparent in water management or distribution, and take advantage of lower-income residents by drastically overcharging for water. Regardless, improved management and protection of all water resources in Querétaro is essential for the sustainability and longevity of the Valle de Querétaro Aquifer and the communities that depend on it.

Changing weather patterns have had a significant impact in México concerning the availability and quality of natural resources, including water. Environmental education about natural resource conservation is crucial because the finite nature of resources is often overlooked or not understood by consumers. Environmental education is necessary in Querétaro because it would allow individuals, private organizations, and governmental agencies to better address environmental issues and effectively manage natural resources. Environmental education enhances an awareness of and promotes a concern for the environment, leading to new patterns of behavior.

As water availability becomes more critical in the Querétaro Valley, it will become necessary for residents to find alternative ways to conserve water for their livelihood. One of the objectives of Peace Corps Volunteers in México, apart from environmental education, is to promote the use of "ecotecnias". An ecotecnia is a low-tech green technology, designed to be accessible to all people regardless of socioeconomic status, and applicable in most climates. Ecotecnias serve as resource-conserving alternatives that help users to be more environmentally conscientious and incorporate more sustainable practices. Examples include solar ovens, wood-saving stoves, rainwater catchment cisterns, biofilters, composting toilets, compost, home and school biointensive gardens, etc. The Dirección de Concertación y Participación Ciudadana (2006) defines ecotecnias as:

> Tools for sustainable development that promote the efficient use of natural resources. They look to take advantage of natural resources in a sustainable manner to address various everyday problems. The goal is that these green practices improve the life of its users by operating cleanly, are efficient with respect to cost and environment, and provide a critical service in the daily lives of people. (p.1)

The ideal result of an ecotecnia (compared to a standard practice/technology) is a net conservation of resources, pollution reduction, or an improvement in quality of life. All ecotecnias provide reasonable and cost-effective alternatives that allow residents to be more environmentally responsible and develop the skills necessary to mitigate and adapt to the effects of a changing climate. With regard to water scarcity concerns in the Querétaro Valley, citizens have already made small adaptations like the construction of pilas to store water in anticipation of water shut offs. This is only one solution to an impending water-shortage crisis, and to supplement their current limited water supply, residents could construct or install a water catchment cistern to collect rainwater and supplement their water supply during the rainy season. Biofilters are natural alternatives for filtering household greywater from showering, bathing, washing, or even dishes, and after its filtration, can be used to water plants or carry out household chores. Composting toilets also decrease the amount of water used and provide an excellent alternative for fertilizer with time. Capacity building workshops by the Mexican government, CEA, or community outreach programs should be established to teach residents about the use of ecotecnias and give them the skills necessary to adapt and maintain them.

Ecotecnias present a feasible alternative for domestic water use, however addressing water issues derived from industrial or agricultural practices present greater challenges. To address the issue of industrial exploitation of groundwater in the Querétaro Valley, it is recommended that industry properly treat residual wastewater on-site to limit further contamination of surface waters. All wastes produced by industry should be monitored by local officials to ensure that discharges meet regulations, and if they do not, industries should be held accountable and fined. Alternatives for agriculture could include evening irrigation to limit the amount of water lost to evaporation and increased use of mulch or compost to increase water retention of the soil and decrease dependency on chemical-laden fertilizers which also pollute waterways.

Remediation and monitoring of contaminated surface waters and a higher concentration of functioning wastewater treatment facilities is also recommended as it would allow for surface waters to potentially supplement the groundwater supply and aid in the recovery of the Valle de Querétaro Aquifer. As the entity responsible for managing and protecting water resources, the CEA should be transparent with residents about water distribution, quality, and availability. As a result, residents will be better informed, better understand the current water crisis in Querétaro, and make the necessary adjustments in their respective households.

It is necessary that the CEA reevaluate current water allocations and adjust them based on the current availability of groundwater and have plans in place for how groundwater will be augmented in order to continue to meet the water needs of the Querétaro Valley.

6 Conclusions

Evaluation of qualitative data confirms that several anthropogenic factors have contributed to the severe depletion of the Valle de Querétaro Aquifer over time. In a hydrologic sense, groundwater availability has been impacted by limited recharge due to the mountainous landscape hydrology of the Valley and anthropogenically by the modification of the landscape as a result of land-use changes associated with urban expansion. A rapidly growing urban population has led to an increase in water demand and corresponding increased groundwater extraction. Over-allocation of groundwater to sustain the agricultural and manufacturing industries has put increased pressure on the aquifer. Unregulated groundwater use, inefficient water distribution systems, and limited water treatment have also contributed to the depletion of the groundwater source. Mismanagement of water sources in the region has resulted in highly contaminated surface waters, limiting their potential to serve as alternative freshwater sources.

The groundwater budget analysis quantitatively confirms that extraction and recharge have been the primary factors impacting groundwater availability. Over-extraction has consistently exceeded recharge rates, contributing to a significant annual groundwater deficit and a corresponding decline in water table elevation across the Valle de Querétaro Aquifer. Freshwater springs depend on groundwater flows for their sustainability. A lowered water table removes the water supply, causing spring production to cease. Therefore, drastically reduced water table across the Valle de Querétaro Aquifer, due to over-extraction and limited recharge, ultimately caused flow cessation in Los Tajos.

7 References

**Aguirre-Díaz, G. J., Ramón Zúñiga-Dávila Madrid, F., Pacheco-Alvarado, F. J., Guzmán-Speziale, M., & Nieto-Obregón, J. (2012). *EL GRABEN DE QUERÉTARO, MÉXICO: OBSERVACIONES DE FALLAMIENTO ACTIVO*. Unidad de Investigación de Ciencias de la Tierra, campus UNAM-Juriquilla, por el Instituto de Geología, UNAM. https://www.ugm.org.mx/publicaciones/geos/pdf/geos00-1/Aguirre-Diaz00-1.pdf.

Alcalá, M. D. (2019). Presentan UAQ y El Marqués Programa de Saneamiento del Río Querétaro. Retrieved April 27, 2020, from http://noticias.uaq.mx/index.php/vida/2579-presentan -uaq-y-el-marques-programa-de-saneamiento-del-rio-queretaro.

Alley, W. M., Reilly, T. E., & Frank, O. L. (2013). *Ground Water Development, Sustainability, and Water Budgets*. U.S. Geological Survey Circular 1186. https://pubs.usgs.gov/circ/circ1186/html/gw_dev.html

Carrera-Hernández, J. J., Carreón-Freyre, D., Cerca-Martínez, M., & Levresse, G. (2016). Groundwater flow in a transboundary fault-dominated aquifer and the importance of regional modeling: the case of the city of Querétaro, Mexico. Hydrogeology Journal, 24(2), 373–393. https://doi.org/10.1007/s10040-015-1363-x

Carreón-Freyre, D., Cerca, M., Luna-González, L., Gámez-González, F.J. (2005). *Influencia de la estratigrafía y estructura geológica en el flujo de agua subterránea del Valle de Querétaro*. Revista Mexicana de Ciencias Geológicas, 22, 1-18.

Castellazzi, P., Martel, R., Rivera, A., Huang, J., Pavlic, G., Calderhead, A. I., Chaussard, E., Garfias, J., & Salas, J. (2016). *Groundwater depletion in Central Mexico: Use of GRACE and InSAR to support water resources management, Water Resour. Res.*, 52, 5985– 6003, doi:10.1002/2015WR018211.

Chaussard, E., Wdowinski, S., Cabral-Cano, E., & Amelung, F. (2014). Land subsidence in central Mexico detected by ALOS InSAR time-series. *Remote Sensing of Environment*, *140*, 94–106. https://doi.org/10.1016/j.rse.2013.08.038

Comité Técnico de Aguas Subterráneas del Acuífero del Valle de Querétaro (CTASAVQ). (2002). *PLANEACIÓN PARTICIPATIVA PARA EL MANEJO INTEGRADO DEL AGUA EN EL VALLE DE QUERÉTARO*. Comisión Nacional de Agua. https://gestionsostenibledelagua.files.wordpress.com/2010/10/2002-planecion-participativa-para-el-manejo-integrado-del-agua-en-el-valle-de-queretaro.pdf

CONAGUA. (2012). *Lerma - Chapala Basin Case Study, Mexico a fruitful sustainable water management experience*. Retrieved from http://www.conagua.gob.mx/CONAGUA07/Contenido /Documentos/LermaChapalaBasinCase.pdf

CONAGUA: Gerencia de Aguas Subterráneas. (2015). *Actualización de la disponibilidad media anual de agua en el acuífero Valle de Querétaro (2201), Estado de Querétaro* (pp. 1–24). Queretaro, QRO: Comisión Nacional del Agua. Retrieved from https://www.gob.mx/cms/uploads/attachment/file/104245/DR_2201.pdf

Cortés Silva, A., Arzate Flores, J. A., & Lozano Guzmán, A. A. (2012). *El Valle de Querétaro y su Geoentorno* (Vol. 2). Querétaro, QRO: FUNDAP.

de la Llata Gómez, R. (2003). *El Sistema de Agua en la Región Querétaro de la Cuenca Lerma-Chapala.* (A. Lozano Guzmán, Ed.) (pp. 5-36). Querétaro, QRO: CONCYTEQ. Retrieved from http://www.concyteq.edu.mx/concyteq//uploads/publicacionArchivo/2017-06-232.pdf.

Diario Oficial de la Federación (DOF). (2009). *ACUERDO por el que se da a conocer el resultado de los estudios técnicos de aguas nacionales superficiales en las cuencas hidrológicas Río Moctezuma 1, Río Extóraz y Río Santa María 3 de la Región Hidrológica número 26 Pánuco.* Retrieved from http://dof.gob.mx/nota_detalle_popup.php?codigo=5097150

Dirección de Concertación y Participación Ciudadana. (2006). *Programa Organización Productiva para Mujeres Indígenas 2008: Guía de Ecotecnias*. Comisión Nacional para el Desarrollo de los Pueblos Indígenas (CDI). http://www.cdi.gob.mx/dmdocuments/ecotecnias.pdf

Estévez, A. (2019). *ACCESO AL AGUA, DERECHO HUMANO*. Magazine Querétaro. http://www.andresestevez.mx/magazine/columnas/brujula-de-queretaro/item/19731-acceso-al-agua-derecho-humano

Gandler, S., Serna Jimenez, A., & Palacios Sierra, P. (2010). *Modernidad y Diferencia: Reflexiones Conceptuales y Estudios Empíricos en Género y Territorio*. Universidad Autónoma de Querétaro: Ciencias Sociales. http://biblioteca.diputados.gob.mx/janium/bv/ce/scpd/LXI/mode_difer.pdf.

González-Sosa, E., Ramos-Salinas, N.M., Mastachi-Loza, C.A., & Becerril-Piña, R. (2013). *Effect of Water Resources in the Querétaro River: Climate Analysis and Other Changes, Climate Change - Realities, Impacts Over Ice Cap, Sea Level and Risks*, Bharat Raj Singh, IntechOpen, DOI: 10.5772/55259.

*Google Earth V 7.3.3.7786. (2018). Tlacote el Bajo, Querétaro, México. 20.664048° N -100.508615° W, Eye alt 6.36 km. Image Data © Maxar Technologies 2020. Map Data © INEGI 2020. OpenGL 2020.

*Groenendyk, D., P.A. Ferré, T., R. Thorp, K., & K. Rice, A. (2015). *USDA Soil Texture Triangle.* (Version 1). PLoS ONE. https://doi.org/10.1371/journal.pone.0131299.g001

Harter, T. (2005). *Specific Yield Storage Equation.* Water Encyclopedia (eds J.H. Lehr and J. Keeley). doi:10.1002/047147844X.gw1086

History.com Editors. (2018). Querétaro. Retrieved April 24, 2020, from https://www.history.com/topics/mexico/queretaro

Instituto Nacional de Estadística, Geografía e Informática (INEGI). (2005). *Censos Económicos (2004): Aguascalientes, Ags., Instituto Nacional de Estadística Geografía e Informática (INEGI).*

Instituto Nacional de Estadística y Geografía (INEGI). (2015). *Encuesta Intercensal* 2015, México.

Instituo Nacional de Estadística y Geografía (INEGI). (2017). *Anuario estadístico y geográfico de Querétaro 2017*. https://www.datatur.sectur.gob.mx/ITxEF_Docs/QRO_ANUARIO_PDF.pdf

*Martínez, M. (2019). *Investigará Profepa contaminación en el Río Querétaro* [Photograph]. Retrieved from https://www.diariodequeretaro.com.mx/local/investigara-profepa-contaminación-en-el-rio-querétaro-3616167.html

**Mesa, A., Luna-Soria, H., & Castilla, J. L. (2016). Water and modernization styles: measuring territorial knowledge based on water management policies in Santiago de Querétaro (Mexico). *Water Policy, 18*(6), 1473–1489. https://doi.org/10.2166/wp.2016.013

Missouri Department of Natural Resources. (2007). *Why Groundwater Levels Change*. Missouri Geological Survey, Water Resources Center. https://dnr.mo.gov/geology/wrc/docs/WhyWater LevelsChange.pdf

National Geographic Society. (2019). *Water Table*. https://www.nationalgeog raphic.org/encyclopedia/water-table/.

Navarro, A., López, M., & Caire, G. (2004). *Estudio, análisis y propuestas para el fortalecimiento de los programas municipales de saneamiento ambiental existentes en la Cuenca Lerma-Chapala*. Retrieved from https://www.agua.org.mx/wp-content/uploads/2010/11/612 Estudio_analisis_propuestas_fortalecimiento_programas_municipales_de_saneamiento.pdf

Neri Flores, I., Raúl, F., Pineda-López, J., Hernández-Guerrero, J. (2019). *Interacciones Entre Agua Subterránea y Agua Superficial: Análisis del Hidrograma del Río Querétaro.* (pp. 13-19). https://www.researchgate.net/publication/335432742_Interacciones_entre_agua_subterranea_y_agua_superficial_analisis_del_hidrograma_del_rio_Queretaro#fullTextFileContent

Noguéz Dávila, L. M. (2007). *La Formación Social Del Ejido de Tlacote el Bajo, Querétaro: Disputas entre Ejidatarios y no Ejidatarios, Pasado y Presente.* (Thesis). Universidad Autónoma de Querétaro, Facultad de Filosofía. [Photographs]. Retrieved from http://filosofia.uaq.mx/nugahu /fils/ant0010.pdf

Noguéz Dávila, L. M. (2012). *La Formación Social Del Ejido de Tlacote el Bajo, Querétaro: Disputas entre Ejidatarios y no Ejidatarios, Pasado y Presente.* (Thesis). Universidad Autónoma de Querétaro, Facultad de Filosofía. http://filosofia.uaq.mx/nugahu/fils/ant0010.pdf

Ochoa-González, G. H., Carreón-Freyre, D., Cerca, M., & López-Martínez, M. (2015). *Assessment of groundwater flow in volcanic faulted areas. A study case in Querétaro, Mexico. Geofísica Internacional*, *54*(3), 199–220. https://doi.org/10.1016/j.gi.2015.04.016

Ochoa-Gonzalez, G.H., Carreón-Freyre, D., Franceschini, A., Cerca, M. & Teatini, P. (2018). *Overexploitation of groundwater resources in the faulted basin* *of Querétaro, Mexico: A 3D deformation and stress analysis. Engineering Geology.* (pp. 192- 206). Querétaro, QRO: El Sevier.

*ONU-Habitat. (2018). IMPLAN QUERÉTARO *Q500, Estrategia de Territorialización del Índice de Prosperidad Urbana en Querétaro.* Retrieved from http://implanqueretaro.gob.mx/im/q500/5/1/Q500-VersionCompleta.pdf

Pacheco-Martínez, J., Hernandez-Marín, M., Burbey, T.J., Gonzalez-Cervantes,N., Ortíz-Lozano, J. A., Zermeno-De-Leon, M. E. & Solis Pinto, M. E. (2013). *Land subsidence and ground failure associated with groundwater exploitation in the Aguascalientes Valley, Mexico, Eng. Geol.*, 164, 172–186.

Perrusquía, G. (2003). *Sistemas Acuáticos Sustentables: Estudio para la ciudad de Querétaro y sus alrededores, proyecto de sabático octubre 2002 - marzo 2003.* Chalmers University of Technology, Sweden & CONCYTEQ. http://www.concyteq.edu.mx/concyteq//uploads/publicacionArchivo/2017-06-222.pdf

Programa de las Naciones Unidas para el Desarrollo (PNUD), Instituto Queretano de la Mujer (IQM), & Comisión Estatal de Agua (CEA). (2011). *Estudio de la situación del agua desde el enfoque de género en el Estado de Querétaro.* Gobierno de México. http://cedoc.inmujeres.gob.mx/ftpg/Qro/QRO_META_14_ESTUDIO_AGUA_2011.pdf

Sanders, L. L. (1998). *A Manual of Field Hydrogeology* (1st ed.). Prentice Hall.

*Soria, K. Y., Palacios, M. R., & Morales Gómez, C. A. (2020). Governance and policy limitations for sustainable urban land planning. The case of Mexico. *Journal of Environmental Management*, *259*, 109575. https://doi.org/10.1016/j.jenvman.2019.109575

Suárez Cortéz, B. (1998). *Historia de los usos del agua en México: Oligarquías, empresas, y ayuntamientos (1840-1940).* Comisión Nacional de Agua, Centro de Investigaciones y Estudios Superiores en Antropología Social, Instituto Mexicano de Tecnología del Agua. Retrieved from https://books.google.com/books?id=Y4ZjLCk5im8C&pg=PA27&lpg=PA27&dq=manantial+de+agua+tlacote+el+bajo+queretaro&source=bl&ots=W9ZpuKCrEs&sig=ACfU3U2i9QoT5hfZBLLlaRgtZ_8te5Adw&hl=en&sa=X&ved=2ahUKEwje8e_vwLboAhXQCTQIHQysCjIQ6AEwCnoECAkQAQ#v=onepage&q=manantial%20de%20agua%20tlacote%20el%20bajo%20queretaro&f=false.

*SUEZ. (2019). *Estudio Geohidrológico Acuífero Valle de Querétaro* (pp. 1–57). Querétaro, QRO: SUEZ.

*United Nations Development Programme (UNDP). (2011). *Practitioner's Guide: Capacity Development for Environmental Sustainability*. https://sustainabledevelopment.un.org/content/documents/954017_UNDP_Practitioner_Guide_CD%20for%20Sustainability.pdf

University of California Santa Cruz (UCSC). (2005). Unit 2.1 - Soils and Soil Physical Properties. In A. Miles & M. Brown (Eds.), *Teaching Organic Farming and Gardening* (pp. 1–46). University of California Santa Cruz: Center for Agroecology & Sustainable Food Systems. https://casfs.ucsc.edu/documents/Teaching%20Organic%20Farming/TOFG_complete.pdf

U.S. Geological Survey (USGS). (2016). *NATURAL PROCESSES OF GROUND-WATER AND SURFACE-WATER INTERACTION: The Hydrologic Cycle and Interactions of Groundwater and Surface Water*. Groundwater and Surface Water A Single Resource--USGS Circular 1139. https://pubs.usgs.gov/circ/circ1139/htdocs/natural_processes_of_ground.htm

U.S. Geological Survey (USGS). (2018a). *Aquifers and Groundwater*. https://www.usgs.gov/special-topic/water-science-school/science/aquifers-and-groundwater?qt-science_center_objects=0#qt-science_center_objects

U.S. Geological Survey (USGS). (2018b). *Surface-Water and Groundwater Interaction Science in Texas - Overview*. Texas Water Science Center. https://www.usgs.gov/centers/tx-water/science/surface-water-and-groundwater-interaction-science-texas-overview?qt-science_center_objects=0#qt-science_center_objects

U.S. Geological Survey (USGS). (2019). *Springs and the Water Cycle*. https://www.usgs.gov/special-topic/water-science school/science/springs-and-water-cycle?qt-science_center_objects=0#qt-science_center_objects

*Villa Alvarado, C. J., Delgadillo-Ruiz, E., Mastachi-Loza, C. A., González-Sosa, E., & Norma Maricela, R. S. (2014). *A Physically Based Runoff Model Analysis of the Querétaro River Basin. Journal of Applied Mathematics*, *2014*, 1–12. https://doi.org/10.1155/2014/586872

* *Refer to Appendix B for permission to republish copyrighted material*
** *Refer to Appendix C for permission letters to republish copyrighted material*

Appendix A: Copyright Permission for Figures 1 & 2

Three images in this report are from Wikipedia Commons. They are all public domain or licensed for reuse under Creative Commons license 3.0. Image labels and coloring were modified by the author using photo editing software on photopea.com. Please see below for full citation and attribution information.

Figure 1. Battroid. (2010). *Querétaro Localidades.svg* [Map]. Licensed under Creative Commons Attribution-Share Alike 3.0 Unported policy. https://commons.wikimedia.org/wiki/File: Queretaro_localidades.svg. Accessed September 27, 2020.

Figure 1. Wikipedia Commons - File: México Querétaro Location map.svg". (2010) [image] Licensed under Public Domain via Wikimedia Commons. https://en.wikipedia.org/wiki/Quer%C3%A9taro_City#/media/File: Mexico_Queretaro_location_map.svg. Accessed September 26, 2020.

Figure 2. Wikipedia Commons - File: México Querétaro Location map.svg". (2010) [image] Licensed under Public Domain via Wikimedia Commons. https://en.wikipedia.org/wiki/Quer%C3%A9taro_City#/media/File: Mexico_Queretaro_location_map.svg. Accessed September 26, 2020.

Appendix B: Permission for Republishing Copyrighted Material

Copyright © Organización Editorial Mexicana (Martínez, 2019)
The user may access, review and use, where appropriate, the content of the website. Unless otherwise provided, the user may make copies of the unrestricted content for this purpose from the website, with the understanding and acceptance that these will be exclusively for their personal and direct use, without any profit or commercial speculation.

Copyright © Google LLC
All uses of Google Maps and Google Earth content must provide attribution to both Google and our data providers. Image © 2020 Maxar Technologies, Map Data © 2020 INEGI.

Copyright © (Groenendyk et al., 2015)
This is an open access article, free of all copyright, and may be freely reproduced, distributed, transmitted, modified, built upon, or otherwise used by anyone for any lawful purpose. The work is made available under the Creative Commons CC0 public domain dedication.

Copyright © Elsevier (Soria et al., 2020)
This Agreement (License # 4945100413114) between Michigan Technological University -- Kelsey Kirkland (Author) and Elsevier Journal of Environmental Management consists of the permission for use of Figure 7b. by the terms and conditions provided by Elsevier and Copyright Clearance Center.

Copyright © (Villa Alvarado et al., 2014)
This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Appendix C: Permission Letters for Republishing Copyrighted Material

Approval for use of Figure 2 adapted from Mesa et al. (2016)

IWA PUBLISHING
the international water association

Republic – Export Building
1st Floor, 2 Clove Crescent
London, E14 2BE
United Kingdom
Tel: +44 (0)20 7654 5500
Fax: +44 (0)20 7654 5555
Email:
publications@iwap.co.uk
www.iwaponline.com

Kelsey Kirkland
Michigan Technological University
1400 Townsend Drive
Houghton
MI 49931
USA

Thursday, December 03, 2020

Dear Kelsey Kirkland,

Permissions request relating to material published in *Water Policy:*

In response to your request to reuse Figure 1 from the following paper to be used in your Master's report

> Aníbal Mesa, Hugo Luna-Soria and José Luis Castilla 2016 Water and modernization styles: measuring territorial knowledge based on water management policies in Santiago de Querétaro (Mexico) *Water Policy* **18**(6) 1473-1489.

We are very happy to grant you permission to reproduce the material specified above without charge, provided that:

- the material to be used has appeared in our publication without credit or acknowledgement to another source;
- suitable acknowledgement to the source is given in accordance with standard editorial practice, e.g., "Reproduced from A. Mesa et al. *Water Policy* vol 18, issue 6, pp 1473-1489 (2016) with permission from the copyright holders, IWA Publishing".
- reproduction of this material is confined to the purpose for which this permission is given.

I trust this permission will be satisfactory; if any point needs clarification or you have any further queries, please do not hesitate to contact us again.

Yours sincerely
[redacted]

Michelle Herbert
Managing Editor
IWA Publishing

Permission letter and approval for use of Figure 3 adapted from Aguirre-Díaz et al. (2012)

November 9th, 2020

Dr. Gerardo J. Aguirre Díaz
Centro de Geociencias, UNAM
Campus Juriquilla, Querétaro
Tel +52 442 2381116 Ext. 107
ger@geociencias.unam.mx

Estimado Doctor,

Soy Lic. Kelsey Kirkland y estoy realizando un reporte de maestría en la Universidad Tecnológica de Michigan titulado "La sobreexplotación del acuífero del Valle de Querétaro y su impacto en las pequeñas comunidades periurbanas". Quisiera preguntarle si sería possible tener permiso para republicar en mi reporte el mapa de ubicación que se encuentra en la Figura 2. de lo siguiente:

Aguirre-Díaz, G. J., Ramón Zúñiga-Dávila Madrid, F., Pacheco-Alvarado, F. J., Guzmán-Speziale, M. y Nieto-Obregón, J. (2012). EL GRABEN DE QUERÉTARO, MÉXICO: OBSERVACIONES DE FALLAMIENTO ACTIVO. Unidad de Investigación de Ciencias de la Tierra, campus UNAM-Juriquilla, por el Instituto de Geología, UNAM. https://www.ugm.org.mx/publicaciones/geos/pdf/geos00-1/Aguirre-Diaz00-1.pdf.

Figura 2. Mapa estructural que muestra la ubicación del graben de Querétaro y de los sistemas de fallas que se intersectan en esta zonaformando un arreglo ortogonal de horsts, grabens y semigrabens.

El permiso solicitado se extiende a futuras revisiones y ediciones de mi reporte, incluidos los derechos mundiales no exclusivos en todos los idiomas, y a la posible publicación de mi disertación por ProQuest a través de su negocio de publicación de disertaciones ProQuest®. ProQuest puede producir y vender copias de mi disertación a pedido y puede hacer que mi disertación esté disponible para su descarga gratuita de Internet a mi solicitud. Estos derechos no restringirán de ninguna manera la reedición del material en cualquier otra forma por usted o por otras personas autorizadas por usted. Su firma de esta carta también confirmará que posee los derechos de autor del material descrito anteriormente.

Si estos arreglos cumplen con su aprobación, confirme por correo electrónico. Muchas gracias.

Sinceramente,

Kelsey Kirkland
Kelsey A. Kirkland

PERMISSION GRANTED FOR THE USE REQUESTED ABOVE BY EMAIL:
By: Dr. Gerardo J. Aguirre Díaz (Centro de Geociencias, UNAM)
Title: Use of Figure 2. from *EL GRABEN DE QUERÉTARO, MÉXICO: OBSERVACIONES DE FALLAMIENTO ACTIVO*.
Date: November 10, 2020

Gerardo Aguirre Diaz 6:09 AM Hide GD

Re: Permiso para el uso de la Figura 2. del "Graben de Querétaro, México. Observaciones de fallamiento activo"

To: Kelsey Kirkland

Estimada Kelsey Kirkland,

Claro. Puedes usar esa figura y cualquier otra de mis publicaciones sobre el tema, mientras le des crédito del autor en el pie de la figura, como se acostumbra (Autor y año).

Saludos

See More from Kelsey Kirkland

--
Gerardo J Aguirre Díaz
Centro de Geociencias, UNAM
Campus Juriquilla, Querétaro
Tel +52 442 2381116 Ext. 107
Email ger@geociencias.unam.mx
website http://www.geociencias.unam.mx/geociencias/areas/geologia/aguirre.html
Researchgate https://www.researchgate.net/profile/Gerardo_Aguirre-Diaz

Approval for use of Figures 7a. & 8 adapted from ONU-Habitat (2018)

UN HABITAT
FOR A BETTER URBAN FUTURE

A better quality of life for all in an urbanizing world

REFERENCE: CMU/18/11/2020/cgVM

18 November 2020

Dear Kelsey A. Kirkland,

RE: Permission to use maps from the Estrategia de Territorialización del Índice de Prosperidad Urbana en Querétaro report

This refers to your email request of 13 November 2020 to use the maps listed below from the publication the Estrategia de Territorialización del Índice de Prosperidad Urbana en Querétaro:

- Mapa 53 Déficit en la recarga de acuíferos on page 151; and
- Mapa 54 Alta permeabilidad y recarga potencial on page 151

In keeping with UN-Habitat's overarching goal to share information in its publications and reports widely, I hereby authorize Kelsey A. Kirkland to reproduce the Mapa 53 and Mapa 54 in the masters' report whose title "The Overexploitation of the Valle de Querétaro Aquifer and Its Impact in Small Peri-Urban Communities" and all subsequent editions of this work and all revisions, versions, derivative works, translations, ancillaries, adaptations, supplementary materials, custom editions, and in advertising and promotion thereof, in all languages, in all formats and media now known or hereafter developed, throughout the world and in perpetuity.

We appreciate that with the appropriate citing of these maps, as illustrated in the below, you acknowledge that UN-Habitat is the copyright holder of this data and will not distort, mutilate or take other derogatory action in relation to the data which would be prejudicial to the honor or reputation of UN-Habitat.

Intext citing – UN-Habitat (2018)
List of References: UN-Habitat. (2018) Estrategia de Territorialización del Índice de Prosperidad Urbana en Querétaro, UN-Habitat Mexico, Mexico

I thank you for choosing to use the information from this report and hope you find other UN-Habitat reports just as useful in your research.

Yours sincerely,

[redacted]

Victor Mgendi,
Head, Production Unit
Communication and Media Unit
UN-Habitat

Kelsey A. Kirkland
Michigan Technological University

UNITED NATIONS HUMAN SETTLEMENTS PROGRAMME
P.O. Box 30030, Nairobi 00100, Kenya

unhabitat-info@un.org
www.unhabitat.org

@UNHABITAT

Appendix D: Elevation Profile

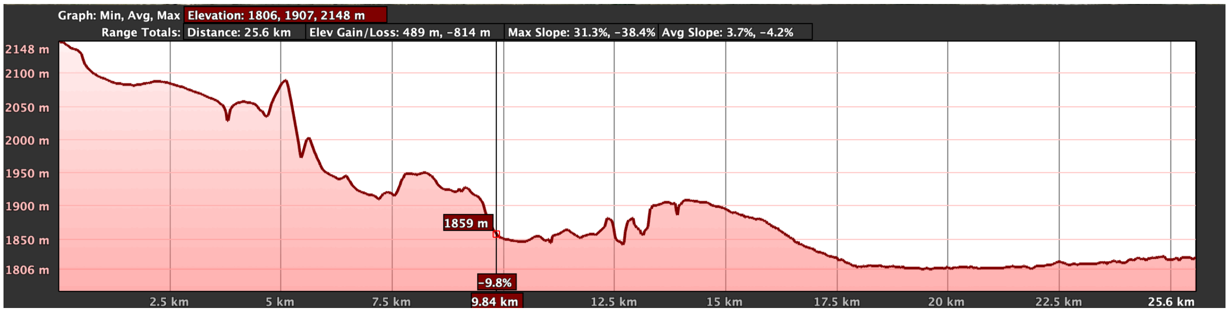


Figure D Los Tajos, Querétaro, México elevation profile (Google Earth (2018)).

Based on the geology of the study area, it is reasonable to classify Los Tajos as a fault, joint, or fracture spring. The site is composed of highly fractured volcanics and situated in close proximity to the Tlacote Fault. Historically, the spring discharged out of the hillside at roughly 1860 meters above sea level. Based on on Figure D above, the spring was located towards the base of the slope; however, the change in topography upslope and downslope of Los Tajos is such that the water table elevation would have mimicked the topography causing groundwater to daylight and have sufficient pressure at that elevation.