Evaluation of the wastewater reutilization for irrigation in high-water stress regions in Chihuahua, Mexico

Thesis for the degree

Master's in Resource Efficiency in Architecture and Planning (REAP)

by

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Acknowledgments

The preparation of this document has been a gratifying challenge in a year that was already a challenge itself for the world, and that is the reason this research has a great personal significance. I would like to thank my supervisors Professor Wolfgang Dickhaut and Mahmoud Moursy from the HafenCity Universität, who guided and advised me throughout the whole process of investigation.

My gratitude goes as well for Mr. Sören Rüd from the GIZ and based in Bonn, who was my first contact with the organization in December 2019 and showed interest in a cooperation for a master thesis since the first moment. This appreciation is particularly extended to Ms. Bianca Corona, from the WaCCliM technical team based in Mexico, who provided an important support to my research for almost a whole year.

I want to thank additionally to Dr. Mario Olmos from JMAS Chihuahua, Dr. Hernández from IMPLAN Chihuahua, and Mr. Martínez from the Rural Development department of the municipality of Chihuahua, who provided key and reliable data that resulted in the completion of this research.

To my family, supporting and loving me from the distance. To my colleagues and classmates, from whom I have learned greatly during these years. To all the people that were and still are in my life and have made this adventure in Hamburg an exceptional experience.

Cheers.

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Abstract

Mexico is one of the most vulnerable countries to water scarcity and climate change worldwide and is currently facing environmental and political crises due to the lack of this resource's availability in specific regions. In this country, agriculture is one of the strongest economic sectors, as well as one of the main water-consumers.

This document intends to depict the existing situation in Chihuahua City, capital of the state of Chihuahua, in the northern region of Mexico, including its climate context, water situation, wastewater treatment infrastructure, and greenhouse gas emissions from this process. To achieve this goal, the methodology of this project comprises an extensive literature research on climate change, the context of Mexico, and international case studies; communication with organizations and authorities in Chihuahua that provide valuable data and information, and calculations based on literature and on the guidelines of WaCCliM.

As a result, from the technical assessment, biologically treated wastewater represents a major opportunity as an adaptation measure against the effects of climate change in the region. Around 11 million cubic meters of wastewater from Chihuahua's south wastewater treatment plant's effluent are available for reutilization, and this volume represents approximately 400 metric tons of carbon dioxide equivalent in greenhouse gas emissions that can be avoided. As the current operation of reusing treated wastewater is not properly documented, a centralized-to-decentralized alternative to irrigate fields is included in this project.

As the city of Chihuahua already accounts for a proper reutilization infrastructure that transports wastewater to the municipality of Aldama, it is possible to adapt this to irrigate the selected fields. Further improvements of this project include the capacity expansion of the wastewater treatment plant, which will potentially increase the available volume of effluent for irrigation, and energy efficiency measures that contribute to the decrease of the treatment plant's carbon footprint.

Research questions and methodology

This research takes place on a context of water scarcity in Mexico, particularly in the state of Chihuahua, a region classified as vulnerable to climate change. To assess the environmental impact of reusing wastewater in agriculture, one of the most water-intensive sectors globally, the following research questions were formulated:

Main research questions

1. **How should the current wastewater operation in Chihuahua be adapted to reuse wastewater in agriculture?**

2. **What are the effects of reusing municipal wastewater for agriculture on the greenhouse gas emissions of Chihuahua?**

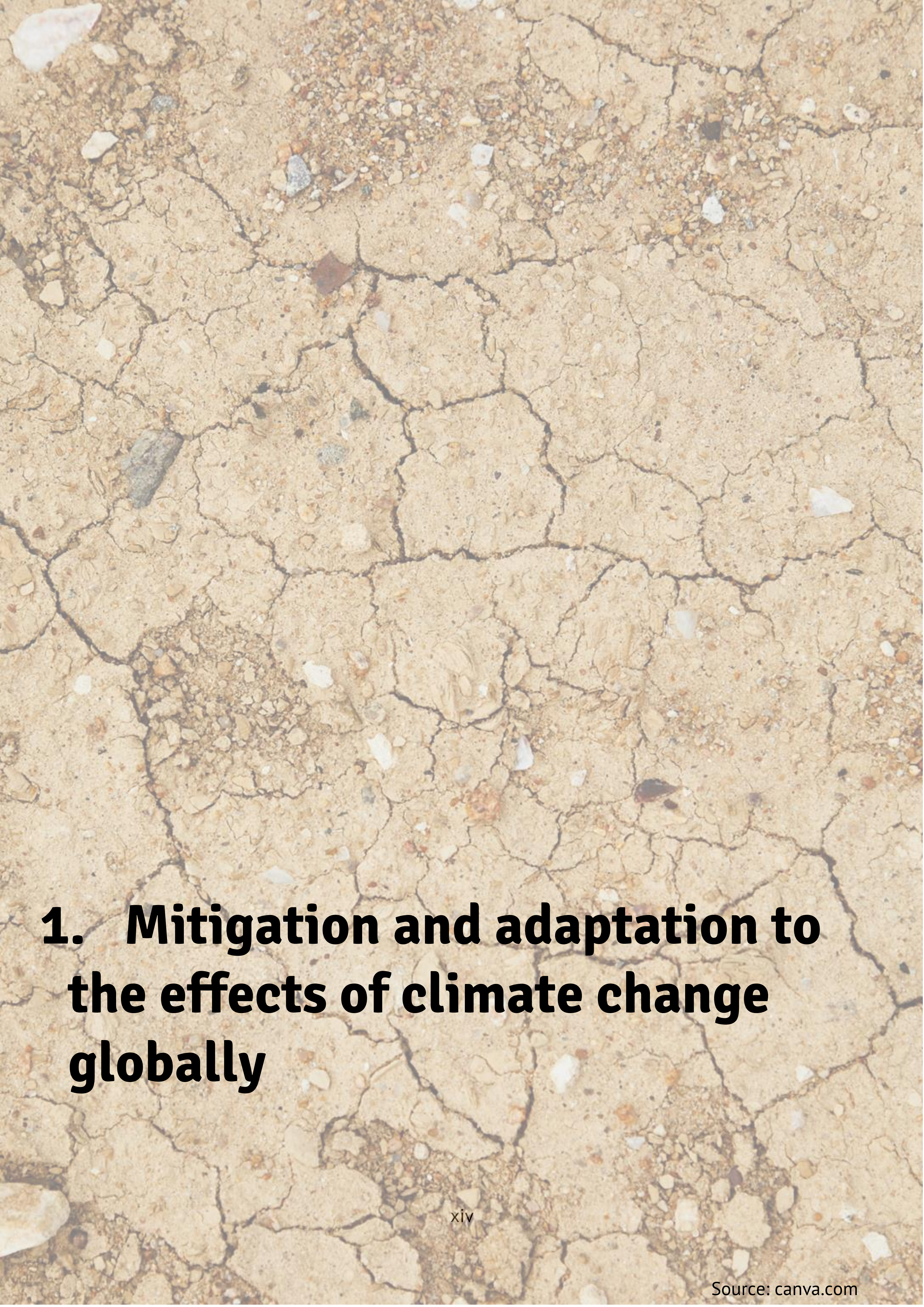
Complementary question

3. **How technically feasible is implementing decentralized water solutions in the state of Chihuahua?**

The methodology of this project consists mainly of an extensive literature research on climate change, the Mexican context, state of art of irrigation technologies, and case studies globally. It is intended that the data retrieval and information on the status quo of the agriculture and wastewater sectors in Chihuahua takes place through establishing contact with authorities and key stakeholders in this city. With this data, the implementation of analysis tools, as well as software and technical assessments, is set to be crucial for the conclusions of this documentation.

The COVID-19 pandemic affected greatly this research, as on-site observations could not take place due to travel restrictions and general lockdown measures in Germany, and in Mexico.

The raw operational data of the South wastewater treatment plant of Chihuahua was provided in confidential terms by the JMAS Chihuahua. A summary and annual averages can be found in the annexes. Nevertheless, if further consultations are to be made, it is possible to consult this data in the complementary files of this document (in the original language), or request them directly to the author (diego.robles08@gmail.com)



1. Mitigation and adaptation to the effects of climate change globally

Source: canva.com

1.1. Climate change definitions

Climate change is understood as the variations on the climate worldwide that are attributable to anthropogenic activities, directly or indirectly, having an impact on the chemical and physical properties of the atmosphere globally (Food and Agriculture Organization, 2014). Human-related activities are widely associated with the generation of greenhouse gas emissions, of which three can be highlighted as the most common: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Pachauri & Mayer, 2015). Other chemical gases are considered to contribute to the greenhouse effect, and which are mostly generated in industrial processes, such as the hydrofluorocarbon family (HFC), sulfur hexafluoride, and the perfluoromethyl family (University of Michigan, 2020). Although considerably lower concentrations of these gases are emitted compared to the three main greenhouse gases (CO_2, NH_4, and N_2O), these usually account for a significant higher global warming potential in 100 years, implying that their overall impact in the atmosphere during this timeframe is potentially higher (University of Michigan, 2020).

Greenhouse gases are produced from naturally sources as well: wetlands, forest fires, oceans, earth-related activity, volcanoes, and animals are some of the natural systems responsible of emitting these compounds, however as of 2016, around 55.5 percent of the global greenhouse gas emissions are attributed to anthropogenic activities (YUE & GAO, 2018). The accelerated development of the industrialization in the last centuries has been a key factor driving the growing amount of greenhouse gas emissions worldwide: the supply of heat and electricity account for approximately one third of the global greenhouse gas emissions as of 2016 (World Resources Institute, 2020a). Other two important sectors in the global context, such as transportation and agriculture (including livestock and crop cultivation) held the 15 percent and 12 percent of the emissions globally, as of the same year (World Resources Institute, 2020a).

As climate change has been a growing concern globally for governments, organizations, and population in general, initiatives and conventions have taken place to address the problematic and make collective and individual commitments to adapt or mitigate the effects of this phenomenon. The Paris Agreement took place in the context of the United Nations Framework Convention on Climate Change in 2016, when 195 signatories agreed to find and deploy efforts to address climate change, and to keep the global temperature rise below two degrees Celsius (United Nations Framework Convention on Climate Change, n.d.b). Signatory states are set to keep track and report the status of their climate-oriented national determined contributions (NDCs) every five years (United Nations Framework Convention on Climate Change, n.d.b).

1.2. Impacts of climate change

1.2.1. Global temperature increase

One of the main effects of climate change globally is the increase in the average surface temperature worldwide. Considering a long-term (100 years, between 1901 and 2000) average global temperature, significant anomalies have been recorded, particularly in the period comprised between 1990 and 2019 (National Oceanic and Atmospheric Administration, 2020). The second-warmest year recorded so far was 2019, when the global surface (including land and ocean) average temperature was registered as around 0.95 degrees Celsius higher than the reference period (National Oceanic and Atmospheric Administration, 2020). The five warmest years recorded since 1880 have all taken place between 2015 and 2019 (National Oceanic and Atmospheric Administration, 2020), in a clear year-to-year rising tendency.

A direct correlation between carbon dioxide concentration in the atmosphere and the rise of global temperatures can be inferred from historical data: by the approximate end date of the industrial revolution, around 1840, the concentration of carbon dioxide in the atmosphere stood at approximately 280 parts per million, and by 2018 this figure reached around 408.5 parts per million, in a clear, unprecedented disturbance of the atmospheric cycle (Our World in Data, n.d.).

Different scenarios have been established to predict the variation in temperatures worldwide as a function of the greenhouse gas emissions and land use behavior (Pachauri & Mayer, 2015). In an optimistic scenario, where climate change adaptation and mitigation measures have taken place, and the temperature rise globally was kept down below two degrees Celsius, the expected global temperature increase might range between 0.3 and 1.7 degrees Celsius, compared to the period between 1986 and 2005 (Pachauri & Mayer, 2015).

The rise of temperatures worldwide is projected to impact ecosystems and living creatures, as well as affecting the global economic and social spheres. The regions of the world with higher projected temperature variations are set to experiment droughts and heat waves, which will directly influence one of the most important human activities: agriculture (Environmental Protection Agency, n.d.). The occurrence of these extreme weather events is expected to jeopardize the agriculture and food supply: population growth, changes in precipitation patterns, erosion, and reduction of water availability are some of the drivers of a potential agricultural productivity worldwide (Environmental Protection Agency, n.d.).

1.2.2. Ocean level rise

Climate change has a direct incidence in the rise of the ocean level. Increasing temperature in the ocean surface (thermal expansion), and an increased melting rate of land-based ice, such as glaciers and ice sheets, are the main factors driving the sea level rise globally (National Oceanic and Atmospheric Administration, 2019).

The phenomenon of sea level rise has been approached and modelled by different studies worldwide, and the common trend is that, since the year 1900, when the first calculation were made, the level of the ocean has continuously increased (Carbon Brief, 2019). For this purpose, a reference value was set considered an average sea level between 1992 and 2006: in 1900, the average ocean level was between 130 and 170 millimeters below the reference value, while by 2015, this variation increased considerably, reaching almost 50 millimeters above the reference period (Carbon Brief, 2019), meaning an overall average sea level variation of around 200 millimeters in a period of 115 years.

For some regions, continuous sea level rise might represent a threat to several industries and sectors, such as transportation, agriculture, and key infrastructure such as roads, water supply and energy generation (National Oceanic and Atmospheric Administration, 2019).

1.2.3. Migration

One of the main effects of the alterations in the global climate is the displacement of humans from regions that are jeopardized by extreme events or variations in meteorological patterns, such as shoreline erosion, coastal flooding, and agricultural disruption (International Organization for Migration, 2008). By 2050, it is expected that around 200 million people will make the decision of leaving their place of residency due to climate change (International Organization for Migration, 2008).

Climate migration is expected to create political and ethnical instability worldwide, as population will seek to leave potentially arid areas to survive (International Organization for Migration, 2008). In this context, the concept of “environmental refugee” has taken more relevance in the past few years: an environmentally-displaced person, or environmental refugee as expressed commonly in the media, is a “person subject to forced migration as a result of sudden, drastic environmental changes” (European Commission, n.d.).

In 2009, the number of environmentally-displaced people amounted to approximately 16.7 million, while in 2019, this figure stood at almost 25 million, while during this period the daily amount of climate migrants ranged between these values, peaking in 2010 at over 42 million people (Internal Displacement Monitoring Centre, 2020). This tendency indicates that, while extreme weather events occur more frequently, the cumulative population displaced is expected to reach critical levels in the following years.

1.3. Vulnerability and exposure to climate change

The Intergovernmental Panel on Climate Change (IPCC) defines vulnerability to climate change as “the degree to a which a person, an area, or a system is affected by climate changes and the extent to which the affected can deal with those impacts”

(Umweltbundesamt, 2019), and a parallel concept, the exposure to climate change, which refers to "the inventory of elements in an area in which hazard events may occur" (Cardona et al., 2012). Although both concepts are similar, they are not overlapped: a specific region might present a climate change exposure, but not being considered vulnerable, which means that alterations in climate are set to take place in an specific area, but this location might present enough resources to modify the existent infrastructure, to mitigate potential losses (Cardona et al., 2012).

The vulnerability and exposure to climate change are present in the environmental, social, and physical dimensions. Physical exposure to climate change is a function of the specific geography, location or place where the analysis takes place (Cardona et al., 2012). In this context, urban and rural areas experiment vulnerability to climate affects in similar ways, but while urban settlements are complex systems with a rapidly growing population, rural regions' vulnerability is driven by its resources availability and the potential social effect in its population (Cardona et al., 2012).

In the rural environment context, it is frequent that climate events have a direct incidence in agriculture (Cardona et al., 2012). The conditions under which this activity is developed globally makes it considerably vulnerable to extreme weather events, such as El Niño phenomenon, which brings extreme drought events, economic and productive losses (Food and Agriculture Organization, 2014). In addition to droughts, the effect of climate change on the amount of rainfall in specific regions is set to alter the hydrological cycle, particularly groundwater infiltration and evapotranspiration, thus the availability of water for irrigation is expected to decrease considerably (Food and Agriculture Organization, 2014).

1.4. Climate change mitigation and adaptation

In the context of climate change-vulnerable and exposed regions, a response to these effects is of considerable importance for humankind and the world as it is known. It is, in fact, an intrinsic feature of living beings to adapt and respond to situations that represent a hazard and jeopardize life.

Practices and initiatives considered in the adaptation to climate change are designed to adjust the existent situation globally to a new context determined by more frequent and intense weather events, and a jeopardized food supply (National Aeronautics and Space Administration, n.d.). National and local governments are key stakeholders in the process of adaptation to climate change, and in the last years, several strategic and planning instruments have been released to address this situation (Intergovernmental Panel on Climate Change, n.d.). Nevertheless, a top-down approach for climate initiatives is compatible with a bottom-up concept, as an increasing number of local leaders and communities have developed climate change adaptation strategies in developed and developing countries, although, in some cases, structural problems in each country or region represent an obstacle of this approach (Intergovernmental Panel on Climate Change, n.d.).

In this sense, adaptation measures require a precise coordination between key stakeholders, and detailed instruments that provide enough information on how to proceed in different circumstances. In the context of agriculture, adaptive measures might include the diversification of crops, in order to avoid the reliance on a single species, introducing programs protecting vulnerable social groups –especially those whose income depends entirely on agriculture-, or deploying financial instruments to decrease the impact of crop losses (Food and Agriculture Organization, 2012).

The term mitigation refers to the identification of the specific causes and sources driving the phenomenon of climate change globally. In the case of agriculture, and as described in previous sections, an important share of the global greenhouse gases emissions is sourced by this sector worldwide. In this sense, mitigation strategies addressing the emission of greenhouse gases from agriculture include specific actions to decrease, remove or treat these emissions (Food and Agriculture Organization, 2012).

In addition to the environmental, political and economic factors playing a role in the adaption and mitigation of climate change, education and awareness on climate change are critical factors in developing sustainable and environmentally friendly practices. (Denton et al., 2014). In this sense, as of 2020, roughly 16 percent of the global population considered climate change their main concern, among other structural problems, such as healthcare, education, employment, or crime (IPSOS, 2020). According to this survey, most of the climate change-concerned population resides in Australia, Germany, or Canada, while on the other side of the extreme, adults in countries such as Turkey, Argentina, or Mexico find different topics more pressing and urgent than climate change (IPSOS, 2020).

1.5. Water stress

As defined by the European Environmental Agency (European Environmental Agency, n.d.), water stress is caused by a high demand of this resource, that exceeds its availability during specific periods of time, or when its consumption is not possible ‘due to poor quality. This phenomenon drives the qualitative and quantitative deterioration of freshwater bodies (European Environmental Agency, n.d.).

One of the factors driving water stress in certain regions worldwide is the excessive consumption from industries, municipalities, and irrigated agriculture (World Resources Institute, 2019). According to the work summarized in the Aqueduct portal from the World Resources Institute (World Resources Institute, 2019), 17 countries (which account approximately for one quarter of the global population reside) face a situation where the three previously mentioned sectors withdraw over 80 percent of the available freshwater supply each year, and as a consequence are classified with an extremely high level of baseline water stress, while 44 countries worldwide account for an, at least, high level of water stress.

Figure 1 depicts a world map with countries classified by its level of water stress

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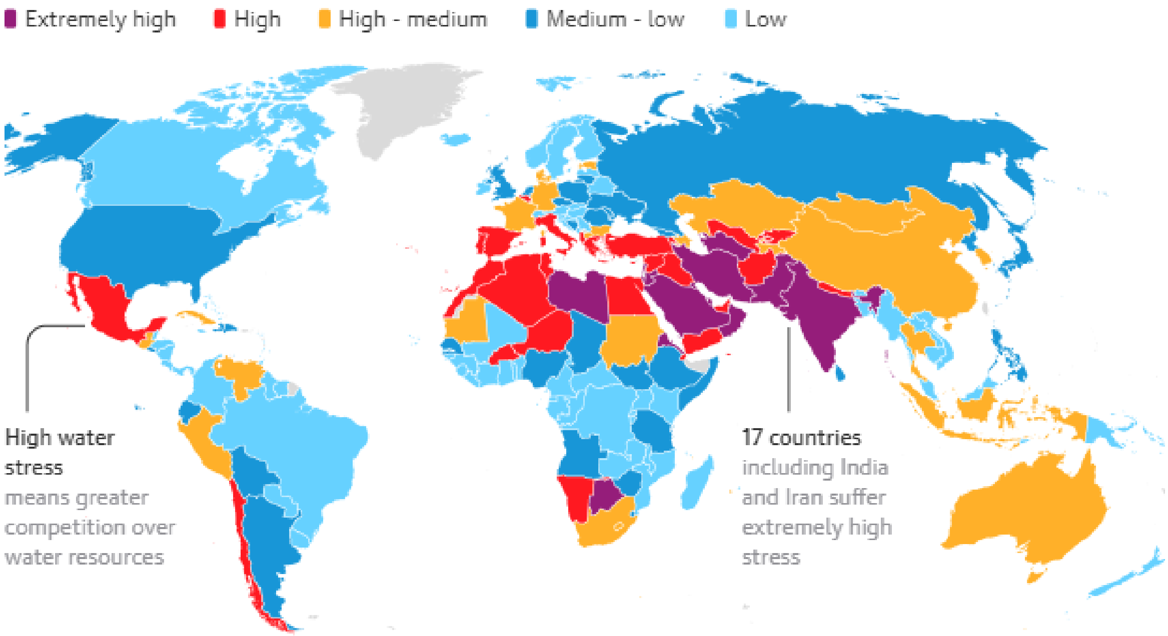


Figure 1. Water stress levels worldwide. (Arreguín-Cortés et al., 2019; Holden & Doshi, 2019; World Resources Institute, 2019, 2020b)

Globally, 17 countries account for an "extremely high" water stress level, most of them located in Asia and the Middle East (Holden & Doshi, 2019), while in the Americas, Mexico and Chile are displayed as the only high-water stress countries in the region. Despite of this, countries in Figure 1 displayed with a low, or medium-low water stress are experiencing difficulties to manage the water resources locally, as is the case of El Salvador, the most populated country in Central America (Lakhani, 2019). According to recent studies, due to the current dynamic of aquifer exploitation, life in El Salvador is expected to be "non-viable" in the following 80 years (EFE, 2016), situation that is aggravated by a context of corruption, violence, and corporate interests, and might derive in a social crisis in the upcoming years (Lakhani, 2019).

The case of Mexico, as one of the most populated countries in the world (World Population Review, 2020), and one of the strongest macroeconomies in Latin America (World Economic Forum, 2014), takes relevance. Among 25-leading countries listed in the Aqueduct portal (World Resources Institute, 2020b) as high-water stress regions, Mexico accounts for the largest water withdrawals per capita (including abstractions for water supply, irrigation, industrial processes, and cooling of electric power plants), at around 703 cubic meters per inhabitant, overcoming the water withdrawal figures from other highly-populated countries, such as China and Brazil (OECD, 2020).

Within Mexico, some regions' water-stress score stood in the "extremely-high" range, particularly the northern and central areas of the country, such as Baja California Sur, Guanajuato, Mexico City, and Chihuahua (El Financiero, 2019; World Resources Institute, 2020a). Figure 2 displays the map of Mexico, divided by federal entity, and their water stress classification according to the baseline adopted by the Aqueduct portal.

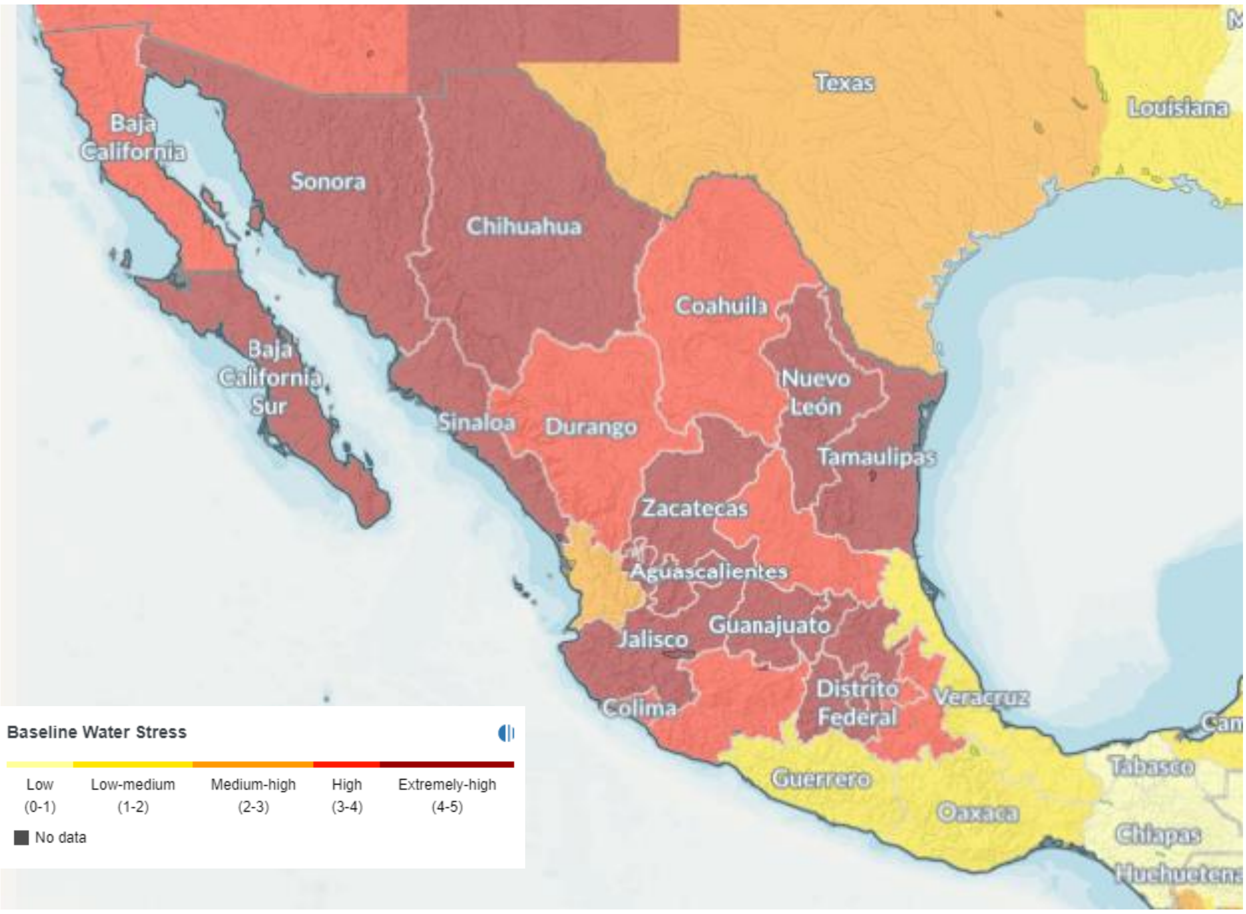


Figure 2. Water stress levels in Mexico, by region (World Resources Institute, 2020b)

1.6. Wastewater

The establishment of human settlements worldwide, and the growth of industrialization consume several resources, thus unavoidably generating solid and liquid waste (Henze & Comeau, 2008). Henze and Comeau (2008) suggest in their study that the generation used water or wastewater, at the household or industry level, likely depends on the lifestyle, the standard of living, and the legal framework surrounding the context.

Around 80 percent of the global wastewater generated is discharged without previous treatment, and this situation takes a critical relevance in a context where almost one third of the population rely on natural water sources (UN-Water, n.d.). In recent decades, wastewater is considered a potential resource to tackle the water scarcity problematic worldwide, by reusing or recycling in different processes after an adequate treatment (UN-Water, n.d.).

A typical (Ajonina, Buzie, Möller, & Otterpohl, 2018) configuration in a wastewater treatment plant is displayed in Figure 3, for the case study of the city of Hamburg.

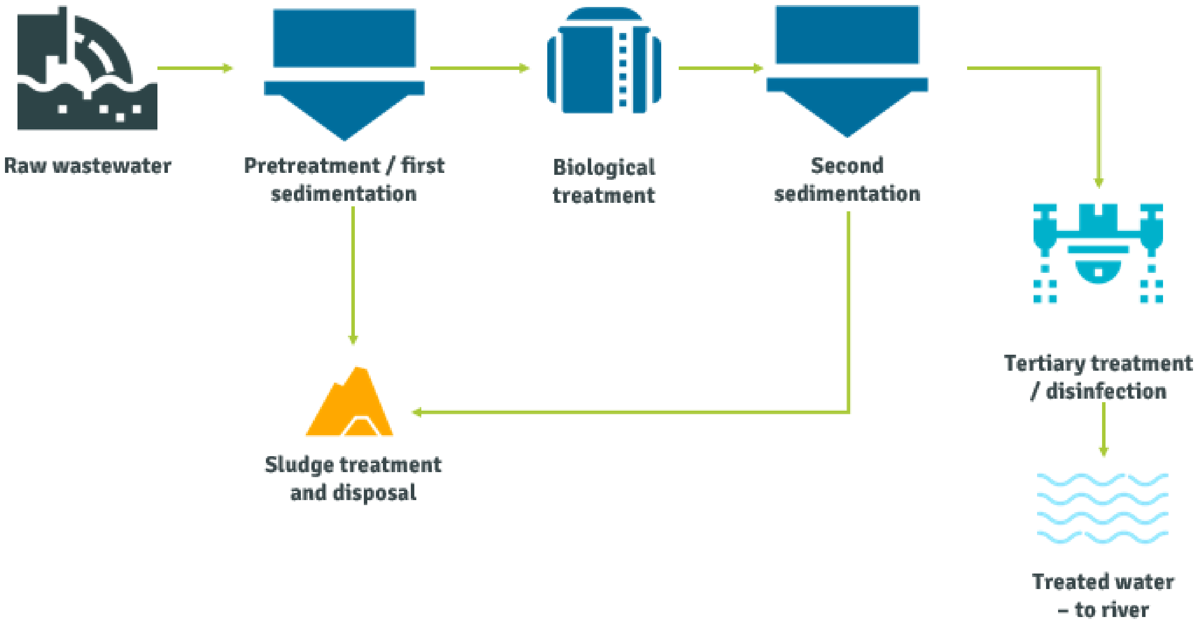


Figure 3. Wastewater treatment scheme for the city of Hamburg (Robles, 2020). Adapted from (Ajonina et al., 2018)

For the purposes of this study, domestic wastewater and its potential reuse applications will be the focus of research. Domestic wastewater accounts for similar characteristics globally, with high concentrations of dissolved organic compounds, such as carbohydrates, lipids, detergents, proteins, and other synthetic products (Pescod, 1992).

Domestic wastewater is generated at the household level, and when it usually is combined and directed to the sewer (Pescod, 1992), it can be classified in four groups: yellow water, sourced by human urine; brown water, generated from human feces and flushed water; black water, which is the combination of brown and yellow water; and grey water, which is sourced by the effluent from kitchens, sinks, bath, shower, and laundry (Hamburg University of Technology, n.d.)

Table 1. Select relevant parameters in domestic wastewater characterization (Robles, 2020). Adapted from (Pescod, 1992)

Physicochemical		Pathogens	Inorganic
Dissolved solids	**pH**	**Enteroviruses**	**Arsenic**
Suspended solids	**Sodium (Na^{2+})**	**Bacteria**	**Cadmium**
Total nitrogen	**Magnesium (Mg)**	**Protozoa**	**Chromium**
Phosphorus (as P)	**Carbonate (CO_3)**	**Helminths**	**Lead**
Alkalinity (as $CaCOP_3$)	**Ammonium (NH_4^+)**		**Mercury**
Sulphate (as SO4)	**Manganese (Mn)**		**Nitrate**
Biochemical oxygen demand (BOD5)	**Zinc (Zn)**		**Selenium**
Chemical oxygen demand (COD)	**Copper (Cu)**		
Total organic carbon	**Chloride (Cl-)**		

The studies of Henze and Comeau (2008) define the chemical oxygen demand (COD) and the biochemical oxygen demand (BOD) as key parameters, as they quantify organic matter, one of the major pollutants in wastewater, thus COD and BOD measure the amount of oxygen that required for the partly oxidation of the organic matter. Differences between both parameters lie analytic procedures, and as experimental trials determined, COD frequently accounts for the double the concentration than the BOD analysis in five days.

Phosphorus and nitrogen are nutrients that are a potential resource for reutilization in different applications, as stated by Zeeman (n.d.), as these compounds play a major role in agriculture as fertilizers, boosting the growth of crops.

According to Pescod (1992), pathogenic organisms represent a major concern when wastewaters are set to be reused in applications that involve contact with humans, particularly agriculture. Nevertheless, as a result of increasing population, water scarcity, and climate change, the use of wastewater as an alternative to the conventional water extraction activities takes relevance (World Health Organization, n.d.)

Table 2. Average wastewater characteristics by selected country. Robles (2020). Adapted from (Dehghani et al., 2018; Garzón-Zúñiga, González Zurita, & García Barrios, 2016; Pons et al., 2004; Revelo, 2016)

Country	COD (mg/L)	BOD5 (mg/L)	Total Suspended Solids (mg/L)	Nitrogen (mg/L)	Phosphorus (mg/L)
El Salvador[1]	450	250	225	67	17
France	634	268	302	52	9.3
Iran[2]	292	41	73	41	2
Mexico[3]	402	143	139	41	9
Netherlands	450	171	237	42	6.7

[1] Average values calculated from the concentration ranges provided by the source (Revelo, 2016).
[2] Case study for the province of Isfahan, Kashan WWTP (Dehghani et al., 2018)
[3] Figures were rounded to the closest whole number (Garzón-Zúñiga et al., 2016).

1.6.1. Greenhouse gas emissions from wastewater

Globally, the generation of waste and wastewater is responsible of around 2.7 of the anthropogenic greenhouse gas emissions (Metz, Davidson, Bosch, Dave, & Meyer, 2007). Where proper sewage and sanitation systems exist, wastewater can be treated in large facilities to discharge it back to the water cycle with acceptable physicochemical parameters, however, in many developed countries, it is recurrent that municipal (particularly slums or irregular settlements) and industrial wastewater are directly discharged into rivers or other water bodies, resulting in high concentrations of organic matter or nutrients (such as nitrogen or phosphorus) in these ecosystems (Bhatt, McDowell, Gardner, & Hartmann, 2014). According to the work of Kim et al. (2019) untreated wastewater discharge onto water bodies in developing countries resulted in a higher biodegradation of organic matter and carbon dioxide emissions, when compared to the emissions generated in conventional wastewater treatment.

On the other hand, the treatment of wastewater generates direct greenhouse gas emissions, intrinsic to the process (through chemical or biological technologies), as well as indirect emissions, mostly associated with the generation of the energy required to operate the plan, and transportation of specific byproducts, such as the sludge generated (Campos et al., 2016).

According to Campos et al (Campos et al., 2016), the technical efforts and investments in wastewater treatment plants had the objective of improving the quality of the effluent, to minimize non-compliances with local or national regulations. Further studies in regards with the performance of conventional wastewater treatment plants indicated that these utilities are an important sources of anthropogenic greenhouse gas emissions (Campos et al., 2016).

Emissions of carbon dioxide are mostly attributed to the biological degradation of the organic matter contained in the wastewater, which is transformed to biomass or released as a gas during the process (Campos et al., 2016), in addition to this, flaring the surplus biogas generated during the anaerobic stages of the treatment is an important source of carbon dioxide to the atmosphere (Campos et al., 2016). Estimates from Daelman et al (2012) indicated that around one percent of the chemical oxygen demand of the inlet wastewater is transformed to methane, mostly attributed to sludge units (thickener, centrifuge, storage) and surplus gas (Yver Kwok et al., 2015). Nitrous oxide, another common greenhouse gas generated in wastewater treatment process, is produced by ammonia-oxidizing and heterotrophic denitrifying bacteria present in the anoxic and aerobic tanks (Tallec, Garnier, Billen, & Gousailles, 2006). Data collected from Campos et al (Campos et al., 2016) suggested that the emissions of nitrous oxide are a result of the conditions under which the treatment plants operated, meaning that it is possible to address the emissions of this gas by modifying the way a plant is operated.

In this context, it is relevant to find alternatives to reduce this environmental impact without compromising the physicochemical parameter of the effluent, or the economic performance of the treatment plants. Additionally, reducing the social and technological gaps to provide a proper sewer and sanitation systems to the largest segments of the population, particularly in developing countries, will decrease the volume of untreated wastewater irregularly discharged onto water bodies.

1.6.2. Wastewater reutilization for agriculture

Around five percent of the global wastewater generated annually (some 7.1 billion cubic meters, or 0.18 percent of the total water consumption) was recycled in agriculture (nearly 50 percent of this amount), or industrial purposes (20 percent of the reused wastewater) (Global Water Intelligence, 2010). Nevertheless, putting this figure in perspective, the amount of recycle wastewater accounts roughly for only one percent of the total water withdrawals for agriculture (Jimenez & Asano, 2008) which represents approximately 525,000 hectares of agricultural land (Winpenny et al., 2010). In this context, China (around 200,000 hectares), Mexico (some 190,000 hectares), and India (nearly 70,000 hectares) were the leading three countries reusing wastewater for agricultural crops worldwide, according to an international survey carried out by Jimenez and Asano (Jimenez & Asano, 2008).

1.6.2.1. Reused wastewater quality

To ensure the expansion of the wastewater reutilization capacity in agriculture for the following years, Ungureanu, et al. (2020) suggest that safe and healthy conditions of wastewater management by the farmers and land workers should be implemented, particularly in regions where there is not a large sanitation coverage in rural areas; nevertheless, treating wastewater chemically or biologically is the “best example of good practice” in this context (Ungureanu et al., 2020). As described in the previous section, wastewater accounts for different properties, and the characterization of these parameters is relevant for the desired purposes of the treated effluent.

According to the research of Ungureanu, et al (Ungureanu et al., 2020), ensuring the physicochemical and microbiological quality of the wastewater is a key factor to preserve the health of the land workers and the crops where this resource is set to bet used. The study of Jeong, et al. (2016) compiles wastewater reutilization for irrigation guidelines and recommendations from several countries and institutions worldwide, including South Korea (Ministry of Environment, 2011), the United States (United States Environmental Protection Agency, 2012), France (Paranychianakis, Salgot, Snyder, &

Angelakis, 2015), Israel (Sustainable Water Integrated Management-Support Mechanism, 2013), the World Health Organization (WHO) (2006), and Mexico was additionally researched through the work of Cisneros and Saucedo (Cisneros & Saucedo, 2016), and whose wastewater characterization guidelines are based on the studies from Ayers and Westcot (1987).

The comparison of selected physicochemical and microbiological parameters for wastewater reuse in irrigation in food crops are displayed in Table A. I of ANNEX I. Each country or institution provide different recommendations regarding the wastewater characterization for its reuse in agriculture: The World Health Organization, for instance, provides guidance in microbiological measures such as coliforms (*E. coli*) (World Health Organization, 2006) and intestinal nematodes (Jeong et al., 2016), however, it is not possible to retrieve recommended values for other parameters from this study. Between countries, there is similarities in the quality requirements of wastewater in terms of total suspended solids, turbidity, and BOD, however, from the surveyed countries, only Israel (Sustainable Water Integrated Management-Support Mechanism, 2013) provided recommendations on the concentration of nitrogen, phosphorus, and chemical oxygen demand.

In addition to the microbiological and physicochemical properties of the wastewater reused for agriculture, the concentration of trace elements, particularly metals and halogens, is a key factor in irrigation with recycled water, as elements such as aluminum and manganese might represent a hazard for crops (Jeong et al., 2016). Nevertheless, studies (Ayers & Westcot, 1985) (Al Omron, El-Maghraby, Nadeem, El-Eter, & Al-Mohani, 2012) suggest that the concentration of heavy metals after the secondary treatment of the wastewater is similar to that in nature, making this resource suitable for its reutilization in agriculture.

A similar comparison of the recommended maximum concentration of selected trace elements across different countries, with the exception of France, and the addition of the Food and Agriculture Organization of the United Nations (FAO) (Ayers & Westcot, 1985) is displayed in Table A. II, of ANNEX I. In the case of the maximum concentration of trace elements allowed in reused wastewater for irrigation, most of the surveyed countries and institutions showed a similar standard, except for Mexico, which is only limiting two of these pollutants.

1.6.2.2. Technologies

The application methods of reusing treated wastewater for irrigation are mentioned in the studies of Pescod (Pescod, 1992), and described by the Food and Agriculture Organization (Food and Agriculture Organization, 2003) in its user's manual for irrigation with treated wastewater. Surface irrigation methods account for around 95 percent of the irrigated area globally, thus, it is the main technology applied in this context, due to its low capital and operational costs, and implementation simplicity (Food and Agriculture Organization, 2003).

In surface irrigation, the transport medium of the water is the soil (Stauffer & Spuhler, 2011), thus, the quality of the soil is directly involved in the infiltration process and use for the crops (Bliesner, Merriam, Clemmens, Burt, & Hardy, 2000).

Table 3. Advantages and disadvantages of surface irrigation. (Robles, 2020). Adapted from (Stauffer & Spuhler, 2011; Walker, 1989)

Surface irrigation	
Advantages	**Disadvantages**
Local irrigators account for a minimum understanding of its operation	**Highly dependent on a good soil quality**
Possible to develop at the farm level with minimum capital investment	**Less efficient than other irrigation methods**
Simple operation and maintenance activities	**Requires well-graded fields**
Low energy requirements (gravity principle)	**Labor-intensive**
Climate conditions and wastewater quality have low impact on the operation	

The main surface irrigation methods are border, basin, and furrow (Food and Agriculture Organization, 2003; Freie Universität Berlin, n.d.e), being basin irrigation the most used of the three, using dykes to prevent runoff, and proved to be an effective method to leach salts from the soil into the groundwater (Stauffer & Spuhler, 2011).

Despite being a popular method for irrigation, according to the research of Walker (Walker, 1989), developing countries face issues implementing this method, particularly regarding the need of precision in soil uniformity, the maintenance of the dykes, and the infeasibility to incorporate modern technology into small areas or basins. Border irrigation is conceived as an expansion of basin irrigation, by adding long rectangular shapes or stripes ranging from six to 30 meters and free draining in the end, thus, the area between the strips is flooded. (Stauffer & Spuhler, 2011; University of California, 2005). Finally, furrow irrigation consists on building small channels following the direction of the water flow, instead of flooding the entire area of interest (Walker, 1989), and are suitable for orchards and vineyards (Bliesner et al., 2000). Walker (1989) suggests that furrow irrigation offers some additional disadvantages compared to the other two methods, regarding salinity sensitivity between the furrows, “limited mobility, and an increased erosion potential". Figure 4 depicts examples of implemented surface irrigation technologies.

a) b) c)

Figure 4. Surface irrigation methods: a) basin, b) furrow, c) border (Freie Universität Berlin, n.d.b; Stauffer & Spuhler, 2011; Walker, 1989)

Sprinkler irrigation is an alternative to surface irrigation that demands more human resources (knowledge and handwork), and capital and operational investments (Freie Universität Berlin, n.d.c; Stauffer & Spuhler, 2012). Table 4 summarizes the advantages and disadvantages of this technology.

Table 4. Advantages and disadvantages of sprinkler irrigation (Robles, 2020). Adapted from (Stauffer & Spuhler, 2012; University of Missouri, n.d.)

Sprinkler irrigation	
Advantages	**Disadvantages**
Requires no terracing	**High energy requirements**
Suitable for most types of soil	**Sensitivity to wind (evaporation losses)**
Low initial capital investment	**High operational costs**
No need of channels or dykes	**Clogging due to sediments**
Independent from the topography of the area	

The studies of Stauffer and Spuhler (2012) suggest that, disregarding the method type for sprinkler irrigation, this technology is suitable for soils with high infiltration rate, and that are not easily clogged by sediments or other type of contamination. In this context, the quality of the water used, particularly wastewater, takes relevance, as mentioned in previous sections regarding the characteristics of treated and untreated wastewater.

The most common sprinkler irrigation methods are: sprinkler heads, center pivot, linear move, travelling big gun, and side roll (Stauffer & Spuhler, 2012). The capital and operational expenses vary depending on the type of technology, as some of these methods involve the need of a motor to carry the structures, or pumps to provide enough water pressure to reach the entire field, thus, requiring additional commodities to make the systems operational (Stauffer & Spuhler, 2012). According to Scherer (Scherer, 2010), the key factors that determine the selection of the appropriate sprinkler irrigation technology are the size, shape and topography of the field, and the availability of time and skilled labor. Figure 5 displays real-life examples of applied sprinkler irrigation technologies.

a) *b)*

Figure 5. Examples of sprinkler irrigation: a) side roll, b) sprinkler heads connected to a pipe (Stauffer & Spuhler, 2011)

Drip and subsurface drip irrigation are technologies with similar principles where water is distributed close to- or below the surface through emitters or tubes (Freie Universität Berlin, n.d.d), allowing an increased precision in the application directly to the roots and requiring less water compared to other methodologies (Stauffer, 2011). Table 5 compiles the advantages and disadvantages of drip and subsurface drip irrigation technologies.

Table 5. Advantages and disadvantages of drip and subsurface drip irrigation (Robles, 2020). Adapted from (University of Missouri, n.d.)

	Drip irrigation	Subsurface drip irrigation
Advantages	Water savings by minimizing vaporization	Low labor intensity
	Reduced nutrient losses from leaching	Suitable for soils with low water retention capacity
	Suitable for irregular fields	Evaporation losses minimized
Disadvantages	High iron content-water causes clogging in emitters	Requires fairly uniform soils
	Intensive maintenance	High salt content in water cannot be used
	Rodents or insects' bites can cause water leaks	Water supply-intensive throughout the season

Commercial drip irrigation systems are usually highly-technical, and involve a complex arrangement of valves, tanks, pipelines, and in case needed, water filters (Freie Universität Berlin, n.d.a; Stauffer, 2011), however, there is currently small-scale and decentralized options that can be applied locally at a household level, with relatively low-cost materials (Resources Centre for Sustainable Development, 2008). According to Stauffer (Stauffer, 2011), if treated wastewater is used for this purposes, it is imperative to install a filter after the treatment and before the irrigation process, to avoid clogging in the distributors. Figure 6 shows a schematic design of a decentralized drip irrigation system.

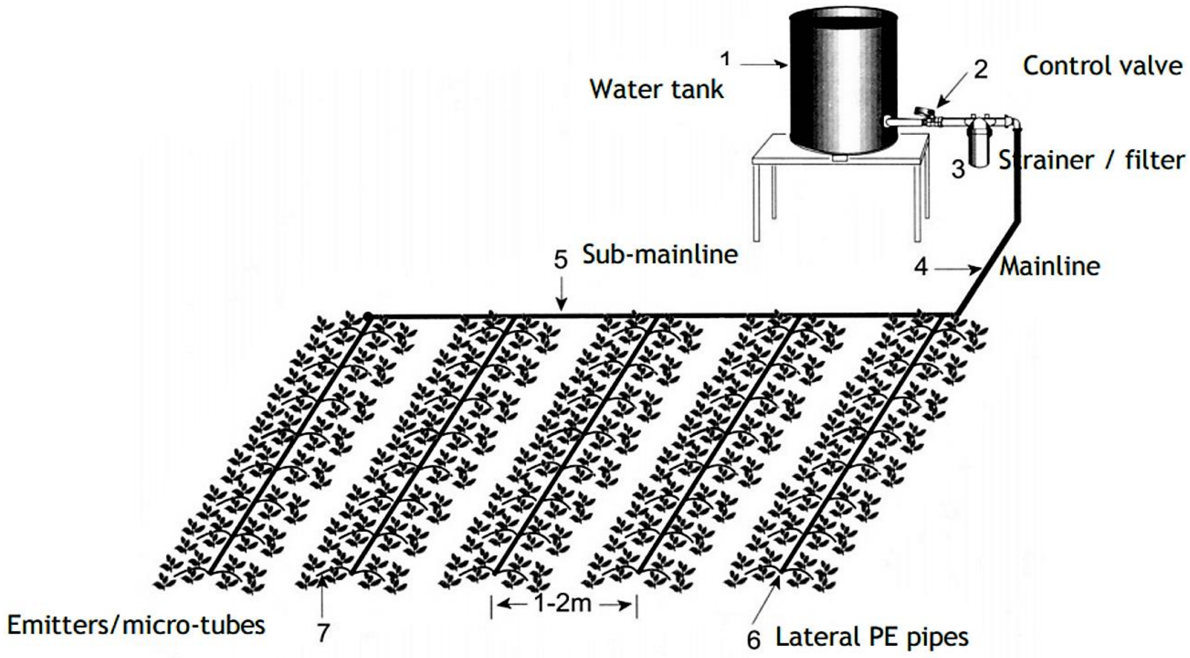


Figure 6. Scheme of a low-cost drip irrigation technology (Resources Centre for Sustainable Development, 2008)

Subsurface irrigation, on the other hand, applies water below the surface, thus the common operational problems from other irrigation methods (such as water losses, crusting or saturation) are eliminated (Stauffer, 2016).

According to Stauffer (2016), a typical subsurface drip irrigation system involves high and automatized technology, and is comprised by a draining pond, valves, filtration units, pipes, and a fertilizer injection unit. Figure 7 shows a layout of a subsurface drip irrigation system.

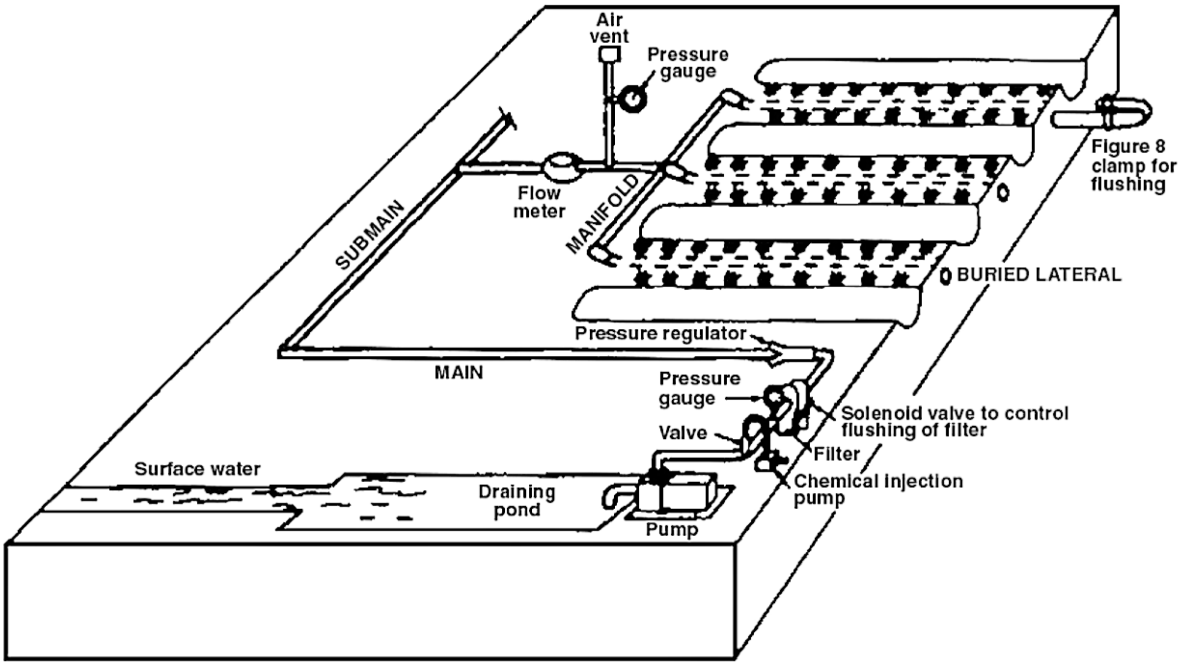
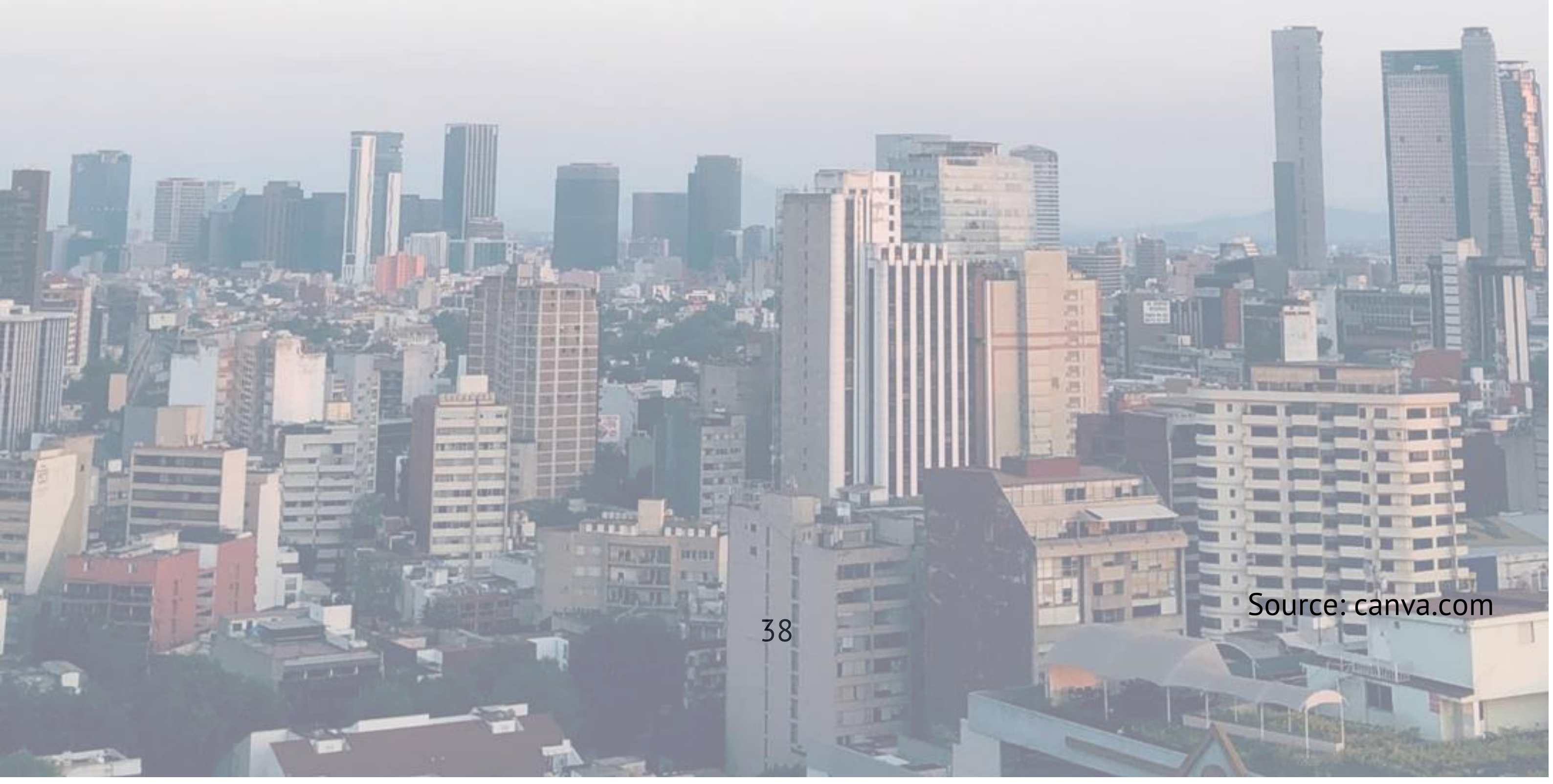


Figure 7. Scheme of a subsurface drip irrigation arrangement (Reich, Godin, Chávez, & Broner, 2019+00:00)

Stauffer (Stauffer, 2016) points out the existence of several other small-scale irrigation alternatives, that frequently experience recurrent operational obstacles. For the purpose of this study, these methods will not be described.

2. Climate and agriculture in Mexico: a literature review



Source: canva.com

For the purposes of this document, a case will be studied for Mexico, due to its key geolocation, and the effect on climate change and water scarcity of a highly-industrialized country with over 127 million inhabitants, and generating almost 1.3 trillion U.S. dollars as gross domestic product (GDP) (World Bank, 2020c) . In sections 1.5 and 1.6, it was described Mexico had a relevant presence among the countries with the highest water stress levels, and how wastewater has a potential role in the regeneration of the water cycle., being recycled and reused for high water-consuming anthropological activities, such as agriculture. This section is designed to provide an overview of the climate and water context in the country, delimit the region of interest within the country, and describing sustainable alternatives in Mexico and worldwide with the objective of reduction the carbon and water footprint of agriculture using wastewater.

2.1. Climate in Mexico

According to the Köppen-Geiger classification of climate, which groups each region of the world in five main categories and 30 sub-categories (Beck et al., 2018), Mexico accounts for several climate zones across its territory, being the most predominant the *BWh* (cold arid desert) and *BWk* (hot arid desert) in the northern part of Mexico, bordering with the United States,, *Cwb* (warm temperatures and winter dry) in the center, and *Aw* (equatorial winter dry) and *Af* (equatorial fully humid) in the southern area of the country, bordering with Guatemala (Köppen-Geiger, n.d.). This classification of climate zones is driven by average historical values of precipitation and monthly air temperature, and is constantly subject to changes due to the variability of the global climate conditions (Beck et al., 2018). As a first approach, Figure 8 depicts a map of the Köppen-Geiger climate classification in a timeframe of 36 years, between 1980 and 2016.

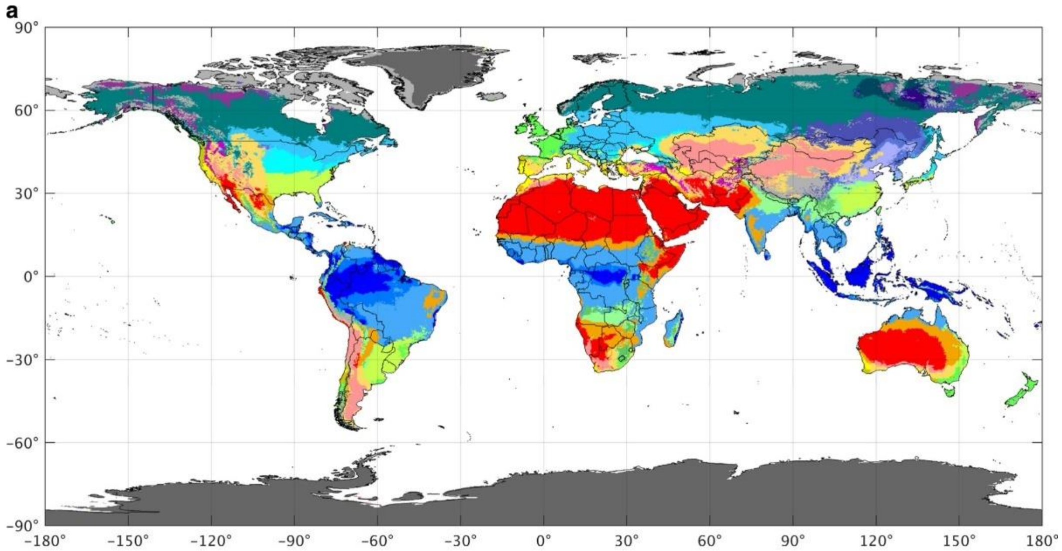


Figure 8, Map of the Köppen-Geiger climate classification between 1980 and 2016 (Beck et al., 2018).

The regions of Mexico classified with a Köppen-Geiger arid and dry climates (category *B*) account for high average summer temperatures and precipitation ranging between 250 and 400 mm (Lumen Learning, n.d.). In this context, the present weather conditions in the northern region of Mexico are expected to be vulnerable to the effects of climate change in the upcoming years.

2.2. Agriculture in Mexico

2.2.1. Importance of agriculture in society and economy

Mexico has a territorial extension of approximately 198 million ha, of which almost three quarters of this area (some 145 illion ha) are currently designated for agriculture activities (Food and Agriculture Organization, n.d.c). The Mexican agricultural land is broken down as follows: around 30 million ha are used for crop production, while livestock and related activities account for 115 million ha (Food and Agriculture Organization, n.d.c).

Agriculture, forestry, and fishing contributed to the gross domestic product (GDP) of Mexico in around four percent in 2019 (World Bank, 2020a), a considerably low value compared to other economic sectors such as industry (around 30 percent of the national GDP) (World Bank, 2020b), and services (60 percent of the GDP) (World Bank, 2020d). Despite of this, the role of agriculture in Mexico transcends the economic impacts of this sector, specifically in the social and environmental spheres (Food and Agriculture Organization, n.d.c). Most of the food products of the country have their origin in local agriculture (Food and Agriculture Organization, n.d.c), this is an important factor regarding food security and accessibility. Additionally, this sector represents an employment opportunity for the population living in rural or remote areas, which is estimated to amount to some 24 million people (Food and Agriculture Organization, n.d.c). Following this, agriculture represents around 42 percent of the family income within this demographic sector (Food and Agriculture Organization, n.d.c).

In 2018, Mexico ranked tenth on the list of leading exporting countries of agricultural products worldwide, as the total value of these exports stood at around 35 billion U.S. dollars (El Economista, 2019). Beer, avocado, tomatoes, strawberries, and raspberries are among the main agriculture-related products that Mexico exports globally (Food and Agriculture Organization, n.d.c) mainly to countries in the region, such as the United States, Canada or Central America, nevertheless, nations such as Japan, Germany or the Netherlands are as well important destinations for agriculture products from Mexico (CEDRSSA, 2017)

In Chihuahua, activities related to agriculture and forestry account for around three percent of the local gross domestic product (Gobierno del Estado de Chihuahua, 2019c).

2.2.2. Agriculture and climate change

Land dedicated exclusively to agriculture and crops in Chihuahua emitted greenhouse gases amounting to around 1.17 million kilograms of carbon dioxide equivalent in 2017 (Gobierno del Estado de Chihuahua, 2019c)

As mentioned in previous sections, this sector is vulnerable to the impacts of climate change and considering the classification of the climate in the Northern-Mexican region, exposure to extreme weather events is considerably likely. In September 2020, it was reported that around 90.7 percent of the usable land for agriculture was affected by droughts, of which 25 percent of this area presents severe to extreme abnormal dry conditions (Gobierno del Estado de Chihuahua, 2020b). Beans, oats, corn, and other temporary crops are among the most impacted by the heatwaves during that year, representing economic losses of approximately 2.7 billion Mexican pesos (some 127 million U.S. dollars) (Gobierno del Estado de Chihuahua, 2020b). Such events have been reported for several years, when heatwaves and lack of precipitation affected the crops production in the Northern-Mexican state (González Sierra, 2019).

2.3. Selection of the area of interest

To limit the scope of this project, of a specific area in Mexico is selected, where the effects of climate change suppose a major threat, due to alterations in weather patterns (precipitation, drought), and vulnerability level in the existing context. Most of this selection process is based in the work of Arreguín-Cortés et al (Arreguín-Cortés et al., 2019), as these authors provide a deep insight on the Mexican situation towards climate change. For this, several indexes are calculated to determine the level of exposure and vulnerability to the alterations of the climate.

2.3.1. Water security index

Water security refers to "the capacity of a society to satisfy its basic water needs, to conserve and make sustainable use of its land and aquatic ecosystems, to produce food without threatening the quality and quantity of available water resources (...), as well demonstrates the social and regulatory mechanisms, related to the water resources, for reducing and handling conflicts or water disputes" (Arreguín-Cortés et al., 2019). Due to the impacts of climate change in Mexico described in previous sections, Arreguín-Cortés et al (Arreguín-Cortés et al., 2019) highlight this country needs for water security measures at different levels of governance, by analyzing the status quo regarding demographic changes and diversification, energy and food consumption, and particularly water management (Martínez-Austria, 2013)

The implementation of the water security index as a concept linked to risk in a probabilistic way, was introduced in the work of Arreguin-Cortés et al. (Arreguín-Cortés et al., 2019). The mathematic approach of security is established in Eq. 1.

$$Security = 1 - Risk$$

Eq. 1. Probabilistic definition of security index (Arreguín-Cortés et al., 2019)

In the same sense, risk comes determined by the hazard – the proximity to harm to a situation, resulting in potential economic or social losses-, and with vulnerability (Arreguín-Cortés et al., 2019). The mathematical approach of risk is illustrated in Eq. 2.

$$Risk = Hazard\ x\ Vulnerability$$

Eq. 2 Mathematical definition of risk (Arreguín-Cortés et al., 2019).

According to the conceptualization described by Arreguín-Cortés et al. (Arreguín-Cortés et al., 2019), the probabilistic nature of the hazard factor depicted in Eq. 2 is determined by the "probabilistic occurrence of a phenomenon given in an estimated period of time", thus, the probability of each event's hazard is calculated a result. In addition to this, hazard is a function of the Global basic water-service access index (GWSAI), annually reported and determined by the CONAGUA in Mexico (Arreguín-Cortés et al., 2019). The GWSAI, which is composed by the access to drinking water and access to sanitation, is a result of the mathematical interaction of several variables, such as drinking water and sanitation coverage, wastewater collection efficiency, and drainage cover, for instance (Arreguín-Cortés et al., 2019). In Eq. 3 it is depicted the addition of the hazard probability for each phenomenon.

$$Hazard = (1 - GWSAI) + Flooding + Droughts + Acquifers$$

Eq. 3. Calculation of the global hazard probability (Arreguín-Cortés et al., 2019)

The necessary numerical data to determine the individual hazard probabilities was compiled by Arreguín-Cortés, et al. (Arreguín-Cortés et al., 2019) from different sources, including CONAGUA. The exact source and the time series of the data compiled is displayed in Table A. III, in ANNEX II. The resulting data was normalized using a normal distribution function, as suggested by Rodell, et al (Rodell et al., 2004), using the function displayed in Eq. 4.

$$F(x) = \int_{-\infty}^{x} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(x-\mu)^2}{2\sigma}} \; for -\infty \le x \le \infty$$

Eq. 4. Normal distribution function for data normalization (Rodell et al., 2004), (Arreguín-Cortés et al., 2019)

To display the results graphically, Arreguín-Cortés (Arreguín-Cortés et al., 2019) integrated the results of Eq. 4 in the map of Mexico using Geographic Information System (GIS) software, to provide a better understanding of the geographic hazard of the analyzed climate and weather events. For instance, Figure 9 depicts the results of the normalized and geopositioned probabilistic data for drought hazard in Mexico.

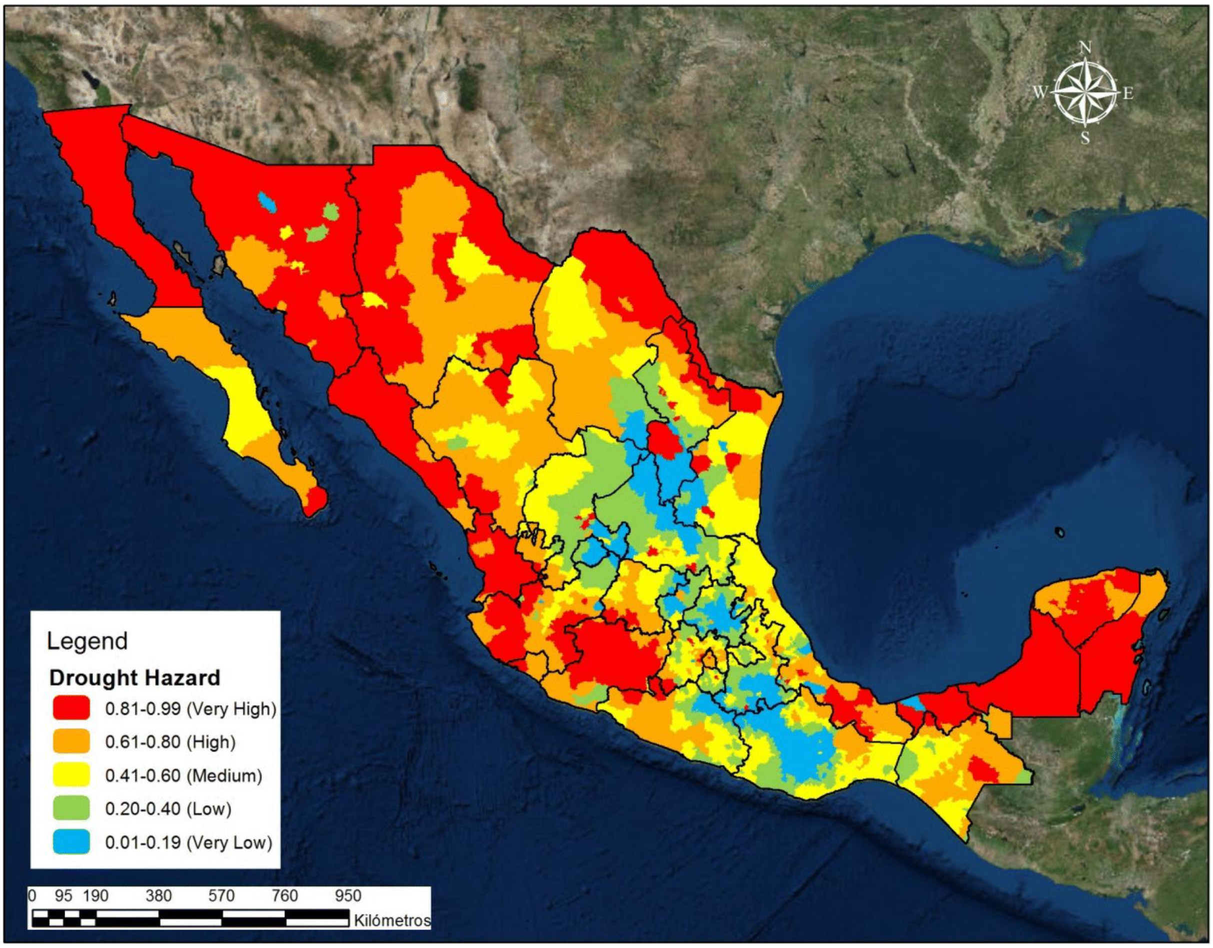


Figure 9. Drought hazard index in Mexico by federal state using GIS software (Arreguín-Cortés et al., 2019)

According to the findings displayed in Figure 9, the northern region of Mexico accounts for the highest drought hazard in the country, which includes the states of Baja California, Sonora, Coahuila, Sonora, and Chihuahua, in addition to particular regions in the center and the Yucatán Peninsula. According to the overall hazard index results from Arreguín-Cortés et al. (2019) the state of Chihuahua accounted for the highest hazard index by area, with around 130, 127 km^2, approximately half of its territory, as depicted in Figure 10.

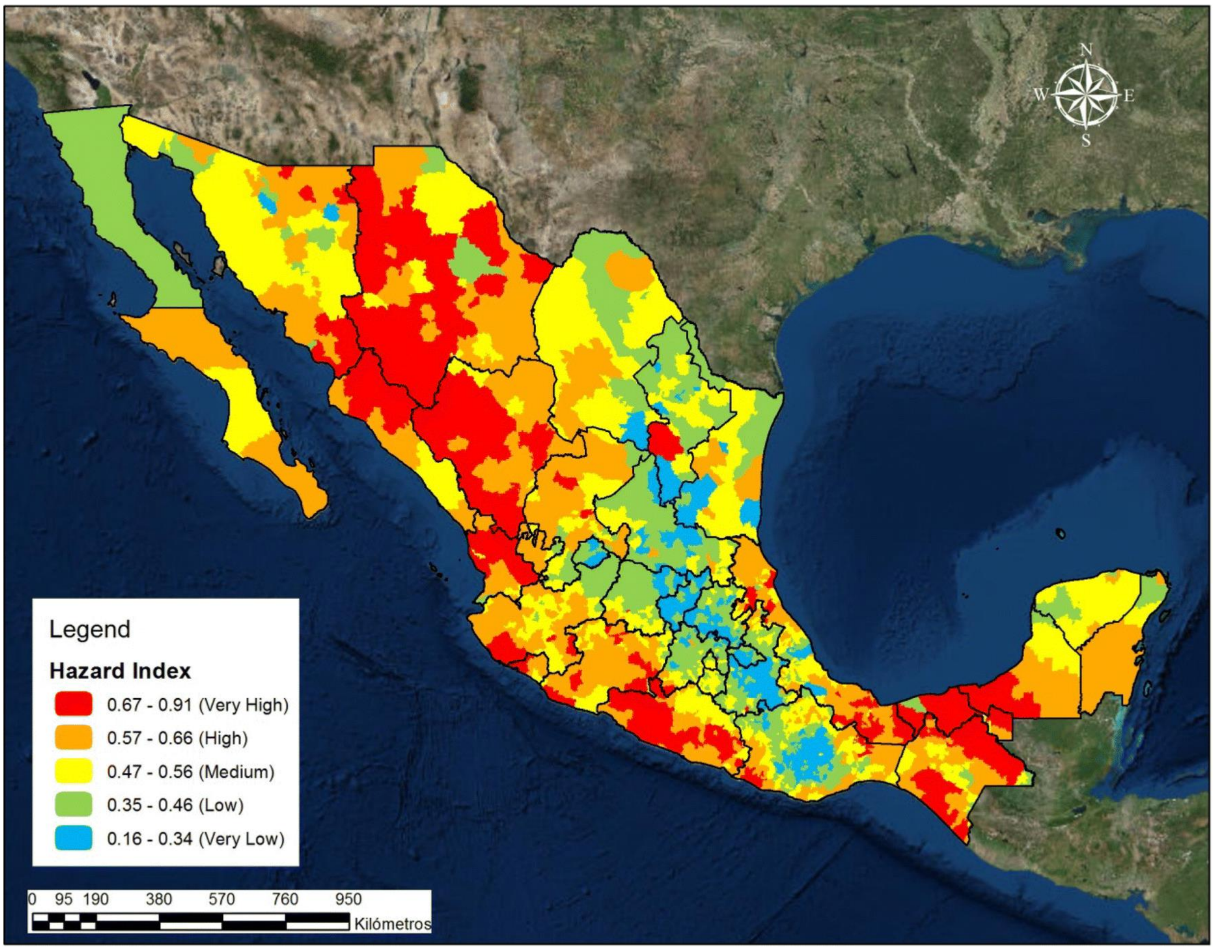


Figure 10. Hazard index in Mexico using GIS software (Arreguín-Cortés et al., 2019)

To complement the calculation of risk mentioned in Eq. 2, the vulnerability factor was determined from the social situation of each municipality, using the indicators described in Table A. IV, in ANNEX I, and recommended by a study from the National Center for Disasters Prevention (CENAPRED by its abbreviation in Spanish) (Centro Nacional de Prevención de Desastres, 2014). The establishment of these indicators driving water vulnerability is described by Arreguín-Cortés (2015) in the Atlas of Water Vulnerability in Mexico, as the "identification of the characteristics of the population susceptible to harm, either to their person or their material goods, as a consequence to some natural phenomenon". The relation between these parameters is depicted in Eq. 5 using the abbreviations displayed in Table A. IV.

$$Vuln = AEL + NP + PWHC\ CMR + I + HWDWS + HWD + HWEF + EAP + EDR + OUR + ILP$$

Eq. 5. Vulnerability index calculation (Arreguín-Cortés et al., 2019)

To present the results from Eq. 5 in a graphic resources, a similar procedure than the hazard index was used, the municipal water vulnerability index was normalized and processed on the map of Mexico (Arreguín-Cortés et al., 2019), as displayed in Figure 11.

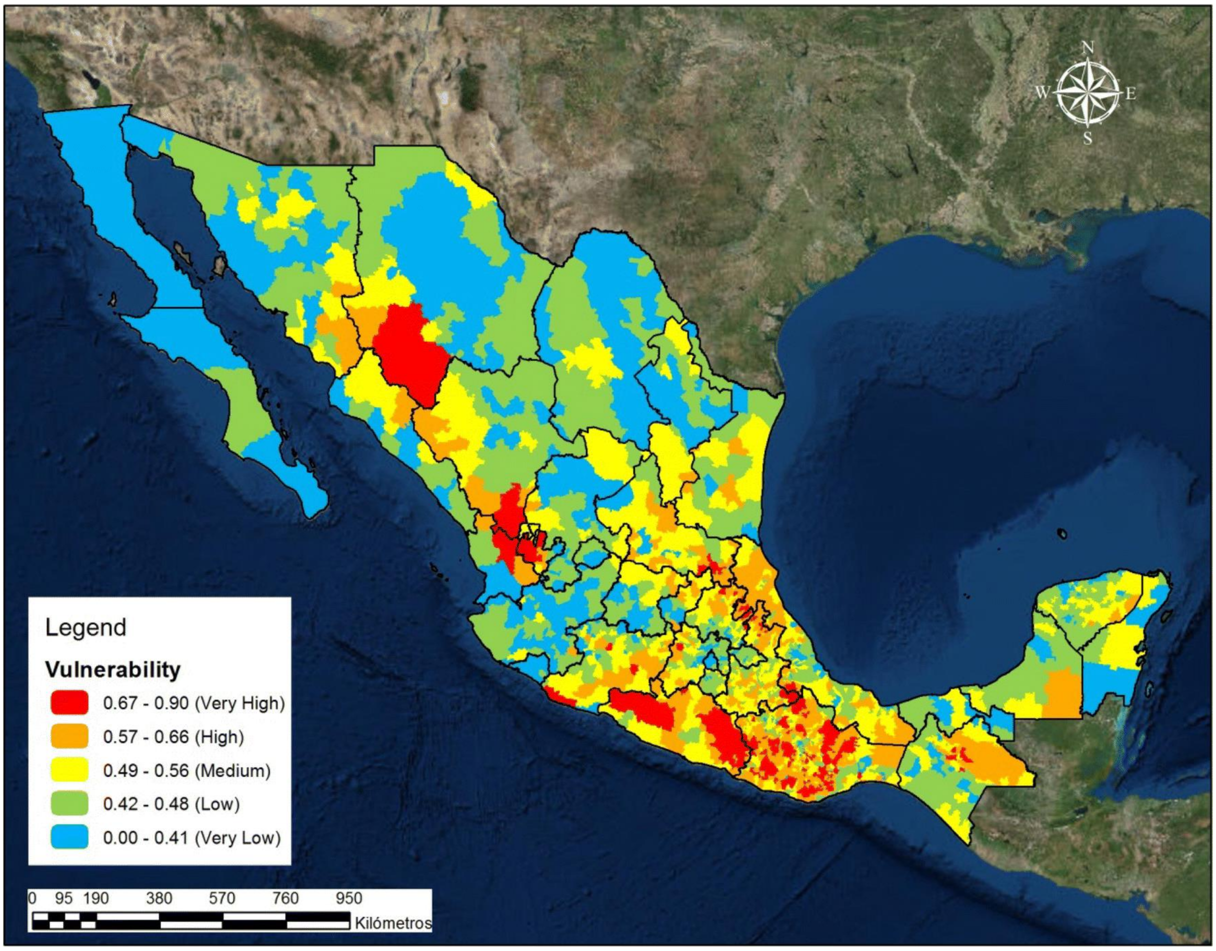


Figure 11. Water vulnerability index in Mexico using GIS software (Arreguín-Cortés et al., 2019)

The graphical representation of the water vulnerability in Mexico suggests that the most vulnerable population to the effects of weather events and natural phenomena residents in the central and southern regions of the country, including the states of Oaxaca, Guerrero, Chiapas, Campeche, and the northern states of Chihuahua and Durango (Arreguín-Cortés et al., 2019).

The determination of the hazard and the vulnerability makes possible to calculate the risk by multiplying each factor (Arreguín-Cortés, 2015) and applying the Jenks natural breaks classification algorithm (Jenks, 1967) to obtain an ideal arrangement of maximum and minimum values displayed in the maps. The maps of Mexico considering the rest of hazard factors (flooding, groundwater depletion, and GWSAI), as well as the risk index map are displayed in ANNEX III.

Overall, Figure 12 depicts the information flow followed in the studies of Arreguín-Cortés et al. (Arreguín-Cortés et al., 2019) to create the water security index map. In the diagram, it is displayed the data compiled, as well as the equations needed for the final product.

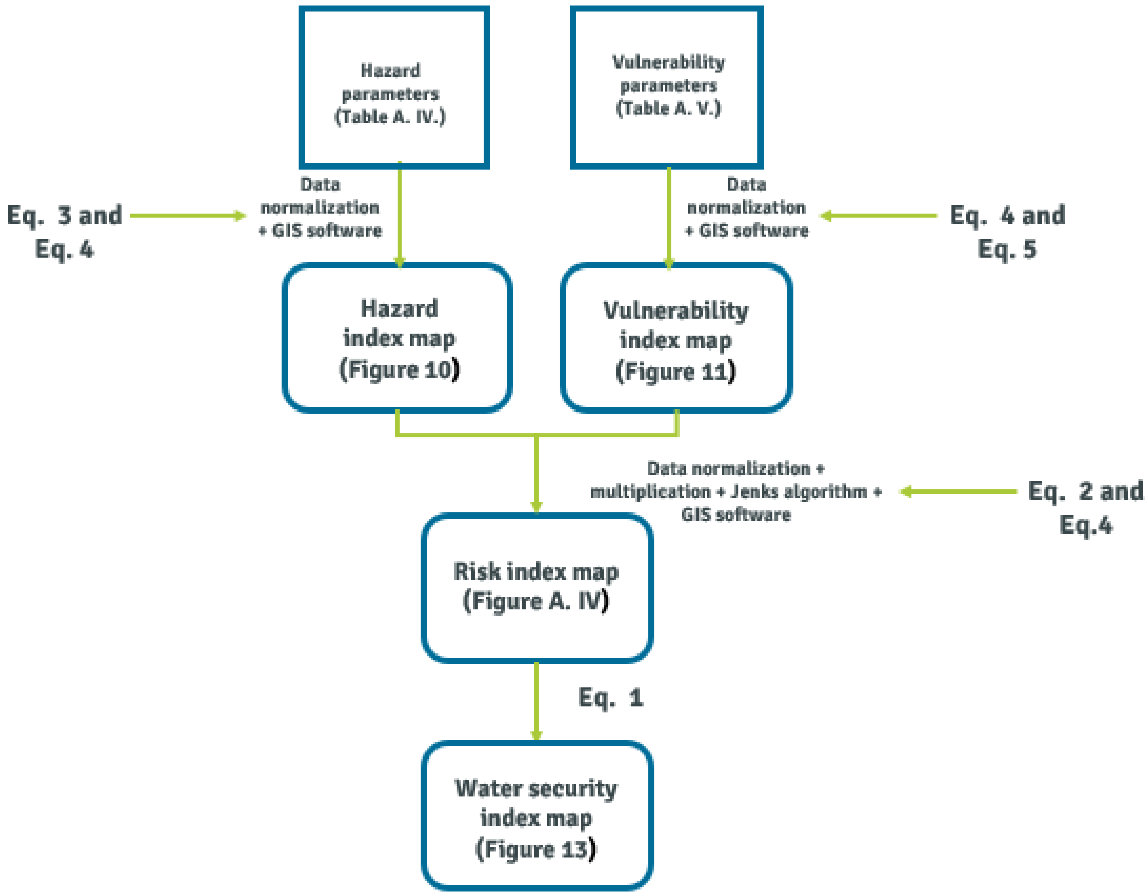


Figure 12. Logic and information flow for the creation of the water security index map in Mexico. Robles (2020). Adapted from (Arreguín-Cortés, 2015)

The water security index map of the municipalities in Mexico, displayed in Figure 13, indicates that most of the country's territory ranged between a normal to a very risky water security index, with particular emphasis in the northern and southern regions.

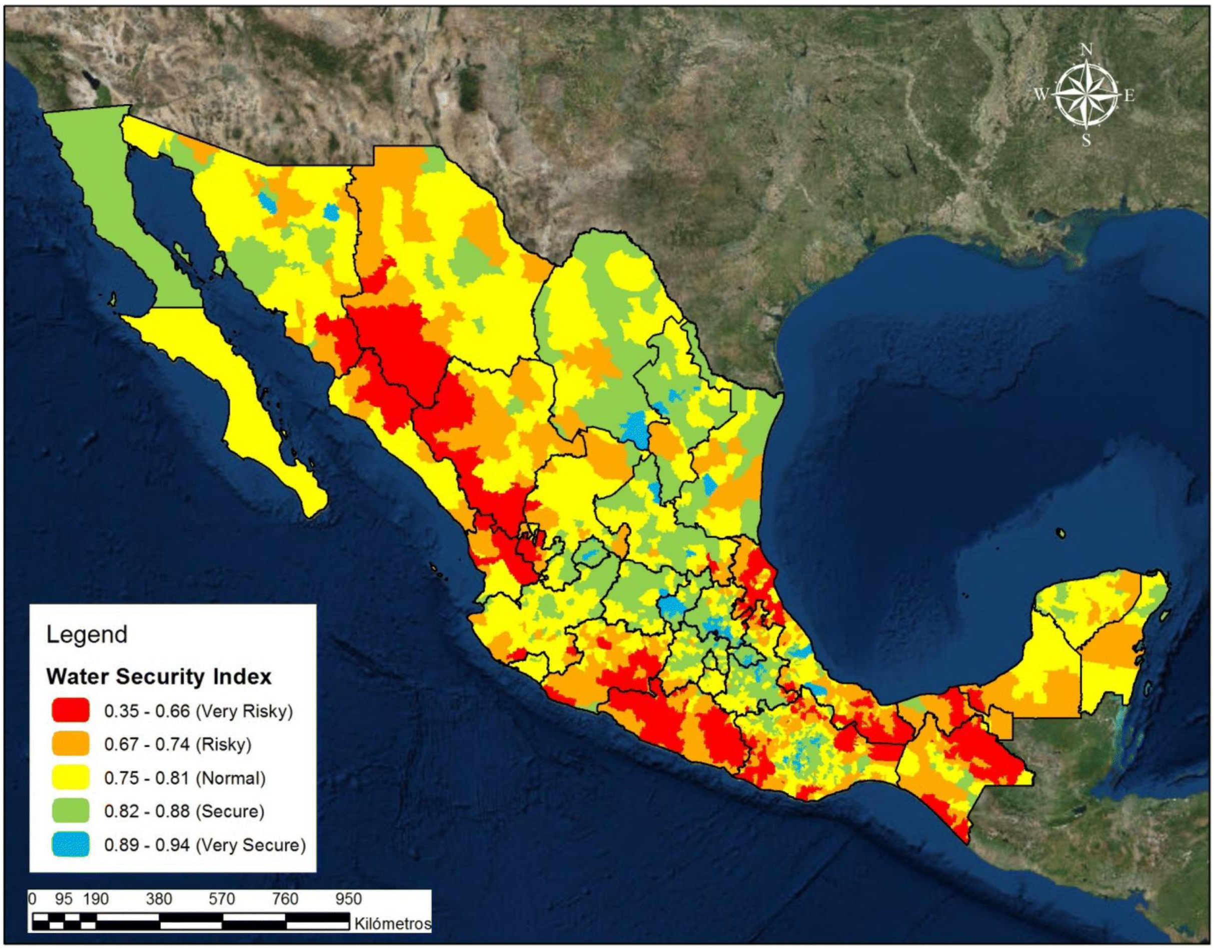


Figure 13. Water security index in Mexico using GIS software (Arreguín-Cortés et al., 2019)

2.3.2. Vulnerability of agriculture to climate change in Mexico

According to the Arreguín-Cortés (2015), on the Atlas of Water Vulnerability in Mexico, irrigation is a key practice to sustain agriculture in this country, and climate variability represents a major threat to this activity through this century. In this sense, the work of Arreguín-Cortés (2015) evaluates how climate change jeopardizes agriculture through three factors that define vulnerability: exposition, capacity of adaptation and sensitivity (Gbetibouo, G. A., Ringler, C., 2009). Figure 14 depicts the logic to determine the vulnerability of the Mexican agriculture towards climate change.

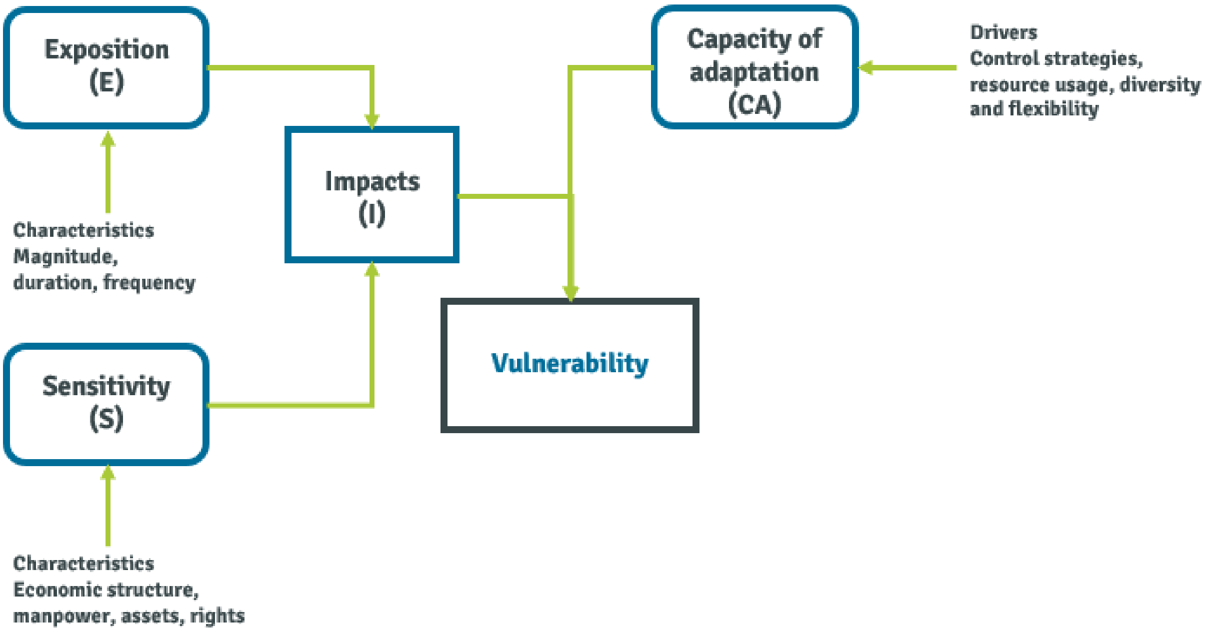


Figure 14. Determination of the Vulnerability to climate change of the agriculture in Mexico. Robles (2020). Adapted from (Arreguín-Cortés, 2015)

The factors determining the level of exposition, capacity of adaptation, and sensitivity to climate change of agriculture are listed from Table A. V to Table A. VII. The mathematical representation of Figure 14 is shown on Eq. 6.

$$Vulnerabilty = f(E + S - CA)$$

Eq. 6. Vulnerability of agriculture calculation (Arreguín-Cortés, 2015)

The numerical result from Eq. 6 was normalized and adapted graphically through GIS software into a map of Mexico for the annual periods "spring-summer", and "fall-winter" (Arreguín-Cortés, 2015). From the complete matrix of states and municipalities of the country, the leading 10 Mexican irrigation districts presenting higher vulnerability indices were selected for further studies and displayed, and are displayed in Table 6. The scope of this project proposal is to determine the potential of reusing treated wastewater in agriculture and evaluate the impact of these initiatives on greenhouse gases emissions emission reductions.

Table 6 Vulnerability index of selected irrigation districts in Mexico during the period fall-winter (Arreguín-Cortés, 2015)

No	Irrigation district	Vulnerability index (%)	Location
1	Río Verde-Progreso	90	Oaxaca
2	Papigochic	90	Chihuahua
3	Río Florido	86	Chihuahua
4	Región Lagunera	86	Coahuila/Durango
5	José María Morelos	81	Michoacán/Guerrero
6	Atoyac	80	Guerrero
7	Cuajiniculiapa	80	Guerrero
8	Don Martín	76	Coahuila/Nuevo León
9	Delicias	70	Chihuahua
10	Estado de Zacatecas	60	Zacatecas
11	Estado de México	47	Edo. De Mex.

The map depicted in Figure 15 allocates the 11 selected irrigation districts in the map of climate change vulnerability of Mexico.

Figure 15 Location of the most vulnerable irrigation districts in Mexico. (Robles, 2020).

The results of the analysis carried out in the previous sections suggest that the regions and agricultural areas that are most vulnerable to climate change are located in the northernmost and southern parts of Mexico. The maps and indices of risk and vulnerability displayed previously indicate that the northern state of Chihuahua is one of the most exposed territories to weather and climate alterations in the following years. This document is focused to evaluate the potential impacts that this jurisdiction would experience implementing climate-change initiatives.

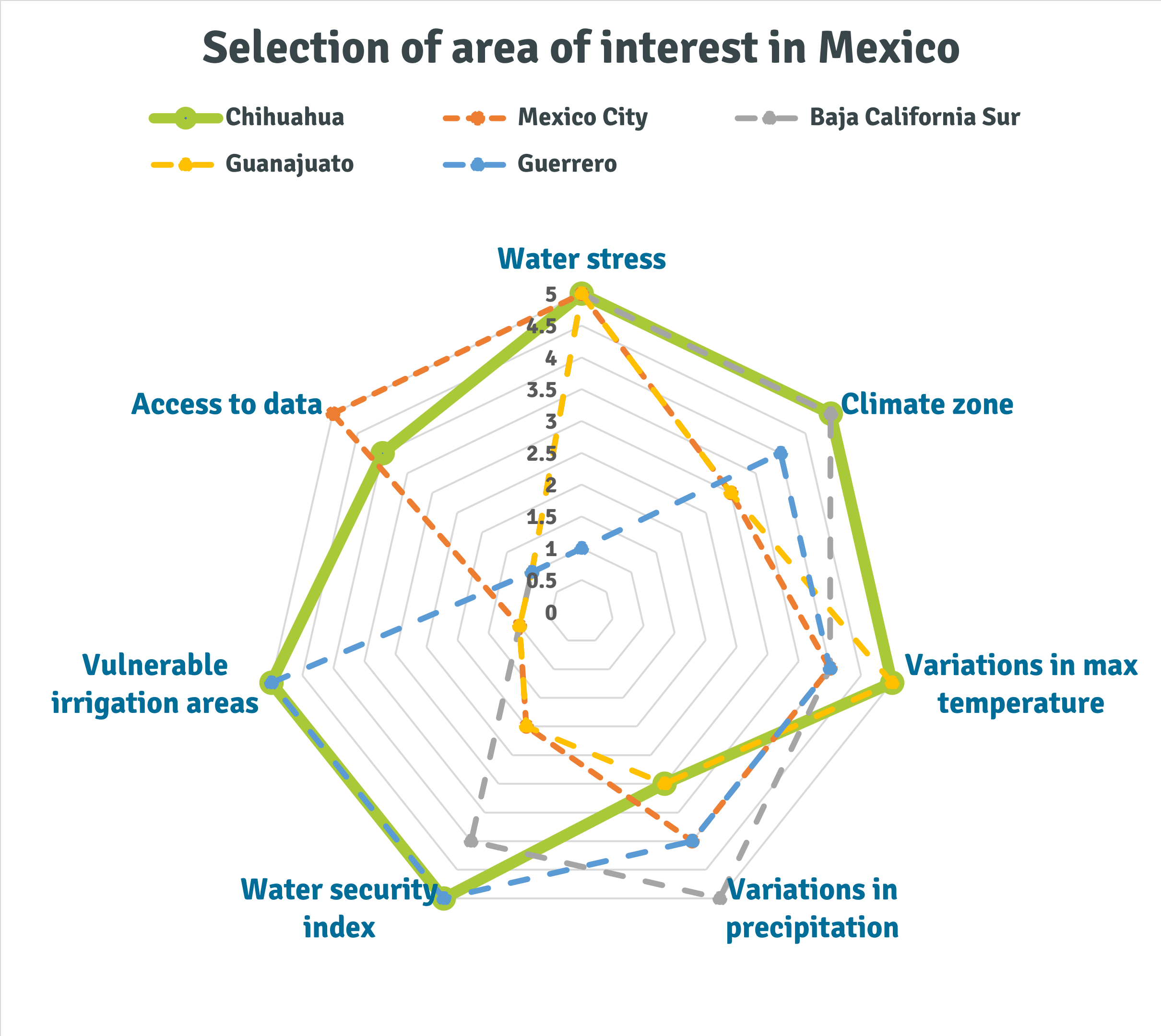


Figure 16. Spiderweb analysis to determine area of interest for wastewater reutilization in Mexico. Robles (2020).

2.4. Chihuahua

The state of Chihuahua is located in the northern region of Mexico, and accounts for almost 3.6 million inhabitants (Instituto de Planeación Integral del Municipio de Chihuahua, n.d.). Figure 17 displays the geographical location of the state of Chihuahua in Mexico.

Figure 17. Geographical location of the state pf Chihuahua in Mexico (Robles, 2020)

The municipality of Chihuahua is the capital of the state with the same name, and accounts for around 9,200 km^2 (Instituto de Planeación Integral del Municipio de Chihuahua, n.d.). In 2015, the population of Chihuahua's municipality amounted to 878,062 inhabitants, and this figure is forecasted to increase to approximately 1.04 million people by 2040, particularly in the urban area (Instituto de Planeación Integral del Municipio de Chihuahua, n.d.).

2.5. Climate in Chihuahua

Within its territory, the state of Chihuahua accounts for different climate zones, being three of them the most predominant. Almost three quarters of Chihuahua's superficial area are classified at least with a semi-dry climate (Instituto Nacional de Estadística y Geografía, n.d.)

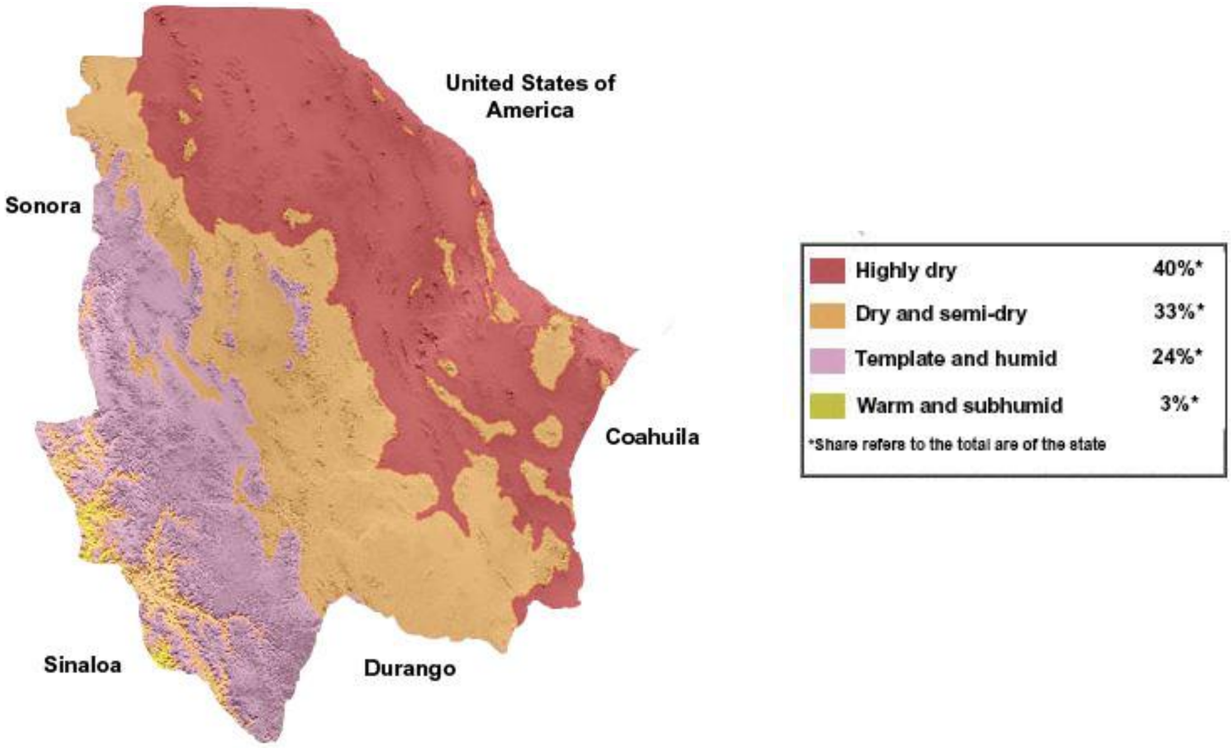


Figure 18. Distribution of different climate zones in the state of Chihuahua (Robles, 2020). Adapted from (Instituto Nacional de Estadística y Geografía, n.d.)

The lack of precipitation is one of the main characteristics in the climate zones present in the northern states of Mexico (Instituto Nacional de Estadística y Geografía, n.d.). Figure 19 displays the average precipitation in Chihuahua, by month. According to these values, some 70 percent of the annual precipitation in this region is concentrated only in three months, between July and August, while the first months of the year are considerably dry.

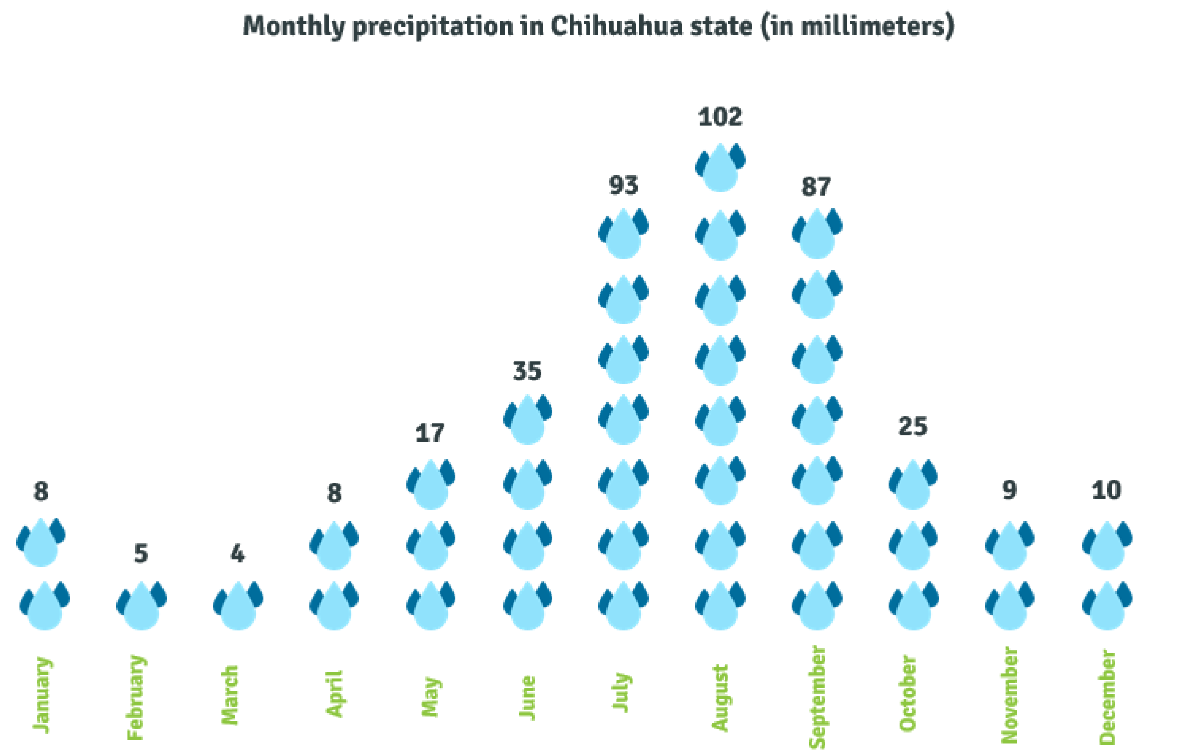


Figure 19. Monthly average precipitation in the state of Chihuahua, Mexico (Robles, 2020). Adapted from (Climate Data, n.d.)

Dry and semi-dry climate conditions are, in general, not suitable for the development of the agriculture, despite it is one of the most important economic activities in Mexico, as this country relies on its climate diversity to grow different types of crops (Gobierno de México, n.d.b). Nevertheless, the absence of rain favors the growth of grasslands, boosting the livestock activity in these regions (Instituto Nacional de Estadística y Geografía, n.d.).

2.5.1. Average annual temperature

In Chihuahua, average temperatures stand at approximately 20 degrees Celsius or warmer between April and October, while the rest of the months, temperatures are usually expected to drop as low as around 1.3 ° degrees Celsius. Figure 20 displays the average, maximum, and minimum temperatures in the state of Chihuahua.

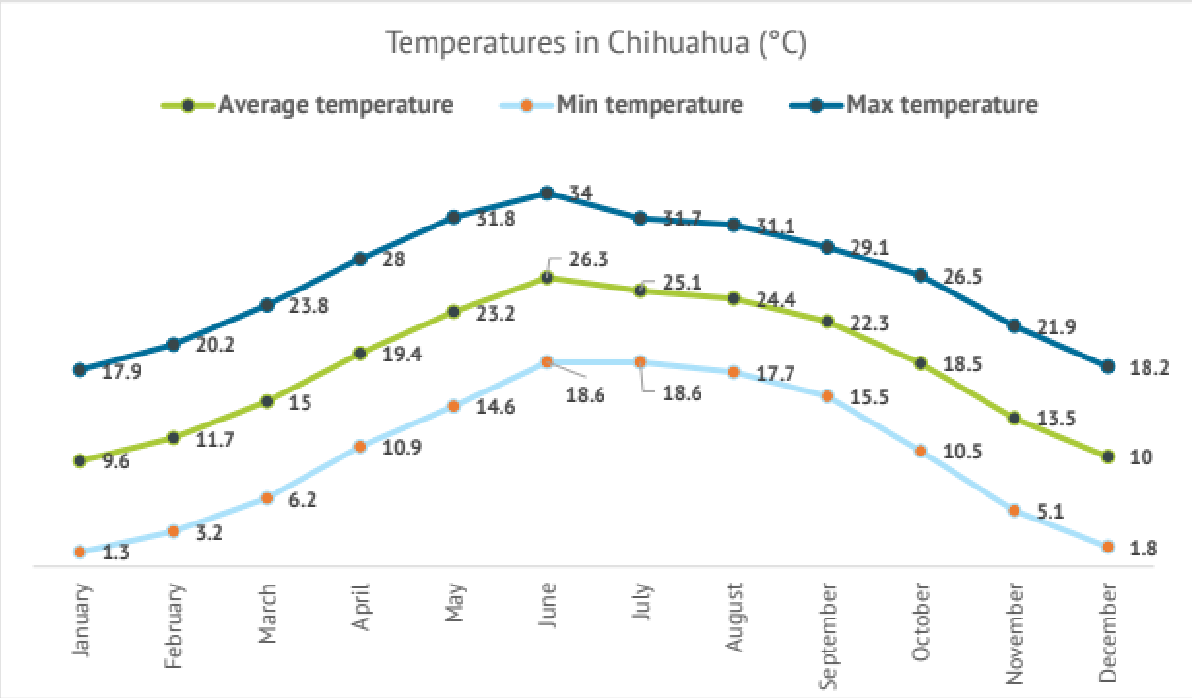


Figure 20. Monthly average temperatures in Chihuahua state (Robles, 2020). Adapted from (Climate Data, n.d.)

Compared to the precipitation values depicted in

Figure 19, the wettest months are usually expected to be the warmest, thus, cold and dry winters are experienced in this region of the country. In the northern municipality and border city of Ciudad Juárez, extreme temperatures have been historically registered, reaching up to 40 degrees Celsius between June and August, and a record of minus five degrees Celsius or lower in the mountainous region of Sierra Madre Occidental, in the southwestern side of the state (Instituto Nacional de Estadística y Geografía, n.d.)

In the last years, the occurrence of events such as heatwaves and droughts has increased, as well as a rise in the average minimum temperatures of the region, which drives the appearance of plagues (Gobierno del Estado de Chihuahua, 2019c).

In 2017, approximately 25 percent of the superficial area of Chihuahua was affected by droughts, while in 2013 was recorded as the year with the harshest drought events in 150 years (Gobierno del Estado de Chihuahua, 2019c), In addition to this, Chihuahua was the fifth state of the country with the highest affected area from wildfires, with around 13,418 ha provoked by 702 events (Gobierno del Estado de Chihuahua, 2019c).

According to the Atlas of Water Vulnerability (Arreguín-Cortés, 2015), in the distant period between 2075 and 2099, drastic changes of the weather conditions are expected for the northern region of Mexico, particularly Chihuahua. Table 7 displays the forecasted variations in precipitation, and maximum and minimum temperatures for this state, seasonally and by RCP.

Table 7. Precipitation and temperature changes in Chihuahua for the period 2075-2099 by scenario. Robles (2020). Adapted from (Arreguín-Cortés, 2015)

Change in precipitation (%)	**Spring-Summer**	**RCP 4.5**	**-4.2**
		RCP 6.0	**-7.5**
		RCP 8.5	**-8.5**
	Fall-Winter	**RCP 4.5**	**-8.2**
		RCP 6.0	**-7.1**
		RCP 8.5	**-10.2**
Change in max temperature (°C)	**Spring-Summer**	**RCP 4.5**	**3.3**
		RCP 6.0	**4.4**
		RCP 8.5	**5.4**
	Fall-Winter	**RCP 4.5**	**3.2**
		RCP 6.0	**3.8**
		RCP 8.5	**5.5**
Change in min temperature (°C)	**Spring-Summer**	**RCP 4.5**	**2.8**
		RCP 6.0	**3.4**
		RCP 8.5	**4.9**
	Fall-Winter	**RCP 4.5**	**2.4**
		RCP 6.0	**3.1**
		RCP 8.5	**4.4**

Changes in maximum and minimum temperatures in Chihuahua are considerably harsher than in other states and regions of the country (Arreguín-Cortés, 2015). Overall, disregarding the projected greenhouse gas emissions trajectory in the next decades, an increase of at least 2.5 degrees Celsius in minimum temperatures, and of around 3.2 degrees Celsius in maximum temperatures is expected in Chihuahua between 2075 and 2099. A comparison of the projected weather alterations among selected states in Mexico is displayed in ANNEX V.

2.5.2. Agriculture in Chihuahua

Chihuahua was ranked fourth among the leading agriculture-producing states in Mexico, with an effective land for these purposes of almost 1.4 million ha (Gobierno del Estado de Chihuahua, 2019b).

Despite having a semi dry climate, and average high temperatures through the year, Chihuahua grows different types of crops, including cyclic crops (which productive period is lower than 12 months), and permanent crops (large cycle, extended over 12 months) (Grupo SACSA, 2016). Table 8 displays detailed information on area and production volume of selected crops in Chihuahua as of 2015, broken down by type.

Table 8. Productive area and volume of selected crops in Chihuahua in 2015, by type. Robles (2020). Adapted from (Instituto Nacional de Estadística y Geografía, 2015).

	Productive area (in ha)	Volume (in metric tons)
Cyclic crops	**1,081,424.91**	**N/A**
…of which		
Cotton	**123,161.53**	**593,981.63**
Corn	**224,882.05**	**1,373,409.72**
Bean	**123,954.75**	**124,764.90**
Onion	**5,349.75**	**269,316.46**
Potato	**2,810.00**	**54,687.70**
Permanent crops	**158,870.15**	
…of which	**43,800.30**	**80,124.26**
Nuts	**26,817.90**	**551,466.63**
Peach	**1,362.40**	**23,476.99**
Apple	**26,817.90**	**551,466.63**

As of 2019, the state of Chihuahua was ranked first in national production of some of the crops depicted in Table 8, such as cotton, apple, nuts, and onions, among others (Gobierno del Estado de Chihuahua, 2019a). Production of cotton in Chihuahua accounted for 70.2 percent of the total production of this crop nationwide in that year (Gobierno del Estado de Chihuahua, 2019a).

The map depicted in Figure 21 shows the geographical location of the regions where selected crops were produced in the state of Chihuahua as of 2016, and the importance of these agricultural products in the national supply mix. Apples, wheat, and cherries are the most important crops grown in the regions nearby the municipality of Chihuahua (the capital city of the state).

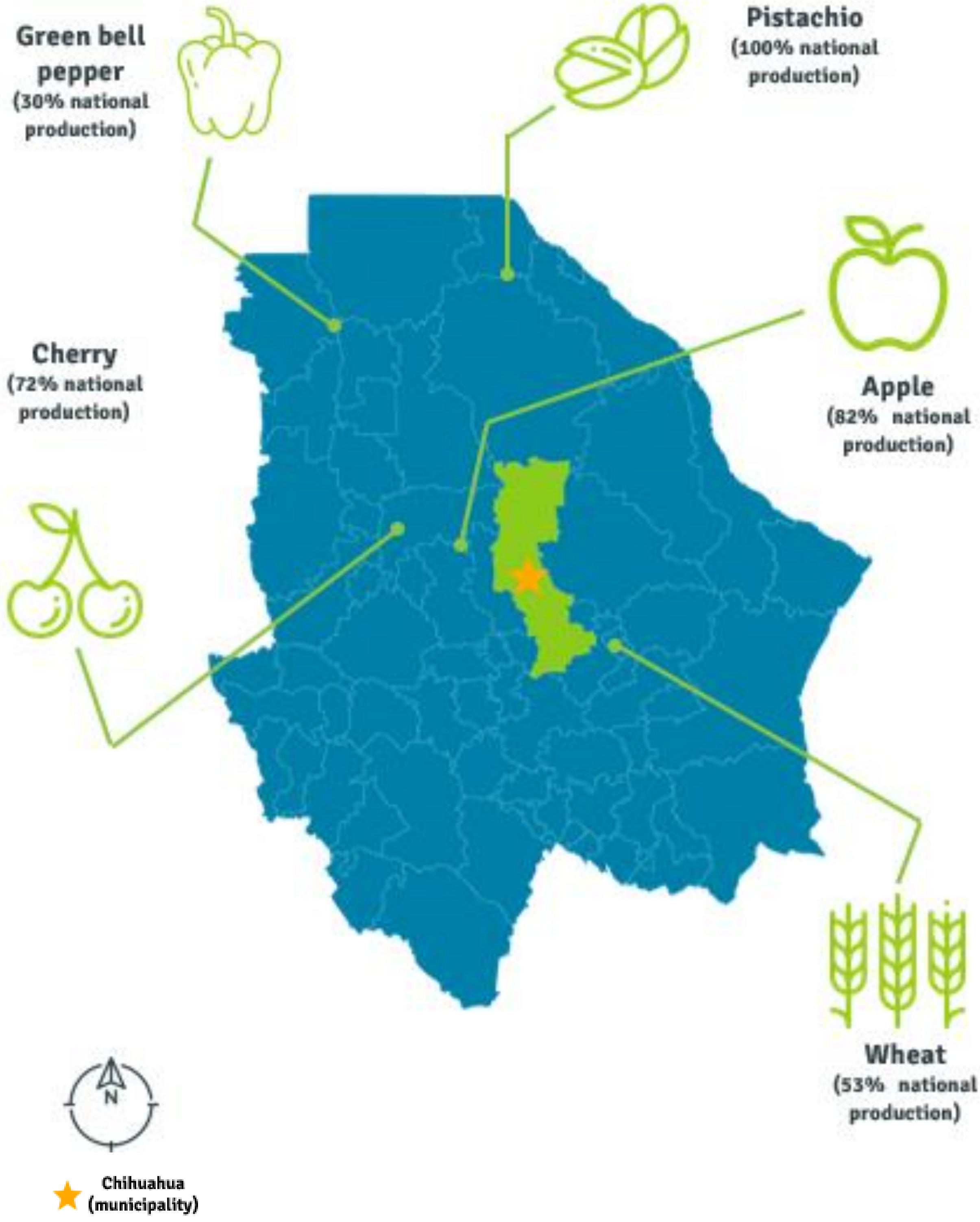


Figure 21. Geographical location of selected crops grown in the state of Chihuahua as of 2016 (Robles, 2020). Adapted from (Referente, 2017)

2.6. The water and wastewater situation in Chihuahua

2.6.1. Overview

Mexico ranked among the leading countries in water extraction and consumption worldwide as of 2018 (Chávez, 2018), while the city of Chihuahua alone overtook the country's figure. The summer water consumption per capita in the capital city of the northern state is roughly 22 percent higher than the country's average (Chávez, 2018; González, 2020), as displayed in Figure 22.

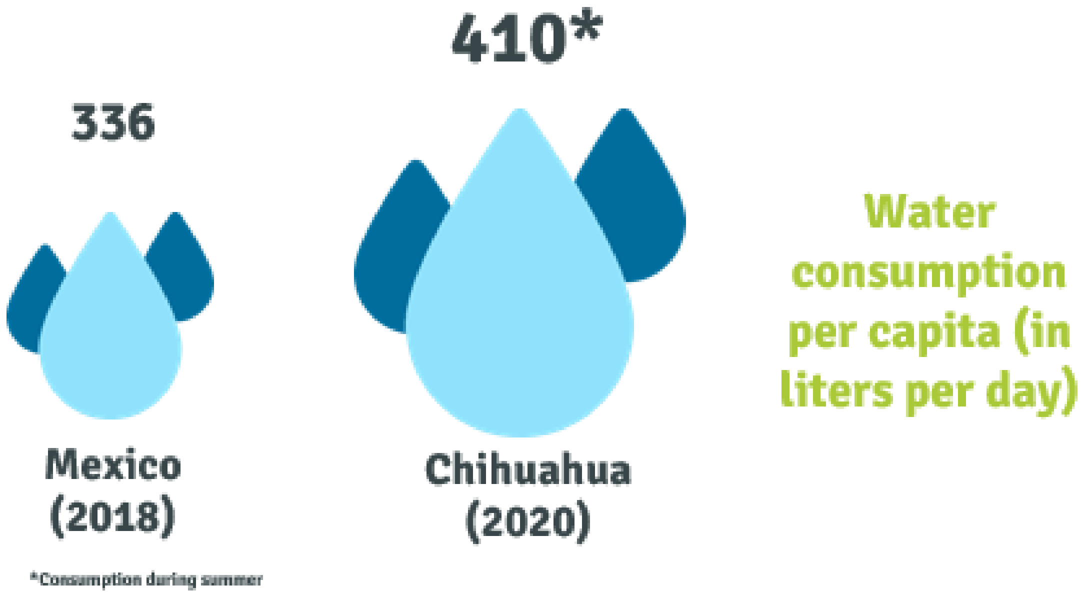


Figure 22. Comparison of the per capita water consumption in Mexico and Chihuahua city, in liters per second. (Robles, 2020). Adapted from (Chávez, 2018; González, 2020)

As mentioned in previous sections, agriculture is a major economic activity for the country, and it additionally represents one of the biggest end-uses for freshwater consumption: while over three quarters of the water extractions are destined to agriculture in the country (Comisión Nacional del Agua, 2015b), Chihuahua city accounts for 82 percent of this share (Espino, 2020).

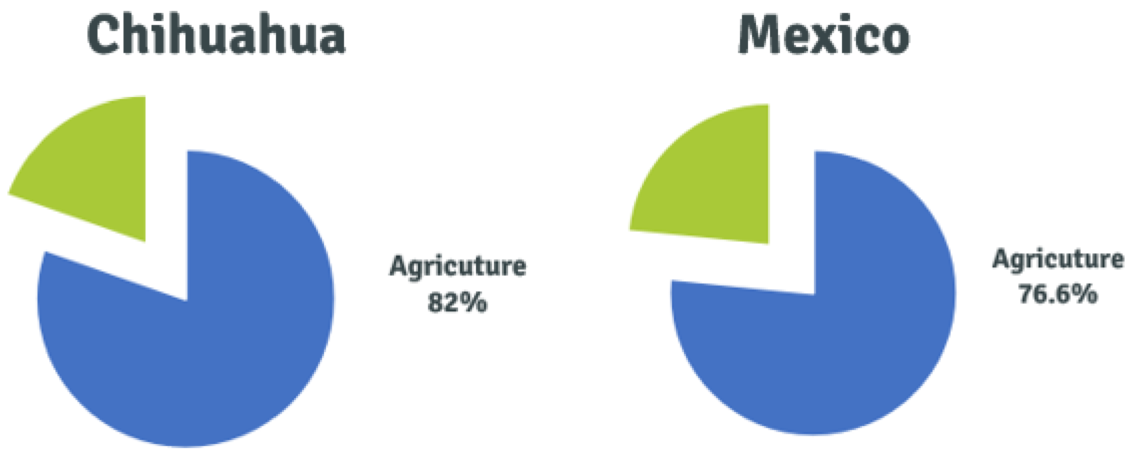


Figure 23. Share of freshwater consumption for agriculture in Chihuahua and Mexico. Robles (2020). Adapted from (Comisión Nacional del Agua, 2015b; Espino, 2020)

In the context of agriculture being a key activity in the conjuncture of Chihuahua, drought events during the year 2020 are expected to have an impact on the Water Treaty with the United States (Gobierno del Estado de Chihuahua, 2020a). The Treaty for the Distribution of International Waters was signed between the United States and Mexico in 1944, and took place in the context of the cooperation and the establishment of the Rio Grande as the political border of these two countries (BBC News, 2020). In this treaty, it is settled that Mexico keeps two thirds of the Rio Grande's current, and would concede the rest (which could not be lower than 431.7 million cubic meters annually) to the United States every five years (BBC News, 2020), and as a counterpart, the latter is set to concede around 1,850 million cubic meters of the Colorado River's current to their southern neighbors each year, in contrast with the first trade agreement (BBC News, 2020). The next five-year period on which Mexico should yield the agreed flow of the Rio Grande's current ends by the 24 of October of 2020, and according to official sources, the country is still missing some 87.5% of the volume (approximately 378 million cubic meters) (BBC News, 2020).

Among the main causes of the Mexican non-compliance of the treaty are the extreme weather events and an increase in the municipal and industrial water consumption, and as a response to this, the federal government is currently exploiting Chihuahua's water basins and catchment areas, in order to concede the agreed water volume to the United

States (Forbes, 2020). As a result of this line of action from the government, farmers and land workers have expressed their concern on not having enough water to use for the agriculture cycle 2021 (Forbes, 2020).

The situation in Chihuahua has escalated to protests and demonstrations against the central government's response, resulting in weeks of disturbs and violence on the streets of the capital of this state (Forbes, 2020). In addition to this, the state government of Chihuahua is represented by the opposition party, resulting in an exchange of statements between local, state, and federal authorities (Forbes, 2020).
In this context, as politicians and other stakeholders are making use of this situation as political propaganda, and it has not been possible to find sustainable solutions for the environment and the affected population segments during this international conflict, it has become imperative to find and implement water-friendly alternatives to preserve the integrity of the basins and catchment areas of the region, particularly in agriculture.

2.6.2. Governance

Mexico is classified as a federal republic, representative, and with a democratic regime, meaning that there's a separation of powers in the government in executive, legislature, and judiciary, periodically and democratically elected by its inhabitants (Llamas M. & de, 2009). The federal executive power accounts for 20 direct dependencies that supervise the functioning of different spheres of society, such as public safety, environment, agriculture, or public health .(Gobierno de México, n.d.c). Additionally, this federal republic is divided by 32 federal entities or states across the country (Secretaría de Relaciones Exteriores, n.d.),
The dependency of the federal government that oversees the status quo, and future projects and instruments related to the environment is the Secretariat of Environment and Natural Resources (SEMARNAT, by its abbreviation in Spanish) (Gobierno de México, n.d.c). Among the responsibilities of this entity is the creation of legislations and instruments that aim to protect the natural resources of the country, as well as address

the impacts of climate change through adaptation and mitigation measures, implementing and monitoring the progress of the nationally determined contributions (NDCs), and emitting reports periodically on the national environmental and sustainable performance indicators (Secretaría de Medio Ambiente y Recursos Naturales, n.d.).

The National Water Commission is an administrative body, dependent of the SEMARNAT, with functions regarding the management of the water resources of the federal territory, and accounts for an executive, financial, and administrative autonomy, in order to fulfill its scope (Cámara de Diputados de México, 2013). CONAGUA operates in two modalities: at the federal level, and at the state level through its Watershed Organisms distributed regionally (Cámara de Diputados de México, 2013).

Among the attributions, scope and responsibilities of CONAGUA described in the National Waters Law (Cámara de Diputados de México, 2013), it is found:

- The management of the quality and quantity of the water bodies in the federal territory,
- create and propose national water legislations,
- design, execute, operate, and maintain projects related to water infrastructure, and
- Promote and raise general awareness on the sustainable and responsible water consumption of water nationwide.

At the state level, the authorities in charge of the management of potable water and wastewater resources are the Central Board of Water and Sanitation (JCAS, by its abbreviation in Spanish) (Junta Central de Agua y Saneamiento de Chihuahua, n.d.). The state of Chihuahua, through its Law of State Waters (Junta Municipal de Agua y Saneamiento de Chihuahua, 2012) lists among the objectives of the JCAS, the formulation of policies, regulations, and other instruments, the administration, conservation, and planning of the water resources within the limits of a specific state.

In addition to the competences of the JCAS, the state of Chihuahua accounts for several dependencies at different levels, such as the District, Municipal, Rural, and Operational

Boards of Water and Sanitation. The Municipal Board (JMAS, by its abbreviation in Spanish) oversees, among other activities, the correct operation of the North and South wastewater treatment plants of this municipality, including the chemical and physicochemical parameters of the effluent, and additionally looks after the compliance of the different water-related regulations and instruments (Junta Municipal de Agua y Saneamiento de Chihuahua, n.d.).

The Law of State Waters of Chihuahua names additionally other organisms of lower hierarchy, such as the water committees, which are conformed by inhabitants of those urban settlements where none of the existent operational organisms has competences, performing an auxiliary role in the provision of potable water, sewage, sanitation or wastewater treatment (Junta Municipal de Agua y Saneamiento de Chihuahua, 2012).

2.7. Current instruments addressing climate change

Since the year 2012, Mexico has developed several legal, economic, planning, and technical instruments to address the problematic of climate change in the country, at the federal, state, and municipal levels. In addition to the documents and laws presented in Table 9, Mexico, as a signatory party of the Paris Agreement in 2015, adopted several commitments to reach the global average temperature below two degrees Celsius (United Nations Framework Convention on Climate Change, n.d.a). One of the main unconditional commitments of the country states as follows: "Mexico is committed to reduce unconditionally 25% of its Greenhouse Gases and Short-Lived Climate Pollutants emissions (below BAU) for the year 2030. This commitment implies a reduction of 22% of GHG and a reduction of 51% of Black Carbon" (United Nations Framework Convention on Climate Change, n.d.a).

Table 9. Instruments addressing water and climate change at the national, state and municipal level (Cámara de Diputados de México, 2016; Gobierno de México, 2019; Secretaría de Medio Ambiente y Recursos Naturales, 2016, 2018)

Instrument	Type	Year	Level	Issue addressed
Ley General de Cambio Climático	Legal	2012	National/State	Climate change
Climate Change Fund	Economic	2012	National	Climate change
National Strategy on Climate Change. Projections on 10-20-30 years	Legal	2013	National	Climate change
Carbon tax	Economic	2013	National	Emissions
Energy reform	Legal/Technical	2013	National	Energy
Special Program on Climate Change	Legal	2014-2018	National/State/Municipal	Climate change
National Registry of Emissions and its Regulation	Legal/Technical	2014	National	Emissions
National Inventory of Emissions	Technical	2014	National/State/Municipal	Emissions
National Water Law	Legal	2016	National/State/Municipal	Water
National Water Information System	Legal/Technical/Economic		National/State/Municipal	Water

In the state of Chihuahua, in addition to the instruments listed in Table 9, the Greenhouse Gas Emissions Inventory of Chihuahua with Projections to 2025, and the State Program on Climate Change are local guidelines to address climate change (Gobierno de México, n.d.a).

In this context, Chihuahua's State Program on Climate Change makes emphasis on the efficient use of the water resources in agriculture and silviculture, as well as in the "transversal topics": sustainable irrigation projects, greenhouse gas emissions inventory, control, and reduction, and environmental education (Gobierno del Estado de Chihuahua, 2014).

As of September 2020, the online tool Climate Tracker classified the efforts of Mexico on reducing emissions according to their guidelines stated on the NDCs as "insufficient" (Climate Action Tracker, 2020).

2.8. The WaCCliM program

Several organizations globally actively address the problematic of climate change and its impacts on an environmental and social scale. The German Society of International Cooperation or Deutsche Gesellschaft für Inrternationale Zusammenarbeit (*GIZ* by its abbreviation in German) is an international association headquartered in Bonn and Eschborn, Germany, with contributions focused particularly in the sustainable development of developing countries, by partnering with governments and local authorities (Deutsche Gesellschaft für Internationale Zusammenarbeit, 2020a). Among the fields of work of the *GIZ*, a focus in sustainable water infrastructure aims to improve conditions of current water policies, sanitation and supply, and general management of the hydric resources in vulnerable regions (Deutsche Gesellschaft für Internationale Zusammenarbeit, 2020b). The Water and Wastewater Companies of Climate Change Mitigation (WaCCliM) is one of the partner projects from the GIZ, addressing water-related sustainable alternatives for climate change.

2.8.1. Scope

WaCClIM is a project aiming for short- and long-term improvements withing the water sector (supply or treatment) in order to reduce the emission of greenhouse gases from these infrastructures, by adopting energy efficiency measures and gradual reformations to the existent systems (Water and Wastewater Companies for Climate Mitigation, n.d.a). This program operates simultaneously on a local, national, and international level, by approaching directly water and wastewater operators, to provide technical support on the monitoring of their greenhouse gas emissions (Water and Wastewater Companies for Climate Mitigation, n.d.c). The main goal is reaching carbon-neutral water utilities, through the implementation of sustainable interventions, and raising education and awareness among the key stakeholders involved in this context (Water and Wastewater Companies for Climate Mitigation, n.d.d)

2.8.2. Role in the energy and emissions improvement of the wastewater sector worldwide

WaCCliM has, or had for years, operations in four countries worldwide, including: Jordan, Mexico, Peru, and Thailand, in which water utilizes and operators followed the previously mentioned roadmap to reach a low-carbon infrastructures (Water and Wastewater Companies for Climate Mitigation, n.d.b).

Jordan is a country with a similar climate with Northern Mexico, according to the Köppen-Geiger classification, thus, extreme drought events occur frequently in this country, and water supply per capital is expected to drop from 100 mm^3/year in 2016, to around 91 mm^3/year by 2025 (Water and Wastewater Companies for Climate Mitigation, 2018a). In addition to this, the water sector's energy consumption accounts for around 14 percent of the total production of the country, making it one of the leading energy-consuming sectors of the country (Water and Wastewater Companies for Climate Mitigation, 2017a). The work of WaCClIM in Jordan was focused in the wastewater utility of the city of Madaba, which information is summarized in Table 10.

Table 10. Select information on the wastewater utility of Madaba, Jordan (Robles, 2020). Adapted from (Water and Wastewater Companies for Climate Mitigation, 2017a)

Resident population	**190,000**
Served population	**187,000**
Water coverage	**99%**
Sanitation coverage	**49%**
Energy consumption	**30,375 MWh/year**
Wastewater volume (in m^3)	**2,390,000**
Treatment system	**Activated sludge**
Reuse of treated wastewater	**100%**

To address the high energy consumption of this utility, alternative energy sources were assessed, such as solar resources, or biogas generation from the sludge processing stages (Water and Wastewater Companies for Climate Mitigation, 2018a).

In Latin America, specifically in Peru, WaCCliM worked with drinking water and wastewater utilities, along with local governments, to address the role of climate change of this sector, and reduce greenhouse gas emissions from water infrastructures (Water and Wastewater Companies for Climate Mitigation, 2018c).

In a country with a comparable governance, culture, and social context to Mexico, the factors that drove this project to success in Peru were the willingness of the political sector to commit with the proposed climate change adaptation and mitigation measures, an implemented bottom-up approach that allowed stakeholder to identify opportunities to improve and escalate them to other actors, and the active cooperation between water companies and academy (Water and Wastewater Companies for Climate Mitigation, 2018c). On the other hand, resistance from certain group of employees from water utilities, and a perception of high investments as a result of the implementation of the measures, were among the main obstacles the project faced during its execution (Water and Wastewater Companies for Climate Mitigation, 2018c).

2.8.3. Projects in Mexico

WaCCliM deployed between 2014 and 2018 projects to improve the carbon footprint of water and wastewater infrastructures in San Francisco del Rincon, Guanajuato, located in the central region of Mexico. (Water and Wastewater Companies for Climate Mitigation, 2017b). This municipality of some 130,000 inhabitants as of 2016 accounts for a strong apparel industry, particularly hats and sport shoes (Water and Wastewater Companies for Climate Mitigation, 2018b). In terms of agriculture, this sector receives around 80 percent of its water supply from a reservoir with freshwater mixed with raw and treated wastewater. (Water and Wastewater Companies for Climate Mitigation, 2018b). The local wastewater treatment plant began operations in 2013, with the purpose of treating the municipal wastewater, using anaerobic sludge to generate biogas (thus, an alternative source of energy), and reutilizing the effluent for irrigation in agriculture, initiative that is currently being developed (Water and Wastewater Companies for Climate Mitigation, 2018b).

Table 11 shows select operational data of the water and wastewater infrastructures of San Francisco del Rincon. It is estimated that increasing the coverage of the wastewater treatment plant for some 52,200 additional inhabitants, contributed to prevent greenhouse emissions amounting to some 2,500 metric tons of carbon dioxide equivalent annually, as raw wastewater emits as much as three times the amount of pollutants than conventionally-treated wastewater (Water and Wastewater Companies for Climate Mitigation, 2017b).

Table 11. Select information on the water and wastewater operations in San Francisco del Rincon, Guanajuato, Mexico. Robles (2020). Adapted from (Water and Wastewater Companies for Climate Mitigation, 2017b).

	Water supply	Wastewater treatment
Treatment technology	NA	Activated sludge
Serviced population	122,200	82,500
Coverage	95%	-
Energy cost	350,000 EUR/a	140,000 EUR/a
Biogas production	-	1,500 MWh/a
Volume supplied or treated	7,150,000 m^3/a	5,200,000 m^3/a
Water reutilization	-	31,600 m^3/a

From the information displayed in Table 11 it is possible to infer that from the around 7.15 million cubic meters of waters served to the municipality, only some 72.7 percent is processed at the treatment facility. Considering that part of this share of missing water is transformed in other processes of the hydrological cycle, such as infiltration and evapotranspiration, further efforts to expand the sewage coverage and wastewater reutilization need to be implemented, in order to create a greater impact in greenhouse gas emissions and water consumption.

The municipality of San Francisco del Rincon accounts for a different climate classification than Chihuahua (Climate Data, 2020), thus there is differences in weather patterns and events. Nevertheless, the experience in the north-central state set a precedent of the work of WaCCliM at the local and federal level, as well as a technical background that increases the feasibility of communication and implementation of further initiatives in other regions of Mexico.

2.9. Wastewater reutilization for agriculture – case studies globally

Part of the methodology of this document consists of researching and describing successful case studies worldwide, in similar climate zones, where the reuse of wastewater for irrigation is deployed at a small or large scale.

2.9.1. Case study 1

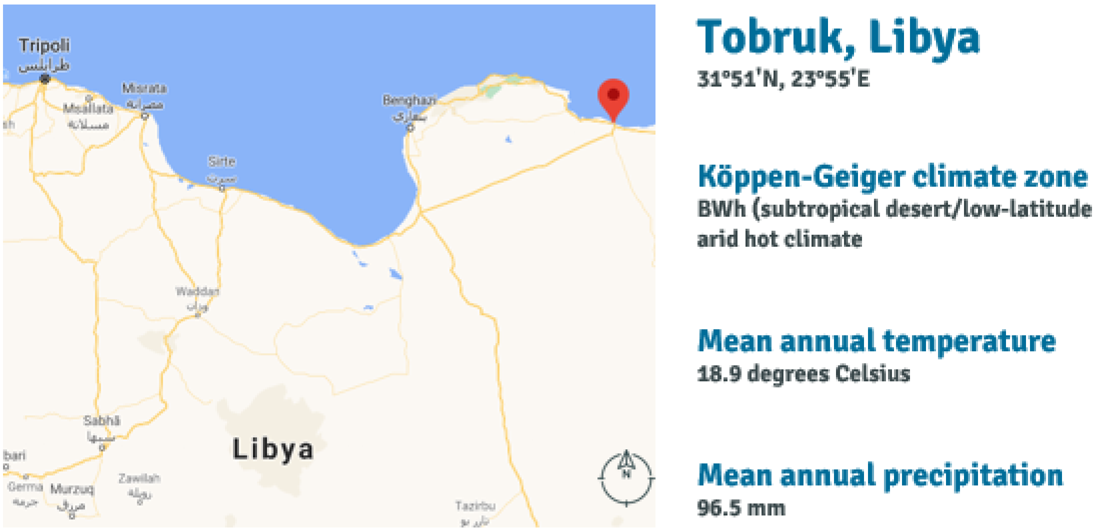


Figure 24. Selected climate and weather data for Tobruk, Libya. Robles (2021). Google Maps (2021). (ClimaTemps, n.d.b)

Tobruk is an urban area located in the northeastern part of Libya, and accounted for a population of approximately 100,000 inhabitants as of 2015 (Abdulla & Ouki, 2015). This region's arable land amounts to around 945 hectares, growing crops such as tomato, pepper, lettuce, and onion (Abdulla & Ouki, 2015).

The absence of surface water bodies and the decline of groundwater resources, due to the high-water consumption patterns of the population and the weather conditions, have driven the necessity of exploring different technologies to obtain water (Abdulla & Ouki, 2015). In this context, the production of desalinated water has become the main source of this resource for the city, including some 3,500 cubic meters per day of water required to cover the demand for agriculture (Abdulla & Ouki, 2015). According to Abdulla and Ouki (Abdulla & Ouki, 2015), the process of water desalination involves the generation of waste and is highly dependent of fossil fuels, thus this technology does not favor sustainability in terms of its environmental impacts.

As a result, Abdulla and Ouki (Abdulla & Ouki, 2015) evaluate the technical and social feasibility of using the treated wastewater for irrigation in agriculture, to alleviate the high water demand in the region, and decrease the consumption of desalinated water.

The physicochemical and biological parameters of the Tobruk's wastewater treatment plant indicate that this effluent is suitable for reuse in agriculture, as the toxicity, salinity, pathogenic, and nutrients assessment fall under the recommendations of several studies and organizations (Abdulla & Ouki, 2015).

Abdulla and Ouki (Abdulla & Ouki, 2015) recommend drip irrigation technologies to manage the reuse of wastewater in agriculture, as it is an economic methodology, and has positive hygienic implications during the operation, that makes it advantageous compared to other irrigation methods.

The study of Abudall and Ouki (Abdulla & Ouki, 2015) suggests that, despite the conventional wastewater treatment produce an effluent with the necessary characteristics for irrigation, waste stabilization ponds could be implemented due to its efficiency in removing pollutants, simple construction, and adaptability to the type of climate of the region.

2.9.2. Case study 2

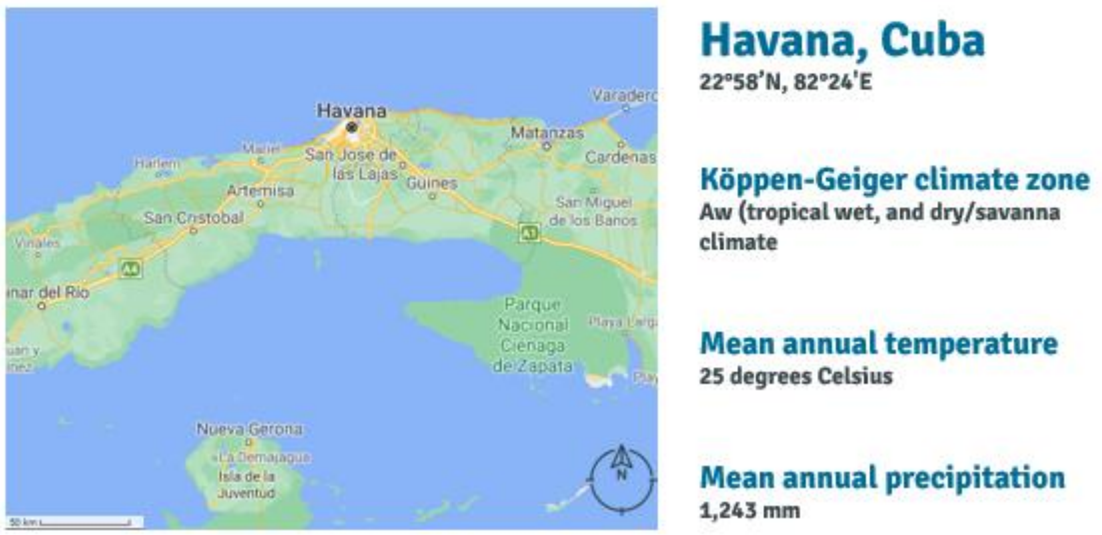


Figure 25. Selected climate and weather data for Tobruk, Libya. Robles (2021). Google Maps (2021). (ClimaTemps, n.d.a)

Méndez et al (Méndez, Ricardo, Pérez, Hernández, & Campos, 2006) studied the reutilization of wastewater for urban agriculture due to the lack of this resource to cover the demand for agricultural uses in Havana, Cuba. This proposal was under three different scenarios:

- Irrigation with raw (untreated) wastewater,
- Irrigation with a mixture of 50 percent raw wastewater and 50 percent freshwater from the city network (dilution),
- Irrigation only with the city network's water.

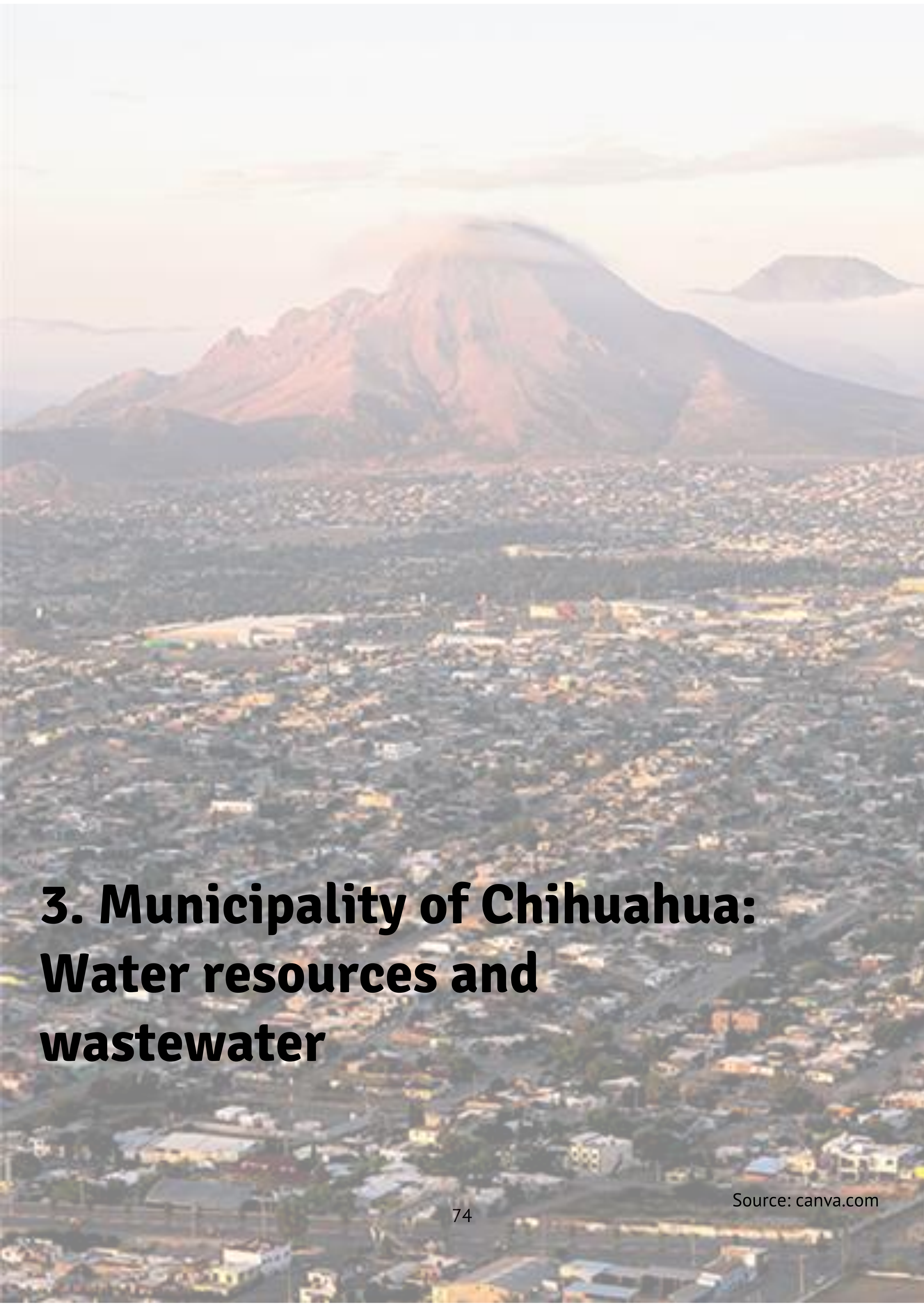
Table 12 depicts selected physicochemical and biological parameters of the raw wastewater used in for this experiment. In this context, four essays took place for this evaluation: two during the rainy season, and two during the dry season. The crops irrigated under the described scenarios were radish, carrot, and the native Mexican flower of Marigold (Méndez et al., 2006).

Table 12. Physicochemical and biological parameters of the raw wastewater used for irrigation in Havana, Cuba. Robles (2021). Adapted from (Méndez et al., 2006)

Parameter	Concentration (in mg/L)
BOD_5	160
COD	114.4
Dissolved Oxygen	0
Fecal coliforms (in NMP/100 mL)	790,000
Nitrite	0.86

From the observations of Méndez et al (Méndez et al., 2006), the authors concluded that, due to the lack of evidence of a decrease in the crop production's performance, wastewater should be used for irrigation under any feasible condition. In the case of wastewater irrigation for carrot and radish, it was observed a slight increase in production rates, due to the high presence of nutrients in this resource (nitrogen, phosphorus, potassium) (Méndez et al., 2006).

The irrigation method implemented in Havana was drip irrigation, showing an good overall good performance (Méndez et al., 2006), nevertheless, as in this case study the wastewater was not previously treated, operational problems appeared through the experiment, such as clogging of filters or emitters (Méndez et al., 2006). The case study of Havana, despite proving that drip irrigation using wastewater is effective on the selected crops, it does not provide major information about other relevant parameters, water volume required, and possibility of using treated wastewater and sludge.



3. Municipality of Chihuahua: Water resources and wastewater

Source: canva.com

3.1. Existing wastewater system evaluation

According to the inventory of wastewater treatment plants with an installed capacity of 200 l/s in Mexico summarized by WaCCliM (B. Corona, personal communication, May 12, 2020), the state of Chihuahua accounts for seven facilities with this characteristic as of 2017, of which the city of Chihuahua (the capital of the state) holds two plants with an affluent of over 200 l/s: north and south WWTP.

The north and south wastewater treatment plants of Chihuahua treat around 400 and 1,350 l/s, respectively (Banco de Desarrollo del América del Norte, 2019), both operating with activated sludge technologies. Figure 26 depicts the location of these facilities in Chihuahua.

Figure 26. Location of the north (in orange) and south (in blue) wastewater treatment plants in Chihuahua (Robles, 2021). Google Maps (2021)

As of the end of 2020, a project about the modernization and rehabilitation of the two existing wastewater treatment plants in the municipality of Chihuahua, state of Chihuahua, is being developed with the financial support of the North American Development Bank (NADB), and which total value amounts to approximately 14.7 million Mexican dollars (some 700,000 U.S. dollars as of October 2020) (Banco de Desarrollo del América del Norte, n.d.).

According to the NADB (Banco de Desarrollo del América del Norte, n.d.), this project is expected to expand the treatment capacity of the North and South wastewater treatment plants, reaching up to 500 liters per second and 1,875 liters per second, respectively, decrease the total volume of sludge generated by 33 percent, and improve the quality of the final effluent, reducing the number of non-compliances with the federal legislations.

3.1.1. Installed technology of treatment

The general diagram of the wastewater treatment process in the South Wastewater Treatment Plant of Chihuahua is depicted in Figure 27.

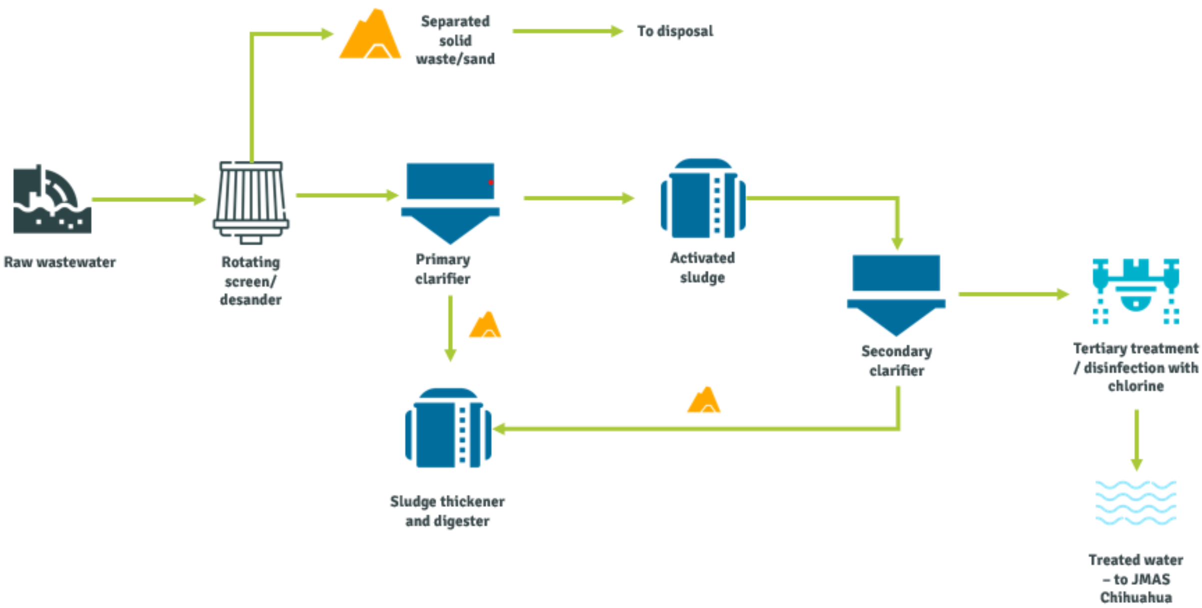


Figure 27. Flow diagram of the South Wastewater Treatment Plant of Chihuahua (Robles, 2020). Adapted from (M. Olmos, personal communication, December 4, 2021)

3.1.1.1. Pretreatment

According to the information shared by Dr. Mario Olmos (M. Olmos, personal communication, December 4, 2021), from the JMAS Haga clic o pulse aquí para escribir texto. Chihuahua, treats around 1,400 liters per second, and in case of an event of exceeding the peak capacity of the facility, the overflow is sent directly to the effluent of the plant.

The pretreatment of the plant consists of an automatic rotating screen with a separation of eight millimeters, which intends to separate garbage, or solid waste, from wastewater, at a rate of around nine cubic meters per day (M. Olmos, personal communication, December 4, 2021). The effluent from the rotating screens is directed to two sand removers with hydrocyclones, with the objective of separating sediments from the water flow, which are washed and treated separately to remove the organic matter from its content (M. Olmos, personal communication, December 4, 2021).

3.1.1.2. Biologic treatment

After the pretreatment, the wastewater is directed to a primary clarifier, with preliminary removal rates for total suspended solids (TSS), BOD, COD, and fats and greases, and where primary sludge is generated and sedimented at the bottom of the tank, while the remaining effluent is sent by gravity to the biologic reactors (M. Olmos, personal communication, December 4, 2021).

The biologic reactors are aerobic, with a technology of activated sludge, where air is introduced in the system to create a mix of microorganisms and organic matter, which results in the flocculation of the mixture, decreasing the concentration of COD and BOD of the wastewater, and transforming the organic matter into carbon dioxide (CO_2) and water (H_2O). (M. Olmos, personal communication, December 4, 2021). To assure a proper removal of the organic matter from the wastewater, an input of around 1.1. kilograms of oxygen per kilogram of BOD should be introduced in the system (M. Olmos, personal communication, December 4, 2021).

As described in previous sections, the microbial floc generated during the activated sludge phase, accounts for a major relevance in the generation of biomass with potential uses in agriculture, due to its high concentration of nutrients.

The effluent from the biologic reactors is directed towards a second clarifier tank, which generates an additional amount of sludge from the biologic reactors, and by the end of this step of the treatment, it is expected to have a removal rate of around 80 percent of the organic matter in the form of BOD and COD, and around 66 percent of removal efficiency of TSS (M. Olmos, personal communication, December 4, 2021).

3.1.1.3. Tertiary treatment

The effluent with low concentrations of organic matter and total suspended solids from the biologic phase, undergoes a final stage of treatment through a disinfection of the wastewater with chlorine (in the form of gas), with aims to decrease the concentration of total and fecal coliforms (M. Olmos, personal communication, December 4, 2021), which as described in previous sections, pose a relevant threat for human health if the wastewater is recycled or discharged in water bodies where populations potentially make use of the water .The effluent has three final destinations, depicted in Figure 28.

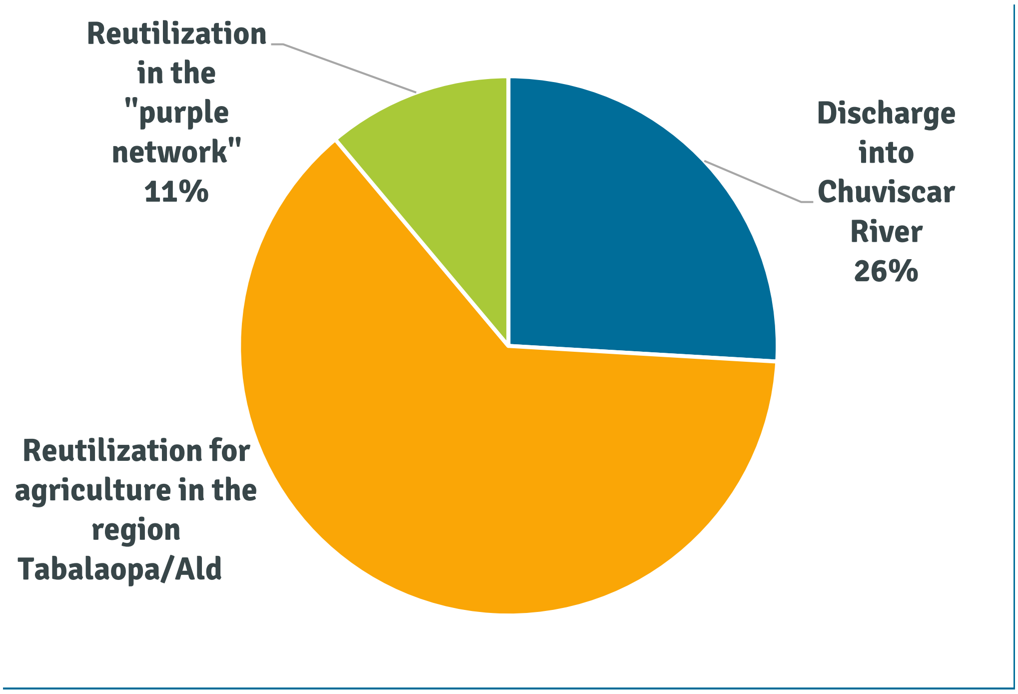


Figure 28. Share of effluent discharges of the Chihuahua's south wastewater treatment plant, by destination. Robles (2020). Adapted from (Banco de Desarrollo del América del Norte, 2019; M. Olmos, personal communication, December 16, 2020)

3.1.1.4. Sludge treatment and disposal

While the sludge generated in the primary clarifier is directly carried to the digestion stage, the secondary sludge from the biologic treatment undergoes a thickening process with a polymer (M. Olmos, personal communication, December 4, 2021).

The mixture of primary and thickened secondary sludge is directed to the digestor, where an anaerobic process (hydrolysis, acetogenesis, and methanogenesis) of the sludge place, and biogas (a mixture of primarily methane and carbon dioxide) is generated, which is internally used for the digestor and water heating (M. Olmos, personal communication, December 4, 2021). The remaining sludge from the anaerobic digestion process is dehydrated through a filter press, with an approximate generation of almost 170 cubic meters per day (M. Olmos, personal communication, December 4, 2021). According to the information shared by the JMAS Chihuahua and Dr. Mario Olmos (M. Olmos, personal communication, December 4, 2021), the south wastewater treatment plant of Chihuahua generates dehydrated sludge that is provided to local farmers and land workers due to its high microbial and nutrient content.

3.1.1.5. Wastewater reutilization methods

As mentioned in previous sections, the information compiled from different sources (Banco de Desarrollo del América del Norte, n.d.; M. Olmos, personal communication, December 4, 2021) indicated that the treated effluent from Chihuahua's City wastewater treatment plant is currently reused in the city (for irrigation of green areas) and in agriculture. Nevertheless, there is a lack of public data concerning how this effluent is transported or which irrigation methods are implementing on the agriculture fields. According to the information of Dr. Mario Olmos (M. Olmos, personal communication, February 5, 2021), the effluent of the wastewater is discharged onto the different rivers and canals of Chihuahua City, and from there it is withdrawn from each land worker or farmer for his or her purposes.

3.2. Aquifers and surface water bodies

As of 2013, Chihuahua was one of the leading Mexican states in freshwater withdrawals from groundwater bodies, at approximately 387.8 million cubic meters annually, as depicted in Figure 29, only behind the State of Mexico and Mexico City (formerly known as Distrito Federal) (Instituto Nacional de Estadística y Geografía, 2013).

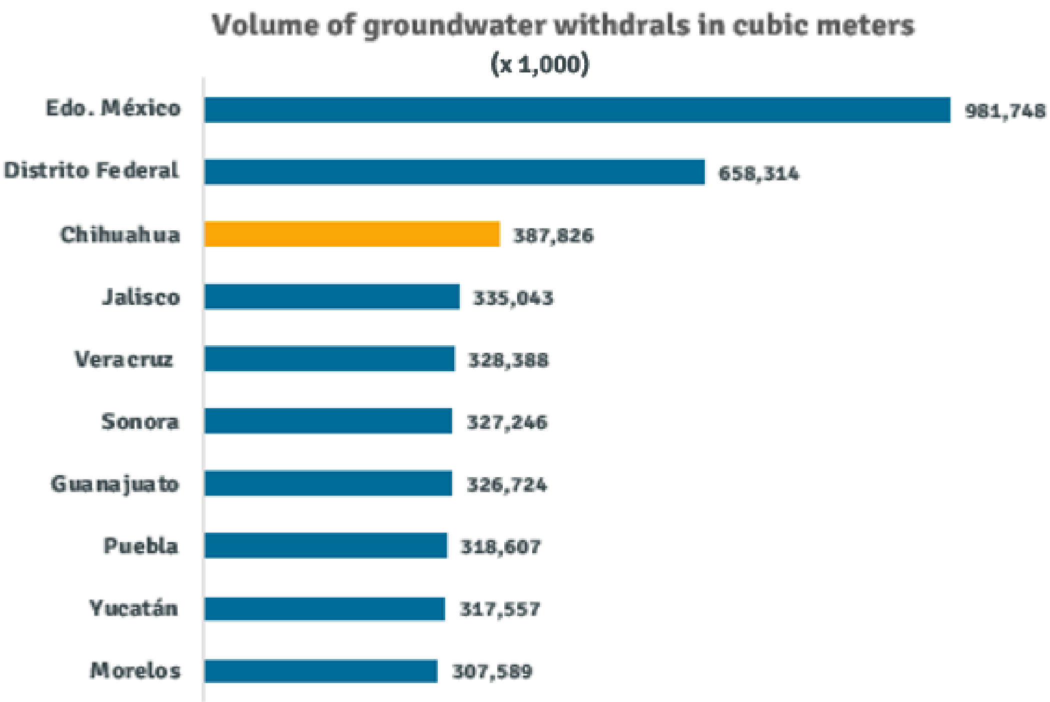


Figure 29. Groundwater withdrawals in Mexico by state, in thousand cubic meters. (Robles, 2020). Adapted from (Instituto Nacional de Estadística y Geografía, 2013)

In this context, around 99 percent of the water consumption described in previous sections is sourced by groundwater bodies, or aquifers, located in or surrounding the municipality of Chihuahua. (Instituto de Planeación Integral del Municipio de Chihuahua, 2009). Figure 30 displays the approximate are of influence of the six aquifers surrounding the city of Chihuahua.

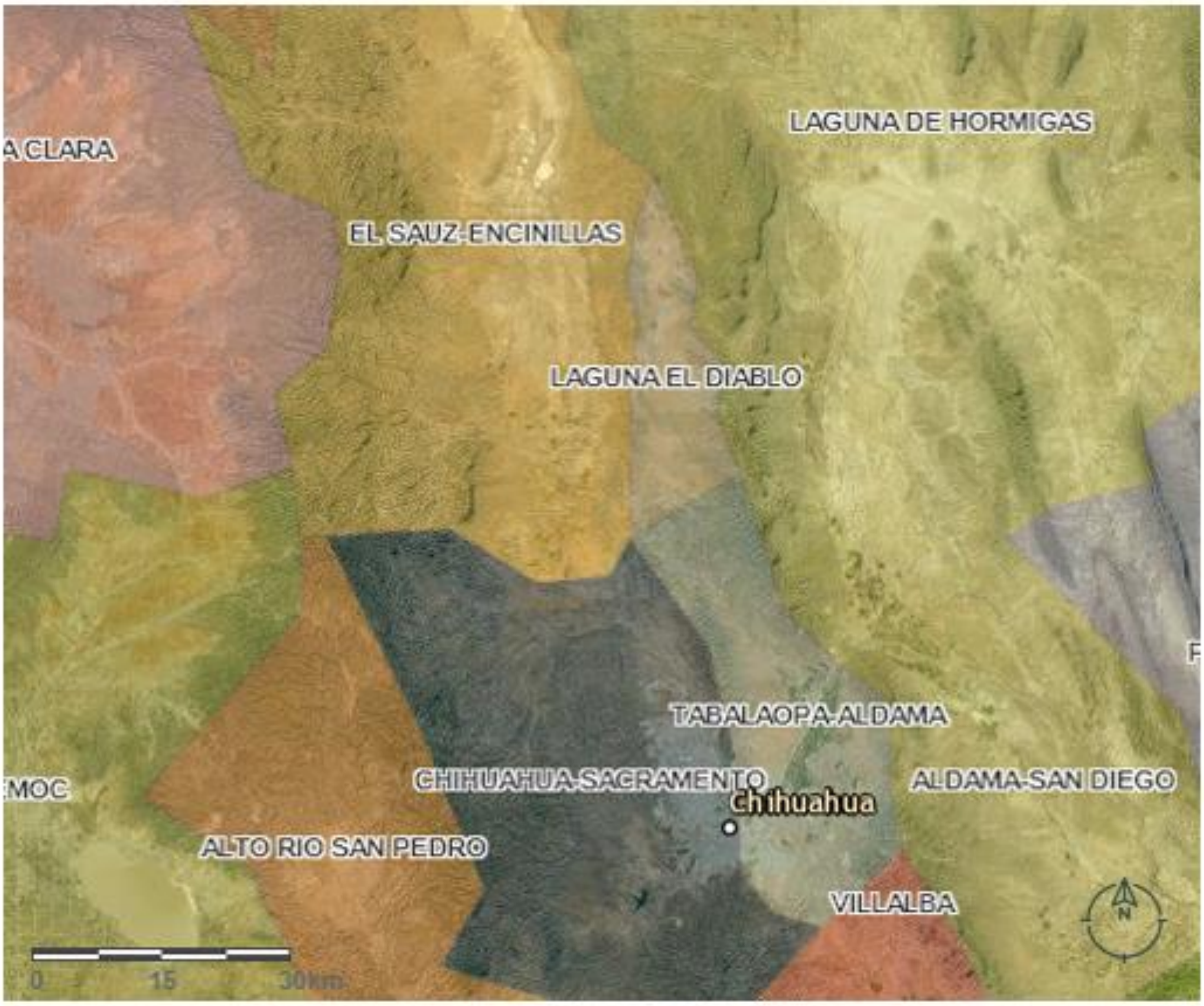


Figure 30. Aquifers influencing the municipality of Chihuahua (Comisión Nacional del Agua, 2018)

From Figure 30 it is possible to determine that the aquifers of Chihuahua-Sacramento and Tabalaopa-Aldama have a considerable relevance due to their geographical position relative to the urban area. To understand the current condition of the six aquifers influencing Chihuahua, Table 13 shows the balance recharge-withdrawals in the water body, and the overall status of the aquifer in terms of its exploitation.

Table 13. Situation of the aquifers in the municipality of Chihuahua. Robles (2020). Adapted from (Instituto de Planeación Integral del Municipio de Chihuahua, 2009)

Aquifer	Recharge (Mm^3/a)	Withdrawals (Mm^3/a)	Situation
Sauz Encinillas	106.5	118.2	Overexploited
Laguna del Diablo	4.3	0.22	Underexploited
Laguna de Hormigas	64	16	Underexploited
Chihuahua-Sacramento	65.8	120.5	Overexploited
Tabaloapa Aldama	55.1	66.1	Overexploited
Aldama-San Diego	35.2	21.1	Underexploited without availability

The study of the National Institute for Integral Planning of Chihuahua (IMPLAN, from its abbreviation in Spanish) (Instituto de Planeación Integral del Municipio de Chihuahua, 2009) determine that three of the six aquifers influence the city of Chihuahua present a condition of overexploitation, of which two of them are geographically ubicated in the urban area.

According to the IMPLAN Chihuahua (Instituto Mexicano de Tecnología del Agua, 2019), Chihuahua City accounts for surface water bodies such as rivers, creeks, and dams, which mostly provide water for agriculture irrigation. Nevertheless, the environmental role and importance of the main surface water bodies Sacramento River, and Chuvíscar Dam and River, has decreased as a result of a prioritization of their urban benefits in the last 50 years, therefore the flow and quality of these rivers and dams has deteriorated (Instituto Mexicano de Tecnología del Agua, 2019). Figure 31 displays the main rivers, creeks, and dams in Chihuahua City.

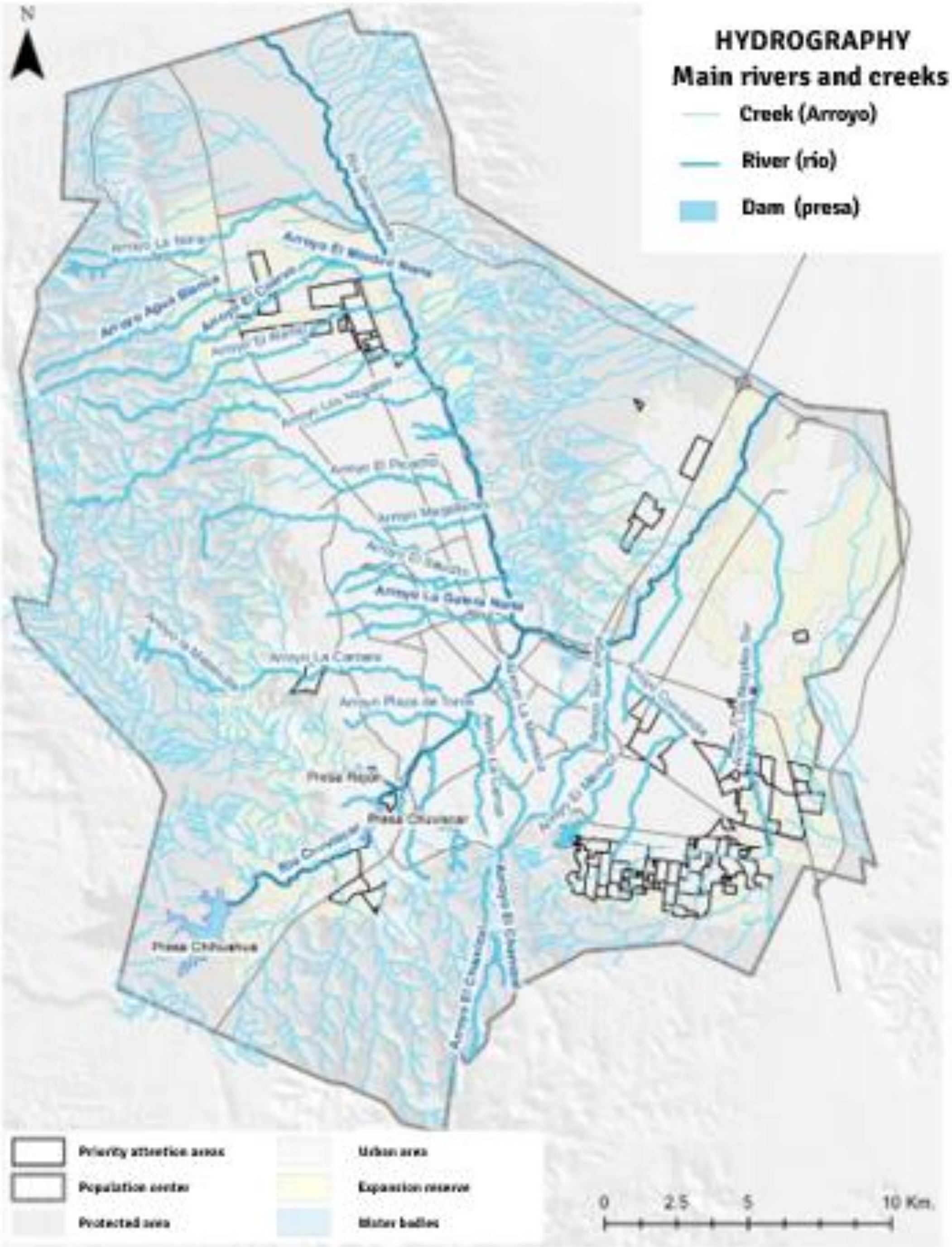


Figure 31. Surface water bodies in Chihuahua City. Robles (2021). Adapted from (Instituto Mexicano de Tecnología del Agua, 2019)

Overall, Figure 32 depicts an analysis of the strengths, weaknesses, opportunities, and threats (SWOT) for the water and wastewater situation in the City of Chihuahua.

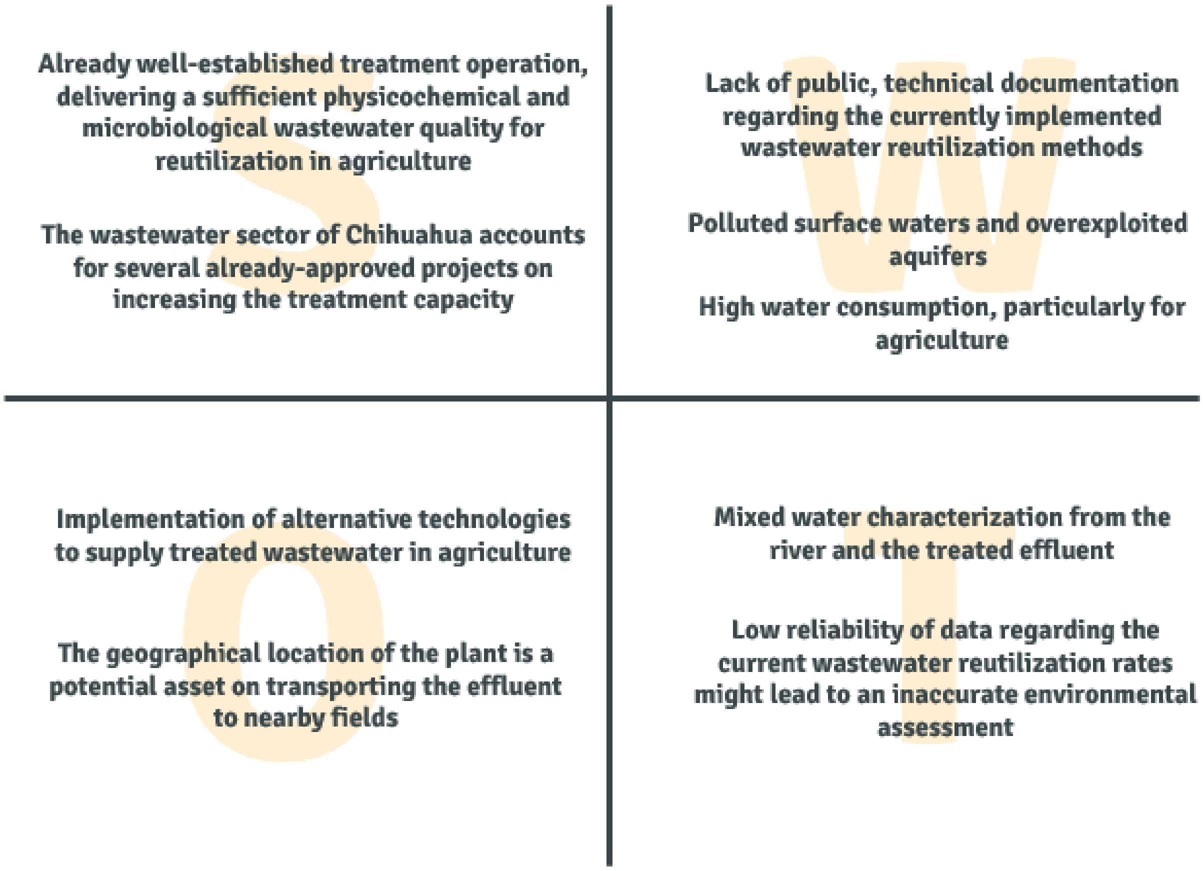


Figure 32. SWOT analysis of the water and wastewater situation in Chihuahua. Robles (2021).

The case study of this research will focus on the area of influence of one of the three groundwater bodies with a condition of overexploitation, Tabalaopa-Aldama aquifer, where geographically the south wastewater treatment plant of Chihuahua is located, and the potential of wastewater reutilization for local agriculture is relevant.

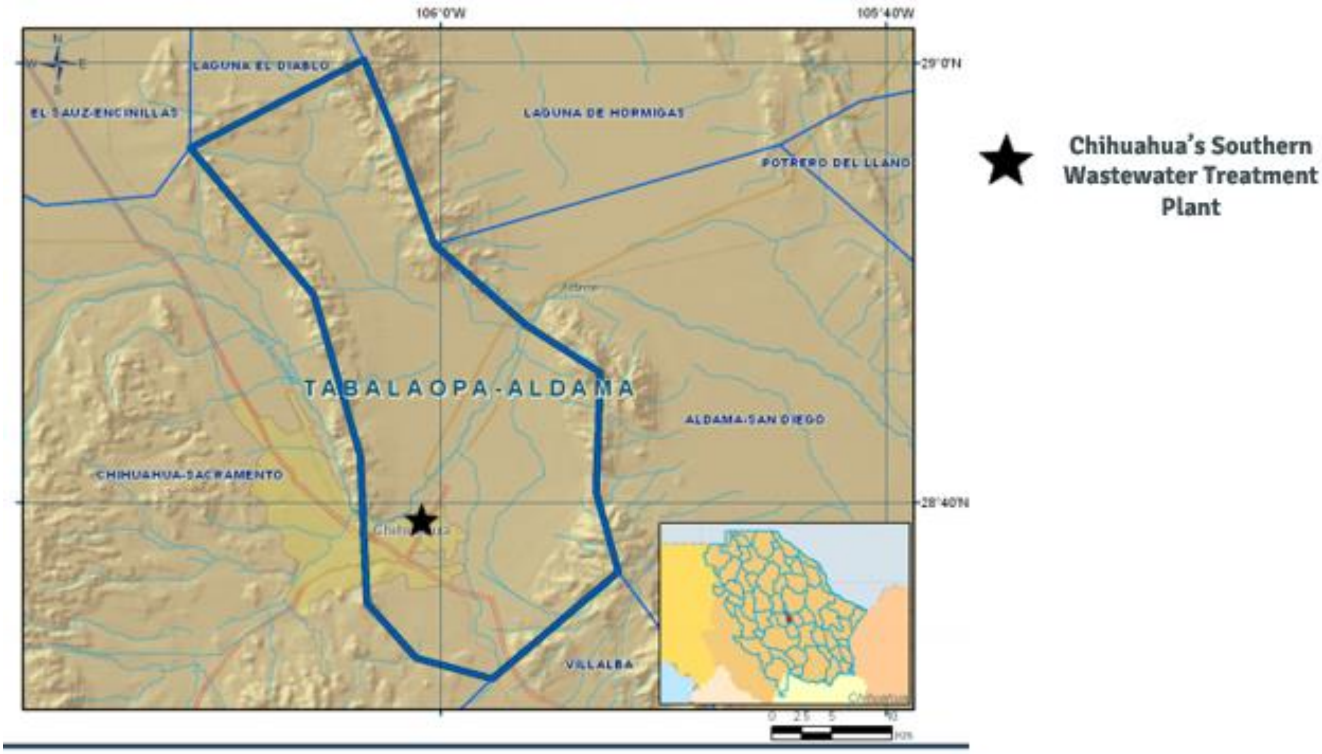
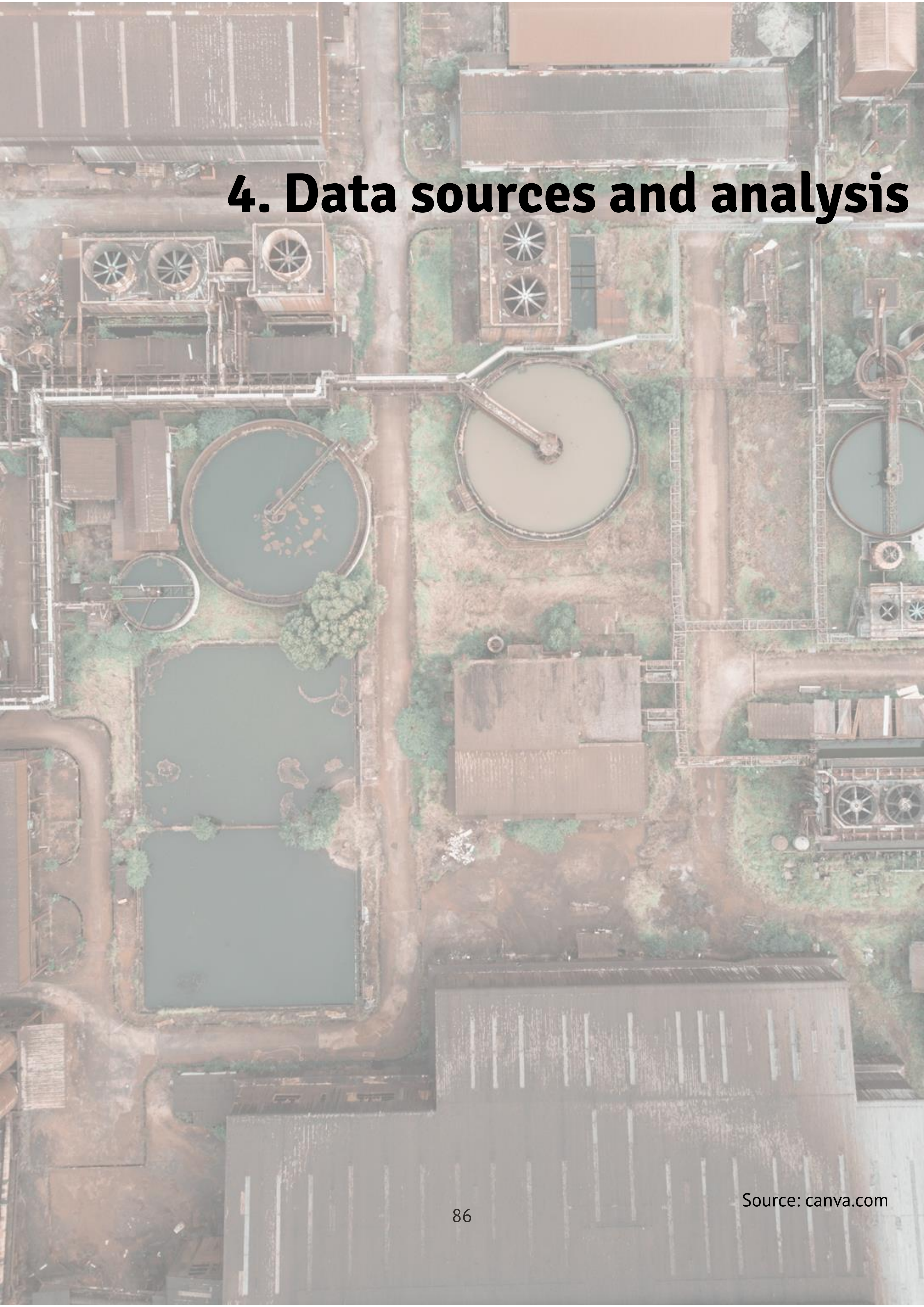


Figure 33. Geographical location of Chihuahua's south wastewater treatment plant within the area of influence of the Tabalaopa-Aldama aquifer. Robles (2020). Adapted from (Comisión Nacional del Agua, 2015a)

4. Data sources and analysis



Source: canva.com

4.1. Current municipal wastewater quality

The JMAS Chihuahua through its chief of sanitation Dr. Mario Olmos (M. Olmos, personal communication, December 14, 2020) facilitated data on the quality of the wastewater affluent and effluent for the south wastewater treatment plant, in the period comprised between January 2019 and November 2020, with the exceptions of the months of January and February 2020, as the monthly operational reports for these months were not provided by the source. Table 14 displays the average values of concentration of the key parameters of the affluent to Chihuahua's south wastewater treatment plant, for the previously mentioned period. The monthly averages of these parameters are shown in ANNEX VII, Table A. X. For a detailed and complete visualization of the raw data provided by the source, please consult the archives "**Monthly operational parameters**" in the supplementary files.

Table 14. Average key parameters of the ***affluent*** *of Chihuahua's south wastewater treatment plant. Robles (2020), Adapted from (M. Olmos, personal communication, December 14, 2020)*

Parameter	Concentration
Volume received (m3)	**78,661,049.00**
pH[1]	**7.61**
Total Suspended Solids (mg/L)	**209.57**
Biochemical Oxygen Demand[2] (mg/L)	**222.5**
Chemical Oxygen Demand (mg/L)	**491.69**
Fecal Coliforms[3] (cfu/100 mL)	**51,341,408.61**
Total Nitrogen[4] (mg/L)	**41.03**
Total Phosphorus (mg/L)	**6.21**

The key parameters of the effluent from the wastewater treatment plant in Chihuahua are displayed in Table 15. The monthly averages of these parameters are displayed in Table A. XI.

*Table 15. Average key parameters of the **effluent** of Chihuahua's south wastewater treatment plant. Robles (2020), Adapted from (M. Olmos, personal communication, December 14, 2020)*

Parameter	Concentration
Volume discharged (m3)	**64,261,156.19**
pH[1]	**7.6**
Total Suspended Solids (mg/L)	**15.06**
Biochemical Oxygen Demand[2] (mg/L)	**12.62**
Chemical Oxygen Demand (mg/L)	**27.82**
Fecal Coliforms[3] (cfu/100 mL)	**< 3**
Total Nitrogen[4] (mg/L)	**21.62**
Total Phosphorus (mg/L)	**3.92**

[1] The pH value is an average only for the period from January to December 2019.
[2] BOD in five days. Value for February 2019 was not provided by the source.
[3] Data provided only for April 2020, and from August to November 2020.
[4] Data between October and December 2019 not provided by the source.

As described in previous sections, the concentration of metals in wastewater is relevant in the context of reutilization for crops growth. Table 16 displays the average concentration of metals in Chihuahua's wastewater treated effluent for the period 2019-2020.

Table 16. Average metals concentration in the effluent of Chihuahua's south wastewater treatment plant. Robles (2020), Adapted from (M. Olmos, personal communication, December 14, 2020; M. Olmos, personal communication, December 16, 2020)

Metal	Concentration (mg/L)
Arsenic	**0.0050**
Cadmium	**0.00009**
Cyanide	**0.0123**
Chrome	**0.0044**
Copper	**0.017**
Mercury	**0.00002**
Nickel	**0.003**
Lead	**0.0002**
Zinc	**0.037**

4.1.1. Interpretation of the wastewater characterization

Comparing the wastewater characteristics in the affluent of Chihuahua's south wastewater treatment with the benchmark presented in Table 2, the whole set of parameters accounts for concentrations ranging the average values in other countries, with the exception of the coliform count and the pH, which were not considered in the international comparison, however, the pH figure of Chihuahua's domestic wastewater amounts closer to the neutral value, slightly directed towards an alkaline behavior (United States Geological Survey, n.d.).

Figure 34 shows in a graphic way the comparison between selected physiochemical properties of the South wastewater treatment plant's effluent, and international benchmarking.

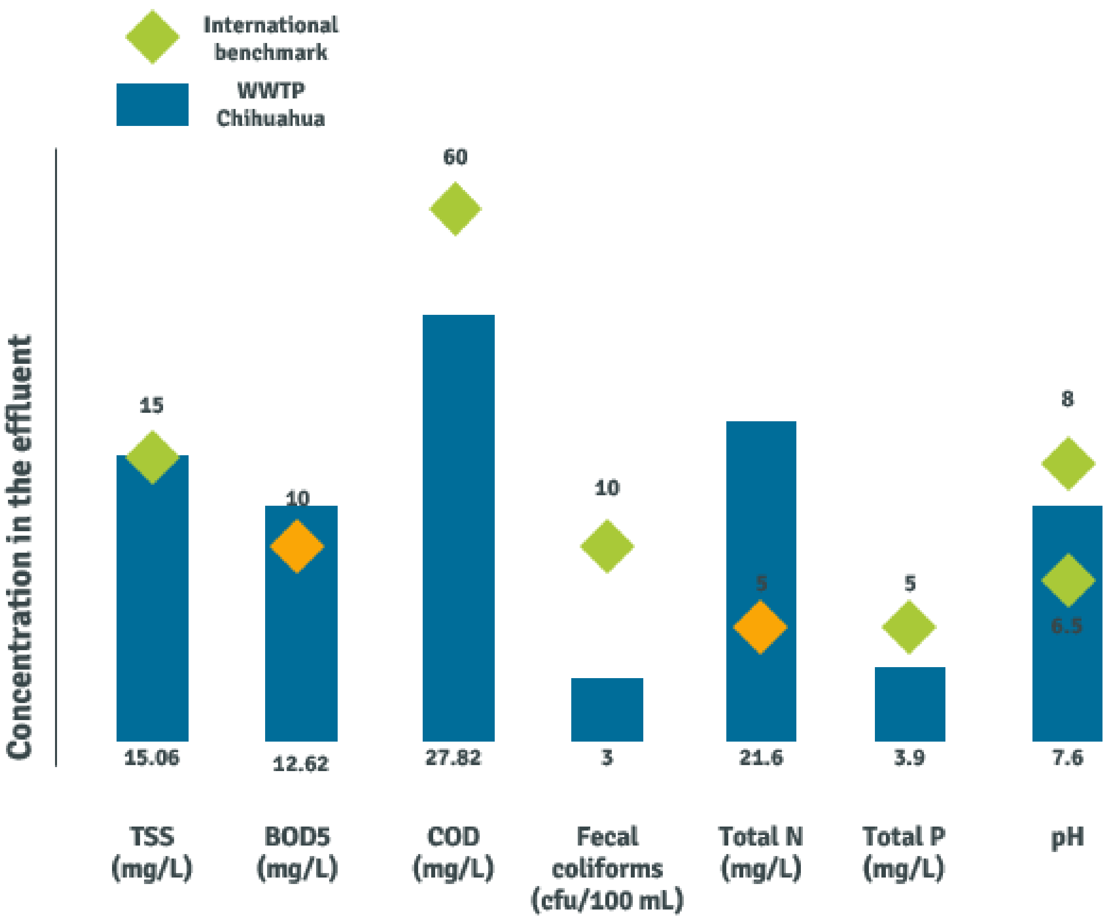


Figure 34. Comparison of the concentration of selected physicochemical parameters in wastewater from the WWTP Chihuahua and international benchmark. (Robles, 2020). Adapted from (M. Olmos, personal communication, December 16, 2020) and sources from Table A. II

Regarding the concentration of metals in the effluent of Chihuahua's south wastewater treatment plant, a comparison against the international benchmark displayed in Table A. II reflects that the current characteristics of the wastewater in the municipal infrastructure are favorable for the reutilization in agriculture. It is important to note that for the comparison displayed in Figure 35, the lowest value of the international benchmarking was considered, disregarding whether source was an organization, or a national authority's value. The value shown for Chihuahua's wastewater treatment corresponds to the average of the data collected from the JMAS Chihuahua (M. Olmos, personal communication, December 16, 2020)

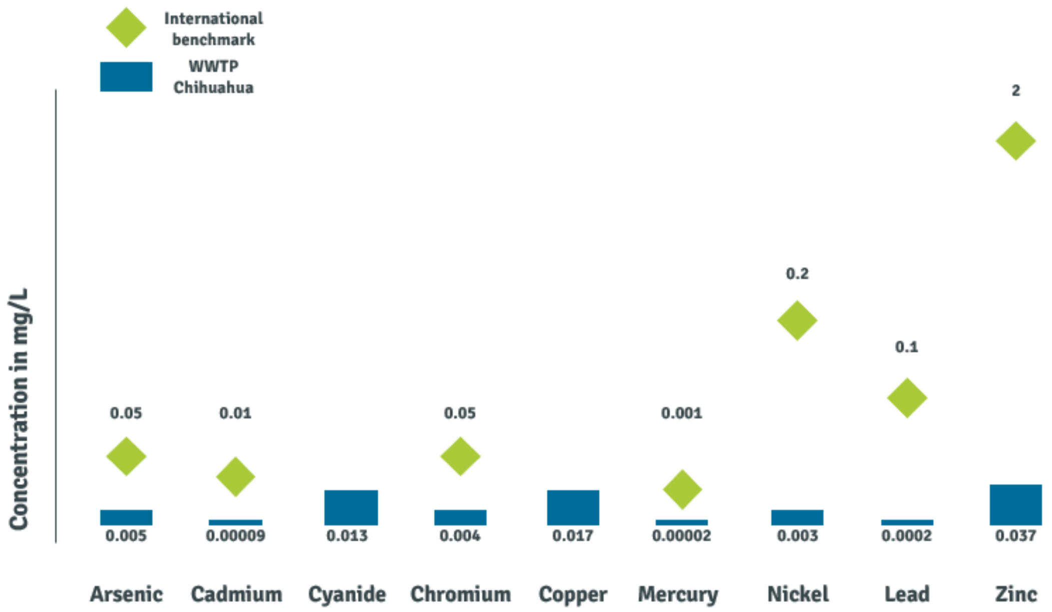


Figure 35. Comparison of the concentration of selected metals in water between the WWTP Chihuahua and international benchmark. (Robles, 2020). Adapted from (M. Olmos, personal communication, December 16, 2020) and sources from Table A. II

It is relevant to remark, the concentration of metals in Chihuahua's treated wastewater in 2019, was a result of one or two days of sampling at the beginning of each month, thus diminishing the reliability of the yearly and monthly averages. For the year 2020, only three months from the period January-November provided details on these figures. The technical staff of Chihuahua's south wastewater treatment plant analyze additional parameters than the ones suggested in the international benchmarking, such as cyanide and copper; however, concentrations of aluminum and iron were not provided by the source.

Despite that the physicochemical and microbiological quality of the treated effluent indicates that no operational changes should be implemented to reuse this wastewater in agriculture, it is crucial to note that this effluent characterization is no longer relevant, as the direct discharge onto already polluted surface water bodies will potentially change the concentration of the different parameters. In this context, the direct supply from the treatment facility

4.2. Energy Performance, and Carbon Emissions Assessment and Monitoring (ECAM) tool

The ECAM tool is developed by the WaCCliM project supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), and it is part of the International Climate Initiative (IKI) (Water and Wastewater Companies for Climate Mitigation, 2018d). According to the methodology manual for this tool (Water and Wastewater Companies for Climate Mitigation, 2018d), ECAM seeks to quantify greenhouse gas emissions from water and wastewater facilities, contributing to the achievement of the Nationally Determined Contributions (NDCs) by implementing measures that improve the energy efficiency and wastewater management.

To estimate the emissions of greenhouses gases at an initial or an advanced stage, the ECAM tool methodology follows the guidelines of the International Panel on Climate Change (IPCC) and its National Greenhouse Gases Inventory, and "complemented with the calculations method from the Biosolids Emissions Assessment Model (BEAM)" (Water and Wastewater Companies for Climate Mitigation, 2018d).

The initial and detailed estimation of the greenhouse gas emissions from the south wastewater treatment plant of Chihuahua is described in the following section. It is possible to consult the entire process of greenhouse gas estimation by accessing the ECAM website and loading the file "Chihuahua South WWTP" with an extension **.json** from the supplementary files.

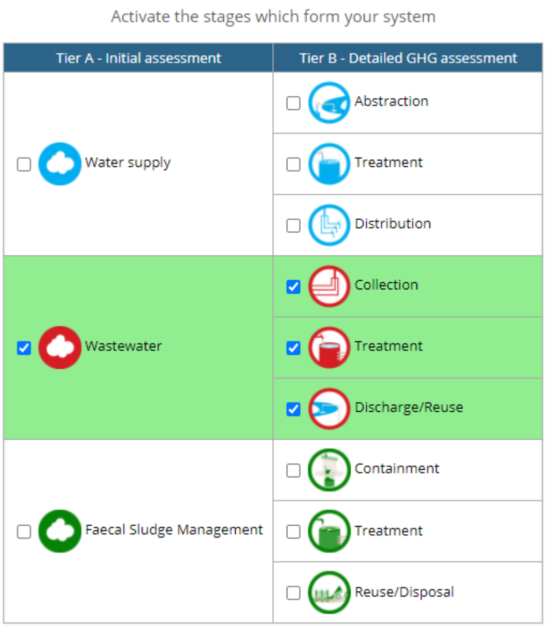
4.2.1. Procedure

To estimate the greenhouse gas emissions from the South wastewater treatment plant of Chihuahua City, a combination of operational data and estimations was necessary. A summary of the real operational data used in this assessment is depicted in Table 17. The rest of the variables, which are compiled from ANNEX IX to ANNEX XII are assumptions or own calculations from the software.

Table 17. Summary of real operational parameters used in the ECAM assessment. Robles (2021)

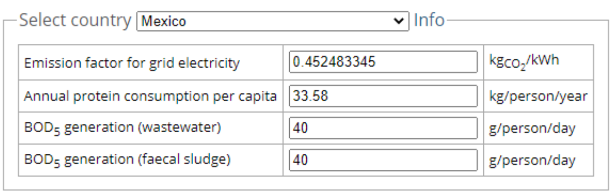
Selected parameters for GHG assessment (only year 2019)	
Parameter	**Value**
Population	**585,374**
Energy consumed from the grid (in kWh)	**7,897,784**
Total treated wastewater - affluent (in m3)	**48,546,535**
Total effluent volume (in m3)	**43,478,810**
Average nitrogen in the effluent (in mg/L)	**16.53**
BOD load in the effluent (in kg)	**642,275**

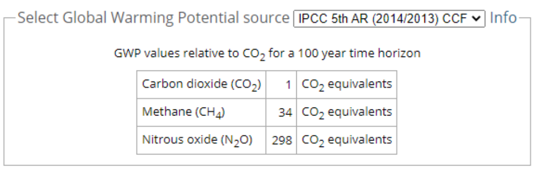
The initial configuration of the procedure involves the stages of the water or wastewater processes for which the evaluation of the greenhouse gas emissions is set to be implemented, for the purposes of this study, which limits this evaluation to the activity taking place at the south wastewater treatment plant, only this option is selected, for its three separate steps: collection, treatment and discharge, and for a timeframe of one year (2019).



To complete the preliminary information necessary for the following calculations, it is necessary to establish the context in which these processes are taking place. By specifying the country, some parameters are established automatically, such as: the emission factor for grid electricity, determined and defined by the original source as the "ratio of carbon dioxide emissions per energy consumed" (Brander, Sood, Wylie, Haughton, & Lovell, 2011), the annual protein consumption, retrieved directly from the database provided by the Food and Agriculture Organization (FAO) (Food and Agriculture Organization, 2020), and an estimate of the amount of organic load, in the form of biochemical oxygen demand (BOD5), generated daily by an individual in a specific country (Intergovernmental Panel on Climate Change, 2006).

The information concerning the global warming potential finds it source in the Fifth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change, 2014).



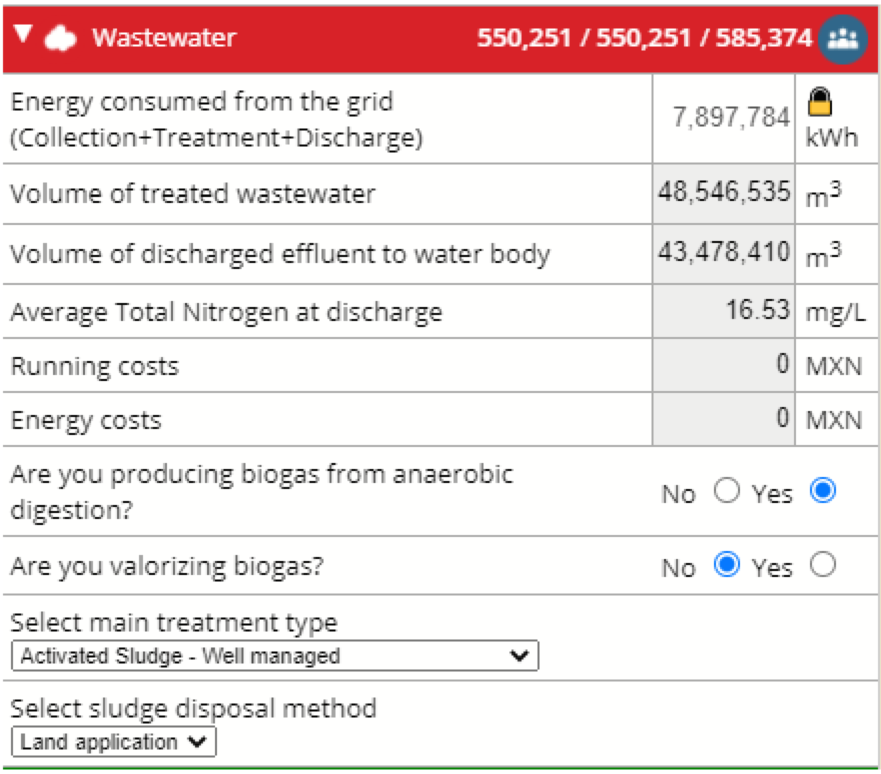


In the next stage, it is necessary to specify the current population of the city or municipality of study, as well as the share of inhabitants connected to the sewer. The total population of the municipality of Chihuahua as of 2015 was 878,062 (Instituto de

Planeación Integral del Municipio de Chihuahua, n.d.). As mentioned in previous sections, Chihuahua accounts for two different wastewater treatment plants serving its population, and in this context, it is necessary to determine or estimate the number of people served by the south wastewater treatment plant. According to the JMAS Chihuahua (Junta Municipal de Agua y Saneamiento de Chihuahua, 2018), this facility treats the generated wastewater from approximately two thirds of the population of the city, meaning some 585,374 inhabitants. Additionally, the North American Bank of Development (Banco de Desarrollo del América del Norte, 2019) stated in its last study, that roughly 94 percent of Chihuahua city's inhabitants were connected to the sewer, making the population served by this treatment plant around 550,251.

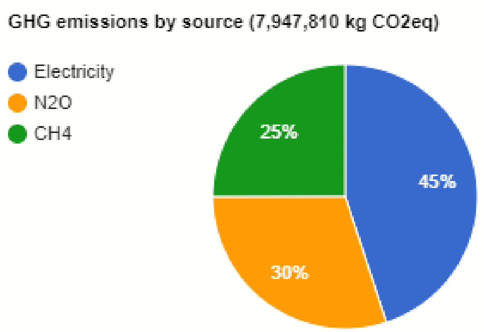
Wastewater		
Resident population	585,374	people
Population connected to sewers	550,246	people
Serviced population	550,246	people

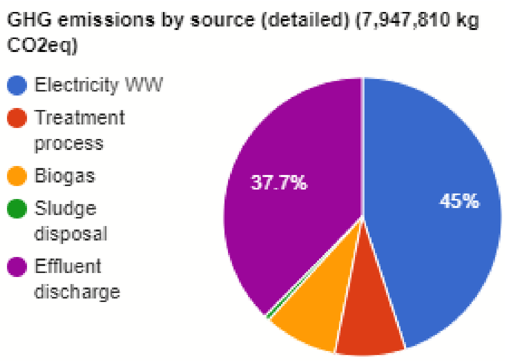
The ECAM tool provides a preliminary estimate for the greenhouse gas emissions from the wastewater process, using the following operational data, sourced by the JMAS Chihuahua (M. Olmos, personal communication, December 14, 2020). It is important to note that, according to the information share for the period of study 2019 (12 months), the affluent to the treatment plant is around 48.5 million cubic meters, and the effluent (disregarding if it is reused or not) amounts to 43.5 million cubic meters. The difference of five million cubic meters of wastewater between can be inferred from the process description shared by Dr. Olmos (M. Olmos, personal communication, December 4, 2021), as it is stated that water steam is released as a result of the activated sludge process, in addition to the water content in biogas, and the recirculation of the water contained in the primary and secondary sludge.



Wastewater	550,251 / 550,251 / 585,374	
Energy consumed from the grid (Collection+Treatment+Discharge)	7,897,784	kWh
Volume of treated wastewater	48,546,535	m^3
Volume of discharged effluent to water body	43,478,410	m^3
Average Total Nitrogen at discharge	16.53	mg/L
Running costs	0	MXN
Energy costs	0	MXN
Are you producing biogas from anaerobic digestion?	No ○ Yes ●	
Are you valorizing biogas?	No ● Yes ○	
Select main treatment type: Activated Sludge - Well managed		
Select sludge disposal method: Land application		

According to the estimation from ECAM, approximately 8,000 metric tons of carbon dioxide equivalent on greenhouse gas emissions are generated from the operation of Chihuahua's south wastewater treatment plant each year (or some 14.5 kilograms of carbon dioxide per served individual annually), mainly sourced by the electricity consumption in the facility (Water and Wastewater Companies for Climate Mitigation, 2020), while the fact of not valorizing the produced biogas on-site (M. Olmos, personal communication, December 4, 2021) results in a significant amount of methane emissions. The emissions value from effluent discharge is considerably high, as it has not yet been determined how the effluent is disposed after the operation. A summary of the variables and their description is summarized in ANNEX IX.





The next stage of the ECAM tool procedure displays a breakdown of the emissions from the wastewater treatment process, by stage. During the collection stage, relevant input data required includes the energy consumption, population served, and volume of the influent. It is relevant to note that, for the purposes of this documentation and following the study of Li et al (Li, Zou, & Wang, 2019), around 70 percent of the energy in a wastewater treatment plant is consumed in the biological process, which is set as "treatment stage" in this procedure. In this context, from the total 7.9 million kWh consumed in the treatment plant, some 5.5 million kWh are consumed in the treatment stage, and the rest will be distributed equally in the other two stages. A summary of the variables for the calculations used by ECAM and their description is summarized in ANNEX X.

INPUTS — Enter values for Collection stages

Description	Current value	Unit
Energy consumed from the grid (wwc_nrg_cons)	1,184,668	kWh
Population connected to sewers (wwc_conn_pop)	550,251	people
Volume of wastewater conveyed to treatment (wwc_vol_conv)	48,546,535	m3
CH_4 emission factor (untreated wastewater) (ww_ch4_efac_unt) Sea and aerobic water bodies (0.06)	0.06	$kgCH_4/kgBOD$
CH_4 emission factor (uncollected wastewater) (ww_ch4_efac_unc) Sea and aerobic water bodies (0.06)	0.06	$kgCH_4/kgBOD$

OUTPUTS — GHG emissions

Origin	kg CO_2eq assessment period	kg CO_2eq per year per serv.pop.	kg CO_2eq per m^3
Electricity (wwc_KPI_GHG_elec)	536,042	0.98	0.011
Total GHG Wastewater Collection (wwc_KPI_GHG)	536,042	0.98	0.011

OUTPUTS — Energy performance and Service Level indicators

Description	Current value	Unit
Population connected to sewers (wwc_SL_conn_pop)	94	%
Energy consumption per wastewater conveyed to treatment (wwc_KPI_nrg_per_m3)	0.024	kWh/m^3

For the treatment stage of the process, some of the previous entered values are used again the wastewater volume, and the serviced population. As previously mentioned 70 percent of total energy consumed in the plant is established in this stage (Li et al., 2019). For the estimation of the emissions generated in this stage, other values are established by the tool, such as the methane emission factor and the BOD removed as sludge, which are determined under specific conditions assumed by the user: for this project, a well-managed activated sludge condition was selected.

INPUTS — Enter values for Treatment stages

Description	Current value	Unit
Energy consumed from the grid (wwt_nrg_cons)	5,528,449	kWh
Serviced population (wwt_serv_pop)	550,251	people
Volume of treated wastewater (wwt_vol_trea)	48,546,535	m3
CH_4 emission factor (wwt_ch4_efac) Activated Sludge - Well managed (0)	0	$kgCH_4/kgBOD$
Influent BOD_5 load (wwt_bod_infl) Estimation: 8,011,655 kg →	11,941,338	kg
Effluent BOD_5 load (wwt_bod_effl) Estimation: 1,194,134 kg →	1,194,134	kg
BOD removed as sludge (wwt_bod_slud) Activated Sludge - Well managed [65%] → (7,761,870)	5,539,989	kg
BOD_5 mass removed (c_wwt_bod_rmvd)	10,747,204	kg

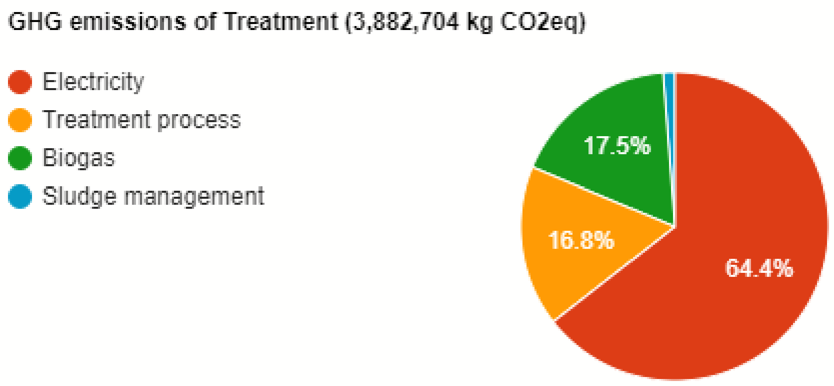
The biogas and sludge analysis of this stage was mostly estimated from assumptions, as the sufficient information to perform this assessment was not provided by the original source.

Description	Current value	Unit
▼ Are you producing biogas from anaerobic digestion?		No ○ Yes ◉
Biogas produced (wwt_biog_pro) Estimation: 2,563,729 m3 →	2,563,706	m3
Biogas flared (wwt_biog_fla) Estimation: 2,563,706 m3 →	2,563,706	m3
Percentage of methane in biogas (wwt_ch4_biog) Estimation: 59 % →	59	%
Fuel type (for digestor) (wwt_dige_typ)	(0) Diesel	
Fuel consumed for the digester (wwt_fuel_dig)	0	L
Are you valorizing biogas?		No ◉ Yes ○
▼ Evaluate sludge management (SM)?		No ○ Yes ◉
Sludge produced in WWTPs (total weight) (wwt_mass_slu) Estimation: 2,798,247 kg →	2,798,221	kg
Dry weight in sludge produced (wwt_dryw_slu) Estimation: 111,929 kg →	111,929	kg
Sludge type disposed of (wwt_slu_disp)	(1) Digested	
SM Evaluate sludge storage in WWTP?		No ◉ Yes ○
SM Is sludge sent to composting?		No ◉ Yes ○
SM Is sludge sent to incinerate?		No ◉ Yes ○
▼ SM Is sludge sent to land application?		No ○ Yes ◉

Description	Current value	Unit
▼ SM Is sludge sent to land application?		No ○ Yes ◉
Sludge sent to land application (dry weight) (wwt_mass_slu_app) Estimation: 111,929 kg →	111,929	kg
Total Nitrogen (% of dry weight) (wwt_slu_la_N_cont) Estimation: 4 % →	4	%
Soil typology (wwt_soil_typ)	(0) Fine-Textured (>30% clay)	
SM Is sludge sent to landfilling?		No ◉ Yes ○
SM Is sludge sent to stockpiling?		No ◉ Yes ○
SM Do you truck transport sludge to disposal site?		No ◉ Yes ○
Do you want to revise the default N2O emissions?		No ◉ Yes ○

As a result, the estimated greenhouse gas emissions from the treatment stage amount to some 3,900 metric tons of carbon dioxide equivalent (Water and Wastewater

Companies for Climate Mitigation, 2020), mostly due to the amount of energy consumed in during this process. A summary of the variables used by ECAM for calculations in this stage, and their descriptions is displayed in ANNEX XI.

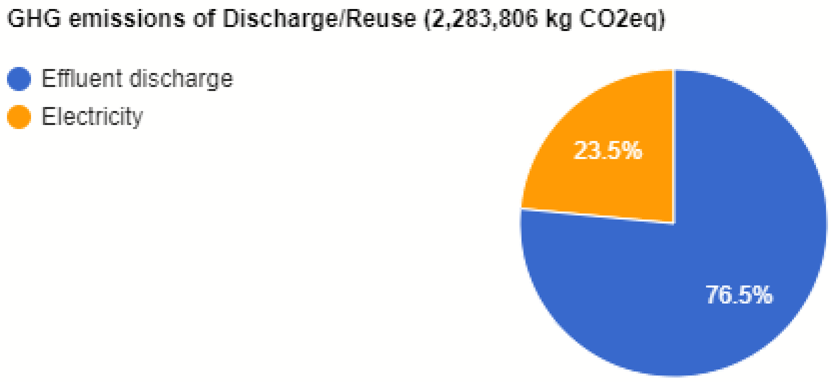


In the assessment of the final stage of the process, it is crucial to determine the volume of water discharged to water bodies and reused (in any purpose). To determine the annual volume discharged in the water bodies and reused (in agriculture or any other purpose), the shares displayed in Figure 28 are taken into consideration as follows: 74 percent of the effluent is reused, and the rest is discharged into the Chuvíscar River. With these values and other assumptions due to lack of additional data, the final inputs for this analysis stand as follows.

INPUTS — Enter values for Discharge/Reuse stages

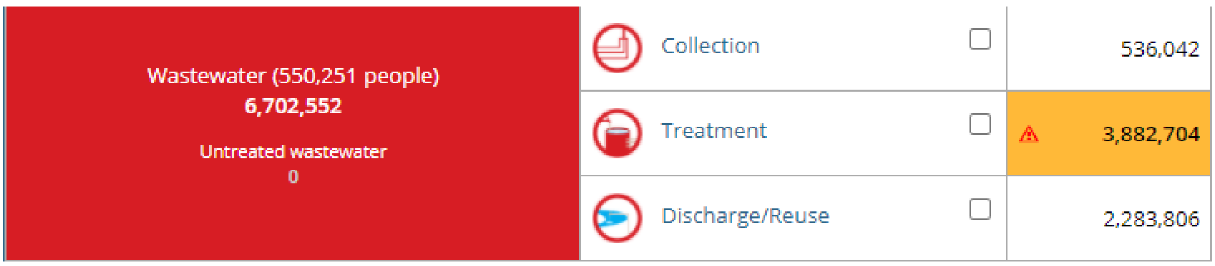
Description	Current value	Unit
Energy consumed from the grid (wwd_nrg_cons)	1,184,668	kWh
Volume of discharged effluent to water body (wwd_vol_disc)	11,304,387	m3
Effluent BOD load (wwd_bod_effl) Estimation: 1,194,134 kg →	642,275	kg
Total Nitrogen concentration in the effluent (wwd_n2o_effl)	16.53	mg/L
CH_4 emission factor (wwd_ch4_efac) Sea and aerobic water bodies (0.06)	0.06	$kgCH_4/kgBOD$
Volume of reused effluent (wwd_vol_nonp)	32,174,023	m3
Do you have truck transport for reused water?		No ◉ Yes ○

The result of this analysis indicates that, despite the high rate of effluent reutilization, around 2,300 metric tons of carbon dioxide equivalent are produced in this stage, corresponding to the discharge process itself, and the smallest share due to the energy consumption. (Water and Wastewater Companies for Climate Mitigation, 2020). A summary of the variables used by ECAM for calculations in this stage, and their descriptions is displayed in ANNEX XII.



4.2.2. Results and interpretation

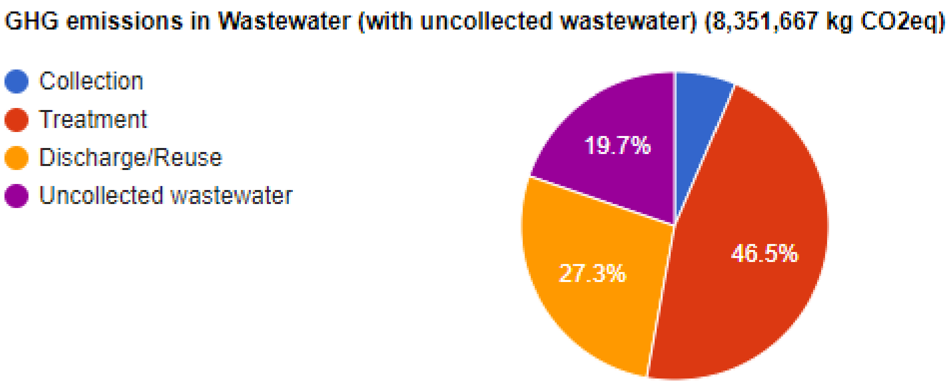
The final results of the ECAM assessment for Chihuahua's south wastewater treatment plant indicate that around 6,700 metric tons of carbon dioxide equivalent are generated annually from the process overall, being "treatment" the largest emitter stage (Water and Wastewater Companies for Climate Mitigation, 2020).



Nevertheless, "discharge and reuse" came as a relevant stage of the treatment process in terms of the emissions generated, it is important to analyze how these emissions are sourced. In this context, the ECAM tool determines the volume of GHG emissions during that stage from the generation of methane and nitrous oxide, as, being the former the main pollutant involved. Both methane and nitrous oxide emissions estimation are calculated from the formulas described throughout ANNEX XII, using real input data from the JMAS Chihuahua and assumptions from the tool itself.

Stage	← Wastewater/Discharge/Reuse
Description	Effluent discharge
Type	Output Formula: `wwd_KPI_GHG_tre_ch4 + wwd_KPI_GHG_tre_n2o;`
Inputs involved	wwd_KPI_GHG_tre_ch4 1,310,241 kg CO_2eq wwd_KPI_GHG_tre_n2o 437,523 kg CO_2eq
Current value	1,747,764 kg CO_2eq

Additionally, the ECAM tool points out that untreated wastewater is the third largest emitter in the process. From previous sections it was determined that approximately 94 percent of the municipality of Chihuahua's population was connected to the sewer. The untreated wastewater that is discharged directly to water bodies represent a total of almost 1,700 metric tons of carbon dioxide equivalent in greenhouse gas emissions. (Water and Wastewater Companies for Climate Mitigation, 2020). If these emissions are added to total the amount generated from the wastewater treatment process, the overall volume emitted in the Chihuahua's wastewater context would reach nearly 8,300 metric tons of carbon dioxide, an increase of almost 20 percent.

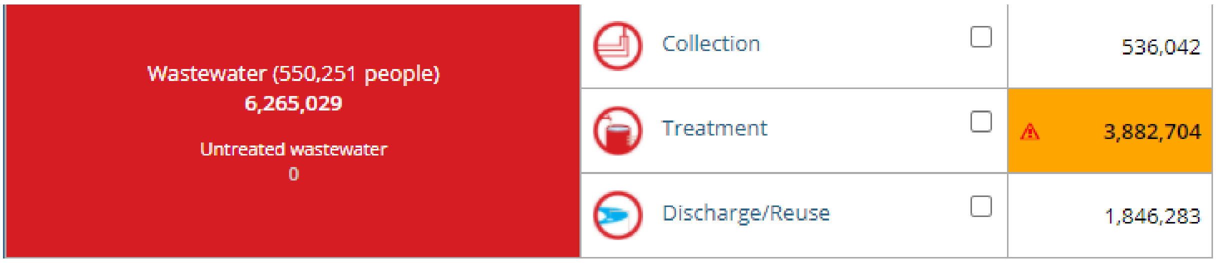


Despite almost 47 percent of the emissions generated in the South wastewater treatment plant of Chihuahua are associated to the biological process and energy consumption, an important share of this amount is sourced by the discharge of raw (uncollected) or treated wastewater into surface waters.

5. Sustainable wastewater solutions for the agriculture in Chihuahua

Source: canva.com

To evaluate the impact of wastewater reutilization in the greenhouse gas emissions at the treatment plant level, an additional assessment with the ECAM tool was performed, assuming a 100 percent of water reutilization (disregarding the purpose of reutilization). According to the estimations of ECAM, compared to the business-as-usual scenario, a complete reutilization of the over 43 million cubic meters of effluent annually, has the potential of avoiding each year approximately 440,00 kilograms of carbon dioxide equivalent in greenhouse gas emissions.



According to the ECAM Methodology Handbook (Water and Wastewater Companies for Climate Mitigation, 2018d), the reduction in greenhouse gas emissions as a result of reusing wastewater is mostly estimated from the reduction in the use of fertilizers (source of nutrients present in wastewater), and the displacement of potable water consumption for irrigation, as this process involve stages of abstraction, treatment, and distribution, that consume energy and resources (Kavvada et al., 2016). This differentiation in the emissions from a scenario with no reutilization of the 11.3 million cubic meters of available, and complete reutilization of this volume is depicted in Figure 36.

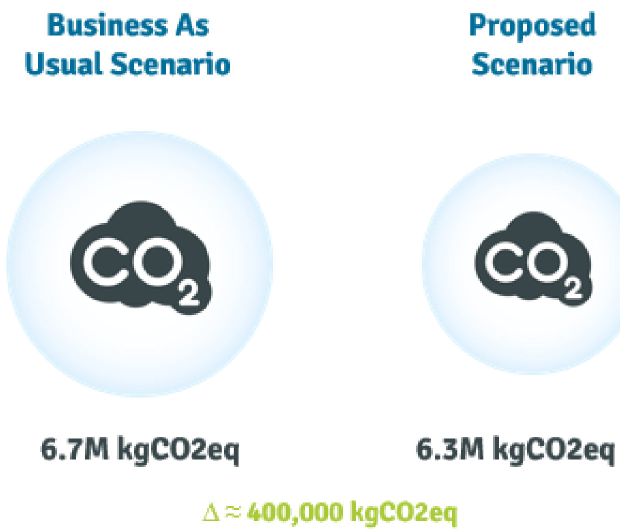


Figure 36. Comparison of GHG emissions with and without a complete wastewater reutilization, by scenario. Robles (2021)

To dimension the relevance of avoiding the emission of 440,000 kilograms of carbon dioxide equivalent, Figure 37 displays the equivalence of these emissions compared to other measurements, such as electricity consumed, distance driven by car, coal burned, or extension of forest that is required to sequestrate this carbon impact.

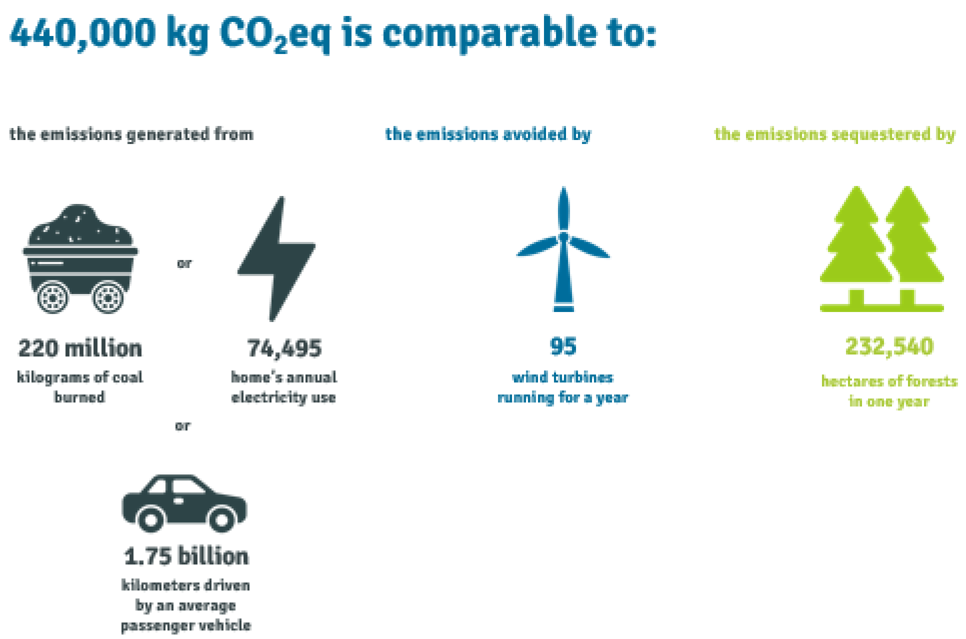


Figure 37. Equivalence of greenhouse gas emissions avoided by reusing wastewater from Chihuahua's south wastewater treatment plant. Robles (2021). Adapted from (Environmental Protection Agency, 2015)

In general, reusing the rest of the wastewater effluent's volume for irrigation avoids greenhouse gas emissions equivalent to large wind energy farms, or comparable to the carbon sequestration from thousands of hectares of forest. In this sense, it is of interest that the complete volume of treated wastewater is directed to reutilization.

For the purposes of this documentation, the area selected to reuse the wastewater effluent from the South Wastewater Treatment Plant of Chihuahua is located in the irrigation district of Tabalaopa-Aldama, due to its closeness to the treatment facility, and the theoretical availability of ground for agriculture, as shown on the map displayed in Figure 38.

The area marked in green represents the location of the selected area for irrigation, while the yellow mark depicts the location of the south wastewater treatment plant of Chihuahua. The green area measured in Google Maps reflects an extension of around 1,348 hectares, and the linear distance from the wastewater treatment plant ranges between 800 meters and five kilometers.

Figure 38. Selected area for implementation of wastewater reutilization in the irrigation district of Tabalaopa-Aldama, city of Chihuahua. Robles (2021), Google Maps (2021)

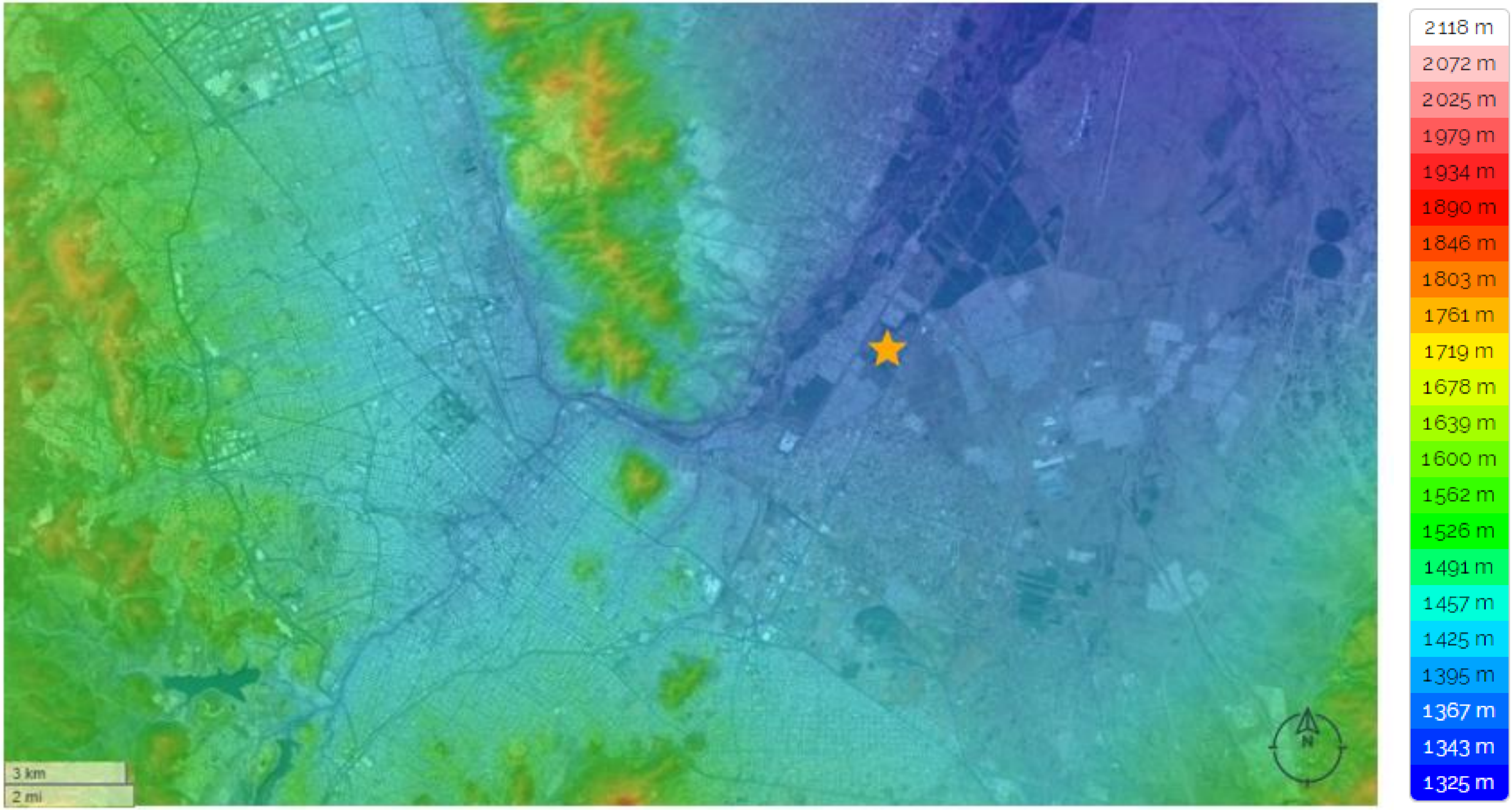


Figure 39. Topographic map of Chihuahua and location of the south wastewater treatment plant (Topographic Map, n.d.)

For the purposes of this proposal, it is **assumed that the whole area of the selected field is suitable for agriculture, and that currently, treated wastewater reutilization is not being implemented in any form.**

According to the information retrieved from the topographic map of Chihuahua City, the minimum altitude in this area amounts to around 914 meters, while the maximum reaches 3,080 meters, mainly in the mountainous regions outside from the urbanization (Topographic Map, n.d.). For the area of interest and the south wastewater treatment plant of the city, the altitude remained with practically no significative variation: from around 1,370 meters close to the treatment facility, down to approximately 1,355 meters by the northeastern side of the area of interest of irrigation (Topographic Map, n.d.).

This observation makes possible to infer the flow of the Chuviscar River (from North to South), and that the transportation of treated wastewater from the facility to the selected fields might not suppose additional pump installations to meet the pressure requirements. In this context the adaptation of the existing wastewater reuse network is technically more feasible.

Regarding the type of agricultural products in this area, the information shared by the Agriculture Department of the Municipality of Chihuahua, through Mr. Julián Martínez (J. Martínez, personal communication, December 17, 2020), the irrigation district of Tabalaopa-Aldama accounts for around 30 different types of crops, perennial or seasonal. The leading agricultural products in this area, based on their total area used where they are grown are cotton (seasonal, spring-summer), and alfalfa and nuts (perennial). Figure 40 displays the distribution of agricultural land used to grow the selected crops as of the year 2019. Cotton, despite being a seasonal product, accounts for the highest share in this category, using over two thirds of the Tabalaopa-Aldama effective agricultural land.

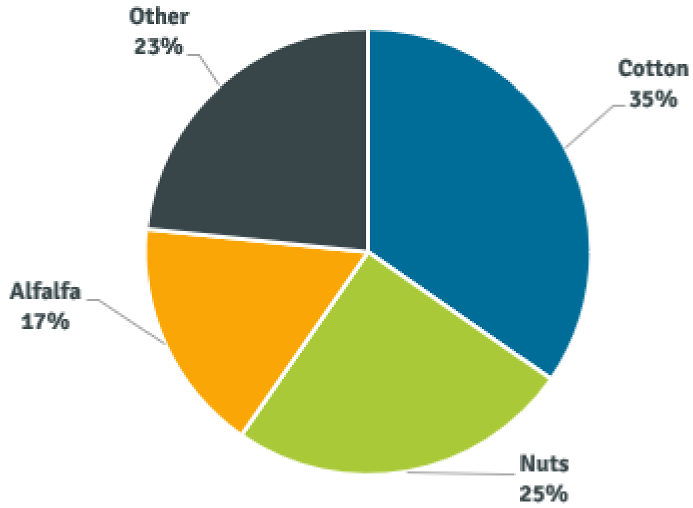


Figure 40. Share of area used for growing selected crops in the irrigation district Tabalaopa-Aldama in 2019. Robles (2021). Adapted from (J. Martínez, personal communication, December 17, 2020)

Considering the amount of effluent from Chihuahua's south wastewater treatment plant specified in previous sections, it is relevant to determine if this volume of wastewater is theoretically enough to cover the irrigation demand of each of these three agricultural products. The Food and Agriculture Organization (Food and Agriculture Organization, n.d.a, n.d.b) and the study of Sifuentes et al (Sifuentes Ernesto et al., 2015) compile different properties of the most frequent agricultural products, including information regarding the water consumed by irrigation. To establish a water demand range, the evapotranspiration rate and crop coefficient are taken into consideration (Food and Agriculture Organization, n.d.a, n.d.b; Sifuentes Ernesto et al., 2015). For the purposes of this project, the highest value of the range was considered to calculate the water demand. According to a report published by the "Waterwise on the farm" initiative of the Peth Region in Australia (Perth Region NRM, n.d.), the conversion stands: one millimeter equals to liter of water applied to a square meter of land.

Figure 41. Water demand of select crops grown in the Tabalaop-Aldamaa irrigation district of Chihuahua. Robles (2021). Adapted from (Food and Agriculture Organization, n.d.a; Sifuentes Ernesto et al., 2015)

To determine the estimated volume of wastewater required to irrigate the desired crops in the selected area of the Tabalaopa-Aldama district, calculations were made based on the assumptions of land conditions and uniformity of crops distribution. The conditions assumed for this project are:

- Due to lack of information regarding the specific distribution of crops in the irrigation district, it is considered that, in the selected area of 1,348 hectares only the desired three crops (nut, alfalfa, cotton) are grown.
- To estimate the distribution of land used by each crop, the shares of territory used by these products in the entire district displayed in Figure 40 were used. For the whole irrigation district Tabalaopa-Aldama, these three crops covered around 77 percent of the land according to the information given by the Agriculture Department of Chihuahua (J. Martínez, personal communication, December 17, 2020). A weighted share was calculated based on this distribution, using the following equation:

$$Weighted\ share = \frac{Actual\ share}{0.77} x\ 100$$

- The conversion of units stands as follows: 1 ha = 10,000 m^2, 1 L = 1 m^3.
- All calculations are based on a period of study of one year (data of 2019).

- According to the information of Mr. Martínez (J. Martínez, personal communication, December 17, 2020), cotton is a seasonal crop. For that reason, the yearly water demand of this product was divided by two, assuming only water requirements for six months.

The results of these estimations and calculations are displayed in Table 18.

Table 18. Summary of annual wastewater and land requirements for irrigation of the desired crops in the selected area of Chihuahua for a one-year period. (Robles, 2021)

Crop	Water demand (in mm)	Conversion	Water demand (in L/m2)	Area of selected terrain (in m²)	Share of land (total Tabalaopa-Aldama)	Weighted share for selected land	Effective land used by crop (in m²)	Water demand (in m³)
Nut	1,310	1 mm = 1 L/m2	1310	13,480,000	25%	32%	4,376,623.38	5,733,376.62
Alfalfa	1,600		1600		17%	22%	2,976,103.90	4,761,766.23
Cotton*	1,300		1300		35%	45%	6,127,272.73	3,982,727.27
Total								14,477,870.13

- Cotton is a seasonal product. Its water demand was divided by two.

According to these results, the total annual water demand to irrigate the three selected crops amounts to over 14.5 million cubic meters, almost 28 percent more than the current availability of wastewater effluent from the south wastewater treatment plant of Chihuahua. Nevertheless, according to the future expansion plans of the treating capacity of this facility (Banco de Desarrollo del América del Norte, 2019), the expected treated effluent is set to completely cover the demand.

To evaluate the performance of this proposal, three different scenarios were considered:

- The **business as usual scenario** considers a situation where the operation remains unchanged, this means, no further reutilization of wastewater apart from the existing volume sent to the Aldama region (around 32 million cubic meters).
- The **proposed scenario** reflects the results of this section, with an available effluent volume of 11.3 million cubic meters that are currently not reused and depicts a deficit of around three million cubic meters to cover the water demand.
- The **long-term scenario** considers an increase of around 25 percent in the effluent volume due to expansion capacity of the treatment plant. Due to this, and to estimate more accurately the greenhouse gas emissions of this scenario, a proportional growth in the electricity demand of the facility was assumed. This

scenario takes place in a context where the expansion plans are successfully implemented, thus, a it is out of the scope of this document. The depiction of this scenario thus, only intends to describe how the city's wastewater treatment can improve their carbon footprint in the future.

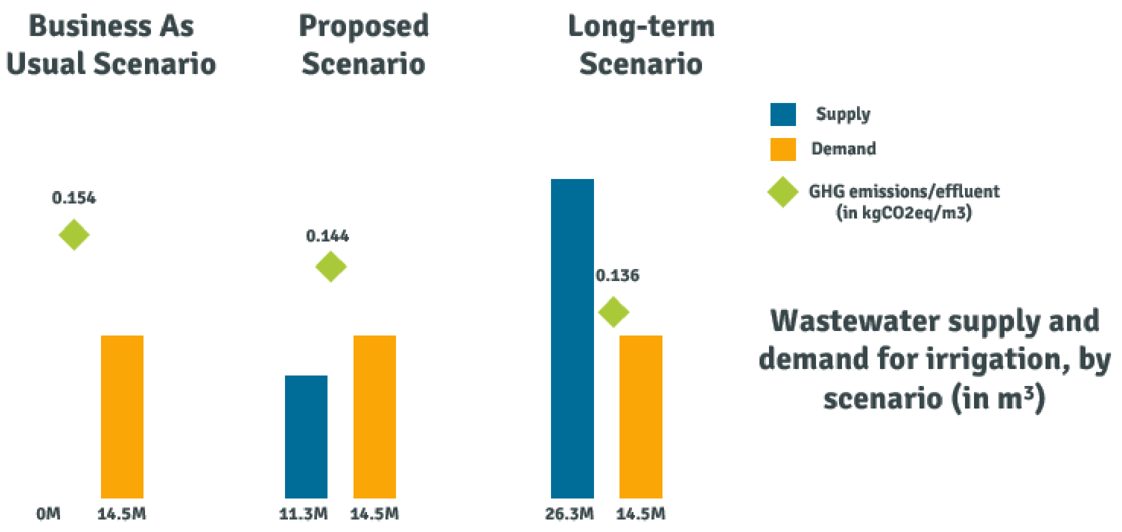


Figure 42. Supply and demand of wastewater to irrigate the desired area, by scenario. Robles (2021)

To transport the effluent volume that is desired to reuse for irrigation, in contrast with the existing practice, and following the recommendation of Kavvada et al (Kavvada et al., 2016), the wastewater will be carried directly from the wastewater treatment plant to small, decentralized irrigation systems installed across the irrigation field.

In this context, studies (Kalfountzos, Alexiou, Kotsopoulos, Zavakos, & Vyrlas, 2007; Lacambra, 2019; Phene, n.d.) agree on subsurface drip irrigation as an efficient method for the three selected crops, in terms of efficiency of production, water requirements, and a positive response against dry climate zones. For this reason, a low-cost alternative of this method is selected to irrigate the crops in the Tabalaopa-Aldama district. Figure 43 displays how the pipeline network of the proposed system is arranged.

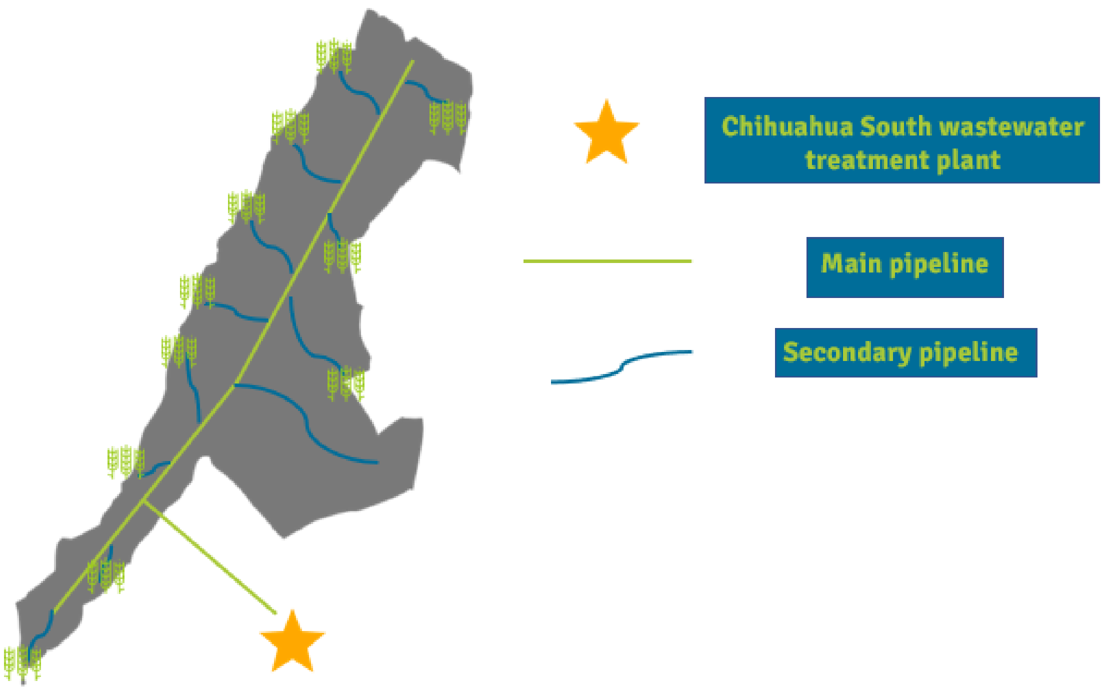


Figure 43. Layout of proposed wastewater reuse network. Robles (2021)

The process diagram flow shown in Figure 44 depicts how the new system would work during normal operation. The available effluent volume of around 11.3 million cubic meters annually represents around 31,000 cubic meters daily of wastewater that should be transported across the irrigation field.

It is proposed that the effluent will be pumped from Chihuahua's south wastewater treatment plant through pipelines until reaching 50 cubic meter-storage tanks distributed in the irrigation field. The wastewater is set to fill these tanks until reaching a certain level, and a sensor will indicate that valves should be closed to this specific tank, so no more water will be pumped. At the discharge of the tank, a small filter for sediments will be installed to avoid clogging of the irrigation diffusors, as the wastewater contains a small concentration of suspended solids. After this filter, the water is directed through a main pipeline, from where several hoses with diffusors (small holes) are fed, irrigating the crops close to their roots.

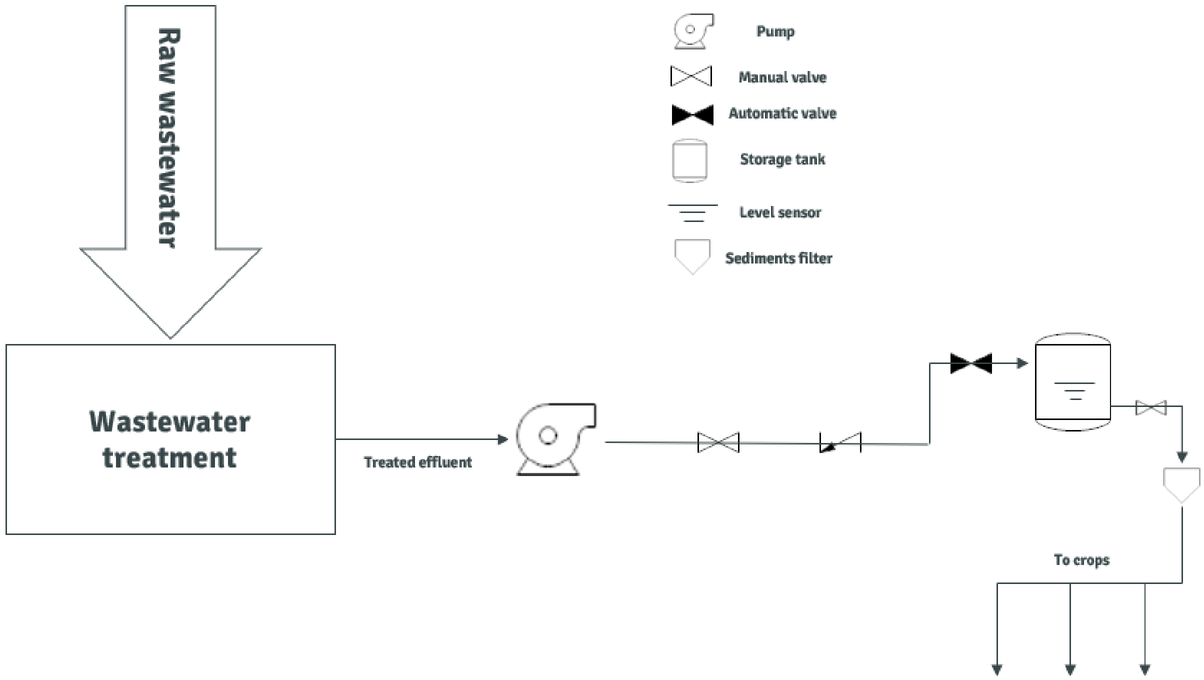


Figure 44. Process diagram flow of the proposed irrigation system in Chihuahua. Robles (2021). Icons from RFFlow (RFFlow, n.d.).

Compared to the current operation of reuse, the implementation of this proposed system has the follow implications:

- Costs and environmental impact of fabricating the necessary materials for the installation of this network, however, this is a one-time situation.
- Energy consumption and its environmental impact by pumping the water up to 5 kilometers.
- With the current operation, the treated wastewater effluent is discharged onto the river, thus, it is likely that the nutrient added value of this wastewater is lost by dilution in a surface water body already declared as polluted (Instituto de Planeación Integral del Municipio de Chihuahua, 2009). This means, that with the current operation, the wastewater retrieved from the river to irrigate already has different physicochemical properties as the effluent from the treatment plant. On the other hand, with the proposed system, it is assured that an unaltered wastewater quality of the effluent will be delivered to the end-use.
- The network's capacity and reach can be expanded for similar projects on the long-term.

Figure 45 depicts how the installation of the proposed system. It is possible to combine crops on the irrigation fields.

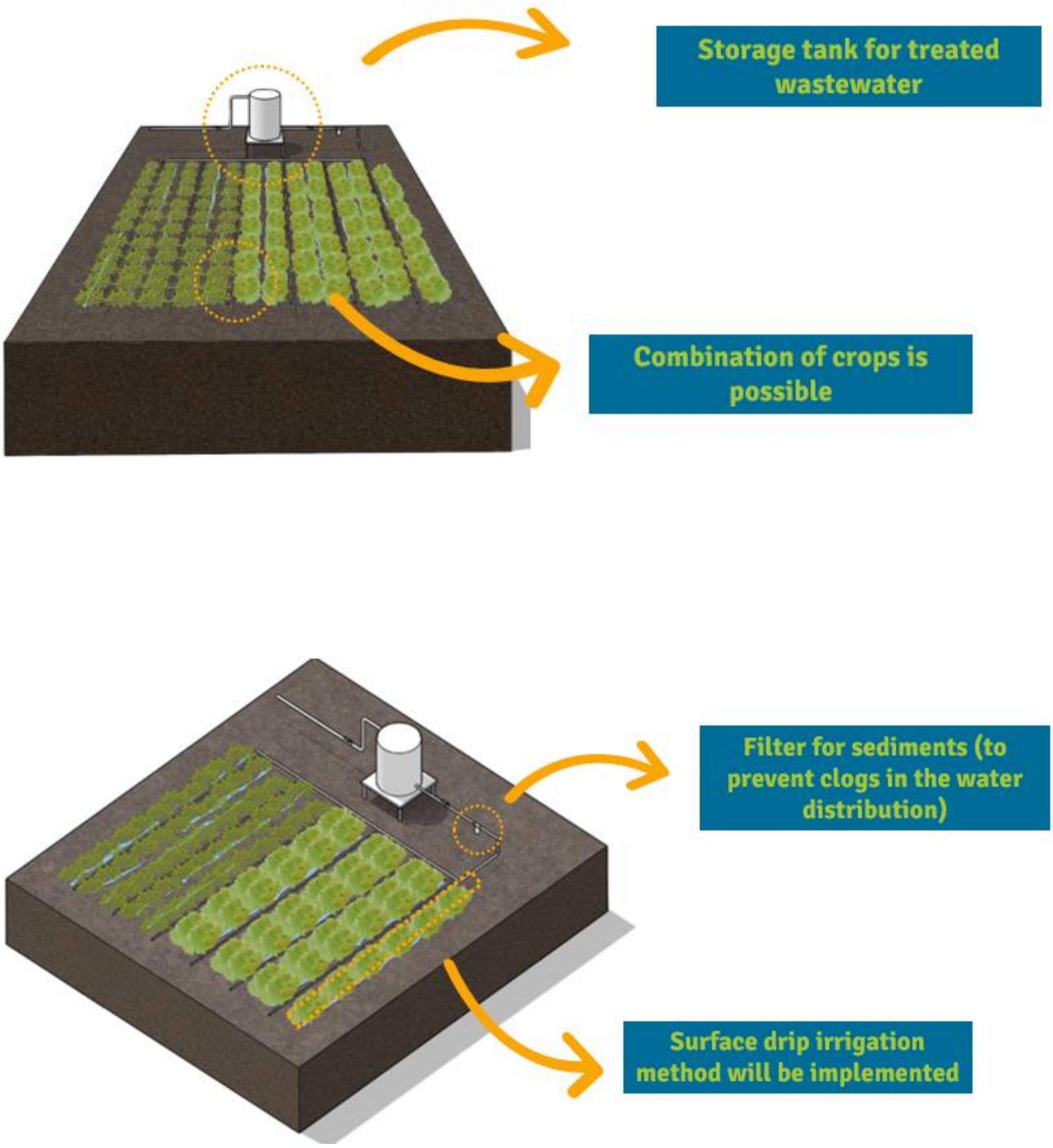


Figure 45. Frontal and ISO views of the proposed decentralized irrigation system in Chihuahua. Robles (2021)

This proposal intends to impact not only the environmental context of Chihuahua, but different spheres of this city's context. A preliminary assessment of the co-benefits of this project is summarized in Table 19.

Table 19. Summary of co-benefits of the proposed intervention

	Economic	Technical / Environmental	Social	Political
Reusing wastewater to alleviate the surface and groundwater withdrawals, avoiding exporting water from other regions	X	X		X
Reducing the consumption of fertilizers for agriculture due to the direct reutilization of nutrients in the treated wastewater	X	X		
Providing an alternative water supply for a region where an important share of the population is dependent from agriculture	X		X	
Involving farmers in the operation and maintenance of uniform, decentralized irrigation systems			X	
Incentivize further projects with a similar scope	X	X		

These co-benefits take into consideration the existing political, economic, social, and technical conjuncture in Chihuahua City surrounding the climate, water, and agriculture contexts, described in previous sections throughout this documentation.

6. Conclusions and outlook

The water crisis in Chihuahua has escalated to a technical (Instituto de Planeación Integral del Municipio de Chihuahua, 2009) and a political (Forbes, 2020) level in the last years. In this context, it is crucial to extend the reutilization of treated wastewater to alleviate the depletion of groundwater resources, particularly in agriculture, where Chihuahua consumes most of its hydric resources for agriculture (Espino, 2020).

The wastewater quality analysis confirms that the physicochemical, pathological and additional (metals) parameters fulfill the local and international guidelines for wastewater reuse in irrigation. On the opposite, the current operation of reuse for irrigation leaves room for several interpretations and improvement, and in this context, a distribution network for a portion the treated effluent is proposed, thus implying a modification of the business-as-usual wastewater disposition

Additionally, the ECAM assessment on greenhouse gas emissions from the wastewater operation indicates that a considerable volume of emissions is potentially avoidable by increasing the reuse rate of the effluent, and by doing so, disrupting discharges of treated wastewater into the Chuvíscar River. The annual volume of greenhouse gas emissions potentially avoidable by reusing water for crop irrigation is comparable to the sequestration effect from several hectares of forest, or the emissions avoided by installing renewable energy sources such as wind power. In a context where the land use in Chihuahua is mostly destined to agriculture or urbanization (Gobierno del Estado de Chihuahua, 2019a), and the most used renewable energy system is solar power, alternative emission reduction methods are crucial in a climate vulnerable region.

For the selected irrigation area in Chihuahua City, the scenario of complete wastewater reutilization does not cover the entire water demand for the three crops that were evaluated, however, in this context, it is crucial that the capacity expansion plans for both wastewater treatment plants of the city are successfully completed, as this would significate a sufficient supply of this resource for agriculture in the area, and a surplus that might be used for future similar projects, or to recharge the already vulnerable aquifers (Instituto de Planeación Integral del Municipio de Chihuahua, 2009).

Different sources (Banco de Desarrollo del América del Norte, n.d.; M. Olmos, personal communication, December 14, 2020) concur that most of the treated effluent from the South wastewater treatment plant is reused, either for crops irrigation or within the city for non-domestic purposes, however, the lack of public available data in literature or shared by the authorities in charge, regarding how much of this volume is transported to which regions, and how is the water irrigated on the fields, might be a potential sign of a severe segregation of the information, as each land owner or farmer withdraws the required volume of water they need for irrigation, without necessarily keeping record of it.

Although decentralized irrigation solutions are not explicitly mentioned as part of its long-term strategies, this project is aligned with Chihuahua's State Program on Climate Change objectives on the efficient use of water resources (Gobierno del Estado de Chihuahua, 2014), concerning strategic initiatives to use water resources efficiently. The assessment of case studies in this documentation indicated that the implementation of such initiatives is technically and economically feasible in a sociopolitical and climate context similar to Chihuahua City. Financial incentives described in the economic and planning instruments of Chihuahua are set to be key in the execution and development of climate-smart projects. This project's technical feasibility is supported by success of the proposed irrigation method in the consulted international case studies with similar climates, the good quality of the treated effluent, and the topography of the terrain.

As this study focuses on the effluent's potential as a resource to decrease freshwater consumption and greenhouse gas emissions, other major stages of the wastewater treatment, such as the biological process, are not assessed in terms of their environmental impact. For this purpose, further interventions and initiatives to reduce emissions from the rest of the stages should be implemented by the JMAS Chihuahua through focused programs such as WaCCliM, mainly including energy efficiency measures, and sustainable utilization of by-products, such as the primary and secondary sludge, and biogas.

Current limitations of this document include the global impact of the COVID-19 pandemic during the year 2020, and beginning of 2021, restricting the possibility of international travels, thus on-site observations and personal interviews were not part of the methodology of this project. Additionally, the flow of information from organizations and authorities from Mexico was limited, as the “working from home” modality implemented in the country made it difficult to reach the people in charge of the required information, moreover, the persistent number of positive COVID-19 cases within the public sector increased the workload of the rest of the employees.

The assumptions of this project were based on personal communication and exchange of information with personnel from the JMAS Chihuahua and the Agriculture Department of the City, and for more precise results, further onsite research and calculations needed to take place, including assessments on: soil analysis, accurate design of pumps and pipelines of the proposed network, as well as its operational parameters, cost evaluation, and an environmental assessment on how the 440,000 kilograms of carbon dioxide equivalent avoided by reusing this volume of treated wastewater are impacted by the operation of the new system.

The feasibility, success, and replicability of this project highly depends on the will of main stakeholders and third parties, such as the state and municipal government, organizations such as the JMAS and IMPLAN Chihuahua, farmers, and population in general.

Overall, reusing treated wastewater for agriculture represents an environmental opportunity for the adaptation to the effects of climate change in a vulnerable region, with co-benefits such as supplying agriculture, a crucial economic and social sector in the state and the country, with a valuable resource, and providing a partial solution for the international crisis between the United States and Mexico, driven by the increasing water scarcity taking place during the last years.

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ANNEX I

Table A. I. Comparison of recommended physicochemical and microbiological parameters of wastewater for reutilization in irrigation across selected countries. Robles (2020). Adapted from (Jeong et al., 2016)

Parameter	South Korea	WHO	U.S. EPA	France	Israel	Mexico
Coliforms (/100 mL)	ND TC[1]	E. coli (cfu) < 1000	ND FC[2]	E. coli (cfu) < 10000	FC (cfu) < 10	-
Turbidity (NTU)	< 2	-	< 2 (average)	-	-	-
Suspended solids (mg/L)	-	-	-	< 15	< 10	-
Biochemical Oxygen Demand (mg/L)	< 8	-	< 10	-	< 10	-
Chemical Oxygen Demand (mg/L)	-	-	-	< 60	< 100	-
Total Nitrogen (mg/L)	-	-	-	-	< 25	< 5
Total Phosphorus (mg/L)	-	-	-	-	< 5	-
pH	5.8 - 8.5	-	6.0 - 9.0	-	6.5 - 8.5	6.5 - 8.0

[1] ND: Not detected, TC: Total coliforms. [2] FC: Fecal coliforms

Table A. II. Comparison of recommended trace elements concentration in wastewater for reutilization in irrigation across selected countries. Robles (2020). Adapted from (Jeong et al., 2016)

Parameter (mg/L)	South Korea	FAO	U.S. EPA	Israel	Mexico
Aluminum	5	5	5	5	-
Arsenic	0.05	0.1	0.1	0.1	-
Cadmium	0.01	0.01	0.01	0.01	-
Chromium	0.05	0.1	0.1	0.1	-
Iron	-	5	5	2	0.1
Lead	0.1	5	5	0.1	-
Manganese	0.2	0.2	0.2	0.2	0.1
Mercury	0.001	-	-	0.002	-
Nickel	0.2	0.2	0.2	0.2	-
Zinc	2	2	2	2	-

ANNEX II

Table A. III. Indicators to determine the hazard factor of climate change in Mexico

Indicator	Scale	Definition and source
Global basic water service access index (GWSAI)	According to municipality and year	CONAGUA, Situation of the subsector drinking water, drainage, and treatment. Data for 2015
Flooding	Emergency announcements (incl. Cyclones, intense rains, flooding, low temperatures, hail, snow, frost, and tornado)	CONAGUA. Data from 2000 to 2016
Aquifers	Depletion of water table according to municipality (considers municipal, industry, and agricultural demand)	Mexican Institute of Water and Technology. Data from 2003 to 2015
Droughts	Abnormally dry, moderate drought, severe drought, extreme drought, exceptional drought	Mexican Institute of Water and Technology. Data from 2003 to 2017

Table A. IV. Social factors to calculate vulnerability to climate change. (Robles, 2020). Adapted from (Arreguín-Cortés et al., 2019)

Indicator	Abbreviation		
Average education level	AEL	Data at the municipal scale	Source of Data: INEGI with data from 2010
Number of physicians for every 1,000 inhabitants	NP		
Child mortality rate	CMR		
Population without health care coverage	PWHC		
Illiteracy	I		
Homes without drinking water service	HWDWS		
Homes without drainage service	HWD		
Homes without electricity	HWE		
Homes with earthen floors	HWEF		
Economically active population	EAP		
Open unemployment rate	OUR		
Indigenous language population	ILP		

ANNEX III

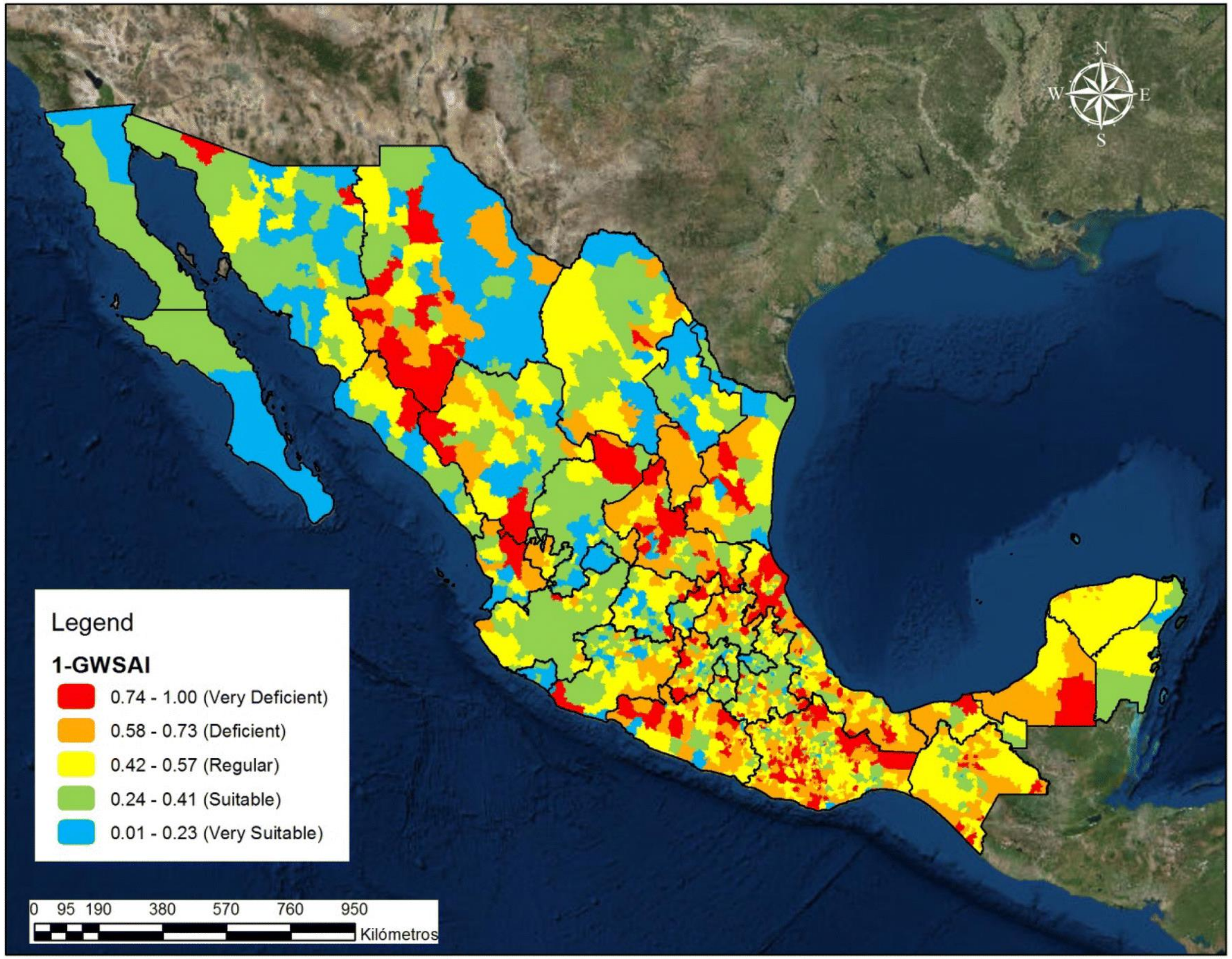

Figure A. I. Water security access indices in Mexico by municipality using GIS software (Arreguín-Cortés, 2015)

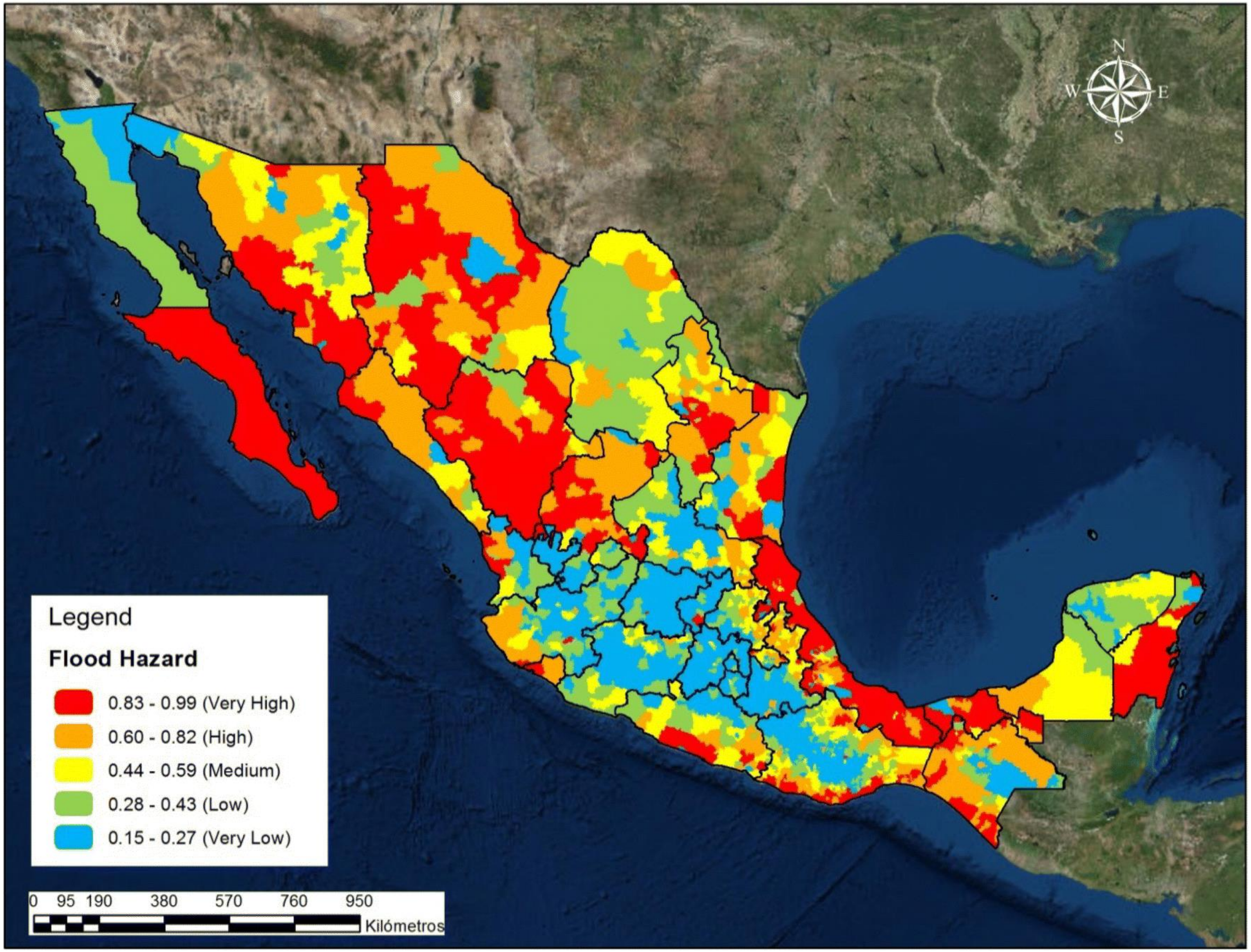

Figure A. II. Flood hazard in Mexico by municipality using GIS software (Arreguín-Cortés, 2015)

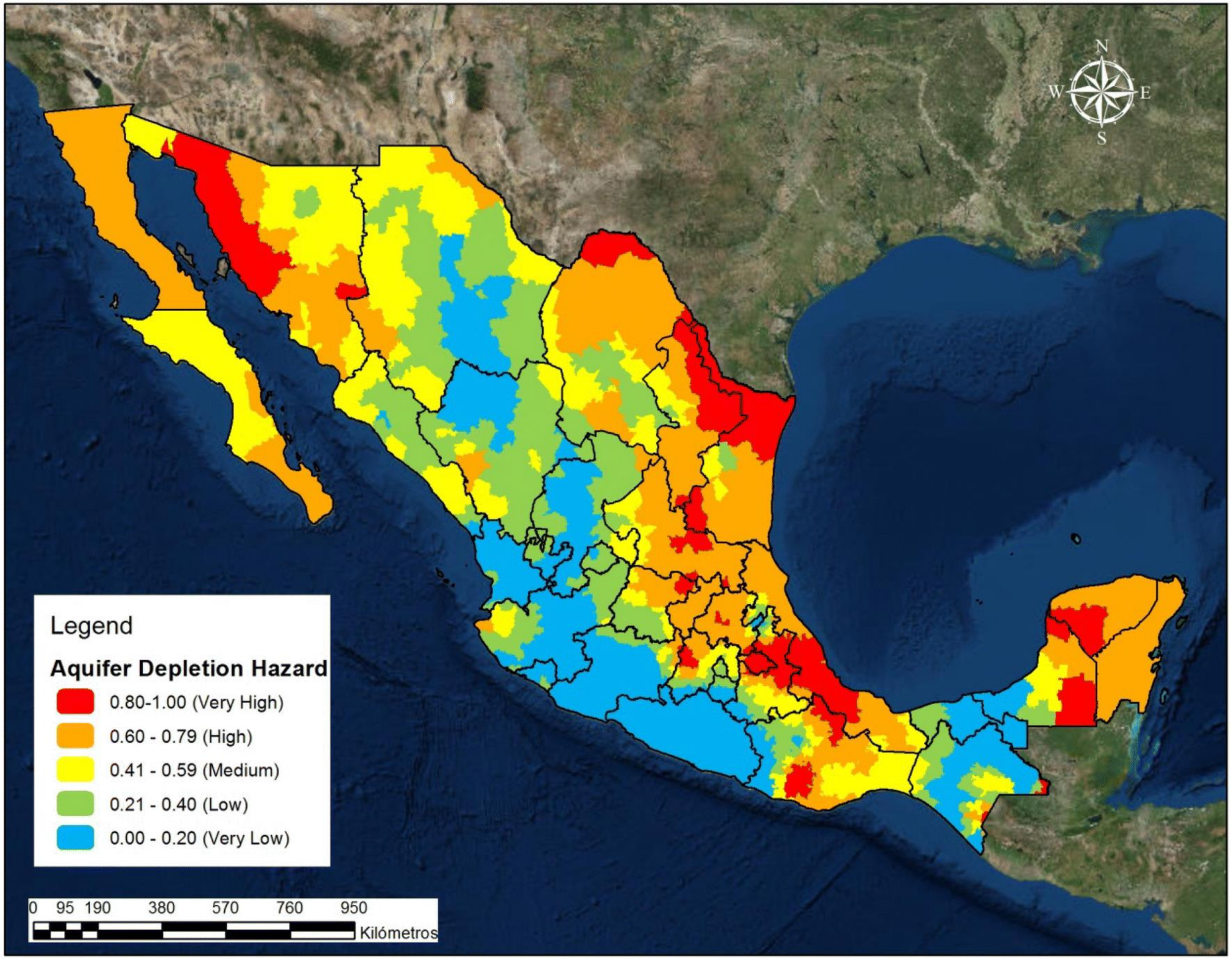

Figure A. III. Groundwater depletion hazard index in Mexico by municipality using GIS software (Arreguín-Cortés, 2015)

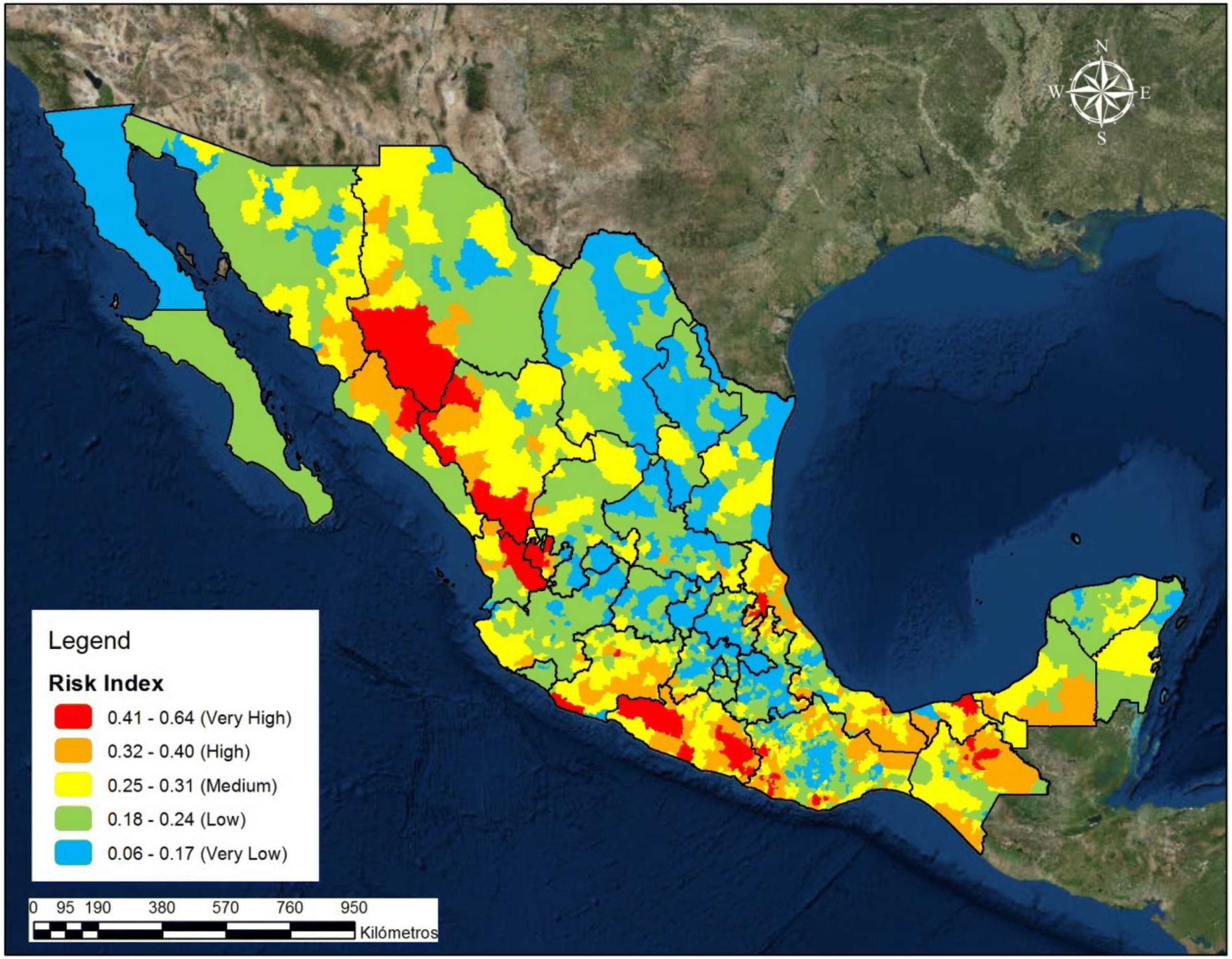

Figure A. IV. Risk index in Mexico by municipality using GIS software (Arreguín-Cortés, 2015)

ANNEX IV

Table A. V. Climate exposure to determine vulnerability (Robles, 2020). Adapted from (Arreguín-Cortés, 2015)

Parameter	Measure	Description	Relation indicator vs vulnerability
Anomaly of daily mean temperature during the agricultural cycle	∆Tav	Projected anomaly in °C during the agricultural cycle between 2075-2099 compared to the base period	+∆T av = + Vuln
Anomaly of max daily temperature during the agricultural cycle	∆Tmax	Projected anomaly in °C during the agricultural cycle between 2075-2099 compared to the base period	+∆Tmax = + Vuln
Anomaly of the cumulative precipitation during the agricultural cycle	∆Precip.	Projected change in % of cumulative precipitation during the agricultural cycle for the period 2075-2099	+∆Precip. = + Vuln
Probability of droughts during the agricultural cycle	Droughts	Project anomaly on the standarized precipitation for 6 months during the cycle Autumn-Winter (March) and Spring-Summer (September) for the period 2075-2099 compared to the base period	+∆Drought = + Vuln
Risk due to cyclones	Cyclones	Risk due to cyclones and storms	+Cyclones = + Vuln
Sea level 5 m	Sea	Potential flooding area, assuming a sea level rise of 5 m	+Sea level = +Vuln
Heatwaves	Heat	Mean heatwaves, assumed when T = 30 C during the base period (1971-2000)	+Heat = +Vuln

Table A. VI. Parameters to estimate sensibility to climate change (Robles, 2020). Adapted from (Arreguín-Cortés, 2015)

Parameter	Measure	Description	Relation indicator vs vulnerability
Rural Population	Rural	% of population with less than 5,000 inhabitants	+Rural = + Vuln
Area of the parcel	Area	Average area of irrigation	+Area = - Vuln
Use of fertilizers	Fertilizer	Use of fertilizers	+Fertilizers = - Vuln
Extreme weather events	Catastrophe	Extreme weather events in a municipal context	+∆Catastrophe = + Vuln
Evapotranspiration	Eto	Annual cumulative evapotranspiration	+Eto = + Vuln
Degradation of soil and aquifer	Degradation	Soils with problems of soluble salts/exchangable sodium, and aquifers with salinization, or overexploitation	+Degradation = +Vuln
Permanent crops	Perm	% of permanent crops compared to annual crop, average for 2002-2011	+Perm = +Vuln
Variability in precipitation	Precip	Standard deviation of annual cumulative precipitation during the base period (1971-2000)	+StdDev Preci = - Vuln
Exposure to fires	Exp	Average fire exposure, area exposed to fires compared to total agricultural area for 2002-2011	+Degradation = +Vuln
Performance	Perf	Maximum corn crops performance in a municipal context 2002-2011	+Perf = -Vuln
Cumulative precipitation	Precip	Cumulative precipitation for the agricultural cycle 1971-2000	+Precip = -Vuln

Table A. VII. Parameters to determine capacity of adaption to climate change in agriculture (Robles, 2020). Adapted from (Arreguín-Cortés, 2015)

Parameter	Measure	Description	Relation indicator vs vulnerability
Neglection	Neg	Degree of neglection	+Neg = + Vuln
Illiteracy	Analf	% of illiterate people older than 15 years	+Analf = - Vuln
Service coverage	Services	% of service coverage in farmer's household (drinking water, sanitation and electricity)	+Services = - Vuln
Dependency	Depen	Number of economically dependent people per agricultural producer	+Depen = + Vuln
Access to urban centers	Time	Time to access urban centers	+Time = + Vuln
Agriculture income	Agr	Share of incomes of the farmer related to agriculture	+Agr = +Vuln
Land use intensity	LUI	Mean percentage of secondary crops during agricultural years	+LUI = -Vuln
Agriculture mechanization	Mech	Share of farmers who use agricultural mechanization	+Mech = -Vuln
Agricultura credit coverage/Agricultural insurance	Cred	Share of credit and insurance coverage	+Cred = -Vuln

ANNEX V

Table A. VIII. Precipitation and temperature changes in selected states of Mexico for the period 2075-2099 by scenario. Robles (2020). Adapted from (Arreguín-Cortés, 2015)

State	Precipitation (%)				Max. temperature (°C)				Min. temperature (°C)			
	Spring-Summer		Fall-Winter		Spring-Summer		Fall-Winter		Spring-Summer		Fall-Winter	
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Chihuahua	-4.2	-8.5	-8.2	-10.2	3.3	5.4	3.2	5.5	2.8	4.9	2.4	4.4
Coahuila	-5.8	-10.5	-6.9	-9.7	3.5	5.4	2.8	5	2.8	4.8	2.3	4.3
Durango	-3.5	-7.5	-7	-8.7	3.2	5.5	3	5.3	2.7	4.8	2.2	4.2
Edo. de México	-6.7	-13.1	-2	-2.2	2.9	5.2	2.5	4.4	2.3	4	2	3.6
Guerrero	-6.7	-12.5	-0.8	0.2	2.9	4.8	2.4	4.1	2.3	4.1	2.1	3.8
Michoacán	-4.8	-11.6	-2.5	-2	2.9	5	2.5	4.3	2.3	4.3	2	3.8
Nuevo León	-7.5	-12.9	-5	-7.9	3.1	5.3	2.5	4.7	2.6	4.5	2.2	4.1
Zacatecas	-4	-9.7	-5.6	-6.7	3.2	5.7	2.8	5.2	2.6	4.8	2.1	4

ANNEX VI

Table A. IX. Matrix for the determination of the region of interest in Mexico. Robles (2020).

Location	Parameter (score)						
	Water stress[1]	Climate zone[2]	Variations in max temperature[3]	Variations in precipitation[3]	Water security index[4]	Vulnerable irrigation areas[5]	Access to data[6]
Chihuahua	5	5	5	3	5	5	4
Mexico City	5	3	4	4	2	1	5
Baja California Sur	5	5	4	5	4	1	1
Guanajuato	5	3	5	3	2	1	1
Guerrero	2	4	4	4	5	5	1

[1] Based on the water stress scores from the WRI (World Resources Institute, 2020b). Cities and countries are scored from 1 to 5, and this score was transferred to the matrix in Table A. IX. Numbers were rounded to the immediate whole number.
[2]
[3] Based on the projections under the RCP4.5 for the spring-summer period 2075-2099 from Arreguín-Cortés (Arreguín-Cortés, 2015). Figures were processed under a weighted average using the minimum and maximum values of the selected range.
[4] Based on the water security index map from Arreguín-Cortés et al. (Arreguín-Cortés et al., 2019). Each classification (from very low to very high) was awarded with one point. In states with more than one classification, the most visually predominant one was chosen.
[5] Based on the selected irrigation areas shown in Table 6. Data was processed through a weighted average, the way that states accounting for more vulnerable irrigation states, amount to higher scores (the maximum was three different irrigation regions out of the top 10 nationwide, with Guerrero and Chihuahua both leading the criteria).
[6] Based on the feasibility to obtain new information from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)

ANNEX VII

Table A. X. Summary of select parameters of Chihuahua's South WWTP's affluent in 2019 and 2020 (Robles, 2020). Adapted from (M. Olmos, personal communication, December 14, 2020; M. Olmos, personal communication, December 4, 2021)

		AFFLUENT									
		Volume (total m³)	Elec. consumption (total KWh)	pH	TSS (mg/L)	BOD5 (mg/L)	COD (mg/L)	BOD Load (kg)	FC (cfu/100 mL)	TN (mg/L)	TP (mg/L)
2019	Jan-19	4099697	645907	7.79	153.35	183.25	385.78	751269.48		32.57	3.32
	Feb-19	3780253	589213	7.72	149.81		406.28	0		28	4.55
	Mar-19	4212637	680876	7.72	217.22	252.05	509.29	1061795.156		44	5.4
	Apr-19	4034292	676632	7.81	224.5	359.29	531.95	1449480.773		41.33	5.97
	May-19	4231152	697428	7.87	202.58	337.44	508.9	1427759.931		40.2	6.98
	Jun-19	3966496	687011	7.39	255.08	294.96	586.35	1169957.66		44.5	5.35
	Jul-19	4025086	721440	7.74	325.7	321.71	583.17	1294910.417		39.75	5.93
	Aug-19	4196019	708198	7.46	213.84	260.75	441.09	1094111.954		35.44	8.84
	Sep-19	3842335	581997	7.43	184.57	236.75	433.7	909672.8113		32	4.48
	Oct-19	4111916.8	523549	7.54	178.41	144.65	404.26	594788.7651			3.35
	Nov-19	4001604.2	655863	7.64	204.79	188.33	430.29	753622.119			3.23
	Dec-19	4045047	729670	7.2	198.96	354.5	545.81	1433969.162			5.9
2020	Mar-20	2502383	141995.6		164.24	113.78	432.39	284718.96	-	36.63	10.86
	Apr-20	3325229	612000		189.70	203.36	478.43	676227.73	1700000.00	43.56	20.38
	May-20	3917580	665760		207.02	216.05	592.19	846398.34	-	49.20	5.20
	Jun-20	2841396	610080		224.90	165.85	510.72	471255.57	0.00	51.55	5.30
	Jul-20	3297681	647049		230.59	162.24	500.86	535022.57		42.69	4.75
	Aug-20	4746453	612960		230.62	173.89	545.21	825355.44	16900000.00	47.99	3.60
	Sep-20	2989967	617717		209.34	140.83	455.63	421087.02	36500000.00	40.49	2.70
	Oct-20	3078604	633120		200.58	160.40	507.93	493819.48	92300000.00	42.00	4.00
	Nov-20	3415221	683520		235.19	179.87	535.35	614288.80	109307043.07	46.69	10.28
	Period total/ average	78,661,049	13,121,985.60		209.57	222.50	491.69	17,109,512.13	42784507.18	41.03	6.21

ANNEX VIII

Table A. XI. Summary of select parameters of Chihuahua's South WWTP's effluent in 2019 and 2020 (Robles, 2020). Adapted from (M. Olmos, personal communication, December 14, 2020; M. Olmos, personal communication, December 4, 2021)

		EFFLUENT								
		Volume (total m^3)	pH	TSS (mg/L)	BOD5 (mg/L)	COD (mg/L)	BOD Load (kg)	FC (cfu/100 mL)	TN (mg/L)	TP (mg/L)
2019	Jan-19	3714818	7.49	21.33	12.44	18.3	46212.34	3	17.53	3
	Feb-19	3403938	7.78	16.35	8.3	17.32	28252.7	3	19.68	3
	Mar-19	3794369	7.78	17.71	15.57	11.76	59078.3	3	9.25	3
	Apr-19	3614103	7.9	25.81	18.58	22.3	67150.03	3	24.03	3.13
	May-19	3670580	8.02	15.41	8.81	16.7	32337.81	3	15.5	3
	Jun-19	3587667	7.83	22.51	19.04	29.35	68309.18	3	12.48	3
	Jul-19	3551164	7.77	20.36	27.08	34.22	96165.52	3	20.08	3
	Aug-19	3589575.4	6.72	16.5	12.66	24.41	45444.02	3	14.26	3
	Sep-19	3520859	7.74	13.7	22.7	25.05	79923.50	3	15.96	3
	Oct-19	3744403.68	7.52	10.05	8.26	13.83	30928.77	3		3
	Nov-19	3630513		10.52	14.6	19.2	53005.49	3		3
	Dec-19	3656420	7.15	8.87	9.7	16.35	35467.27	3		3
2020	Mar-20	1810247.00		25.02	4.78	48.41	8647.74	-	19.375	7.725
	Apr-20	2259332.00		7.08	42.25	4.77	95456.78	0	25.56	14.83
	May-20	2584806.00		11.64	8.73	45.85	22553.94	0	31.43	3.03
	Jun-20	2129118.51		13.34	5.15	46.34	10972.06	0	29.58	2.28
	Jul-20	2212319.00		10.35	5.46	36.73	12073.86	0	24.04	3.10
	Aug-20	2231415.00		15.13	5.65	46.38	12616.42	3	31.80	3.65
	Sep-20	2364395.00		10.46	4.66	35.30	11029.41	3	25.14	2.85
	Oct-20	2392740.60		11.35	5.76	37.59	13773.21	-	26.00	4.00
	Nov-20	2798373.00		12.77	4.76	34.10	13320.26	0	27.48	4.73
	Period total/ average	64,261,156.19		15.06	12.62	27.82	842,718.62	0.86	21.62	3.92

ANNEX IX

*Table A. XII. Summary of abbreviations and nomenclature used in the ECAM code and calculations in the **preliminary** stage (Water and Wastewater Companies for Climate Mitigation, 2020).*

Code	Name	Type	Current value	Formula	Unit	Description
ww_resi_pop	Resident population	Input	585 374	--	people	Number of permanent residents within the area of service for wastewater services managed by the undertaking (whether they are connected or not) at the reference date
ww_conn_pop	Population connected to sewers	Output	550 251	wwc_conn_pop	people	Number of permanent residents within the service area managed by the undertaking which are connected to the sewer system at the reference date
ww_serv_pop	Serviced population	Output	550 251	wwt_serv_pop	people	Serviced population is referred to the number of inhabitants (or inhabitant equivalents) within the area of service managed by the utility which are connected to a sewer system and which wastewater are receiving treatment in a WWTP.
ww_uncl_pop	Population whose wastewater is not collected	Output	35 123	Math.max(0 ww_resi_pop-ww_conn_pop-fs_onsi_pop)	people	Population whose wastewater is not collected
ww_untr_pop	Population whose wastewater is collected but not treated	Output	0	Math.max(0 ww_conn_pop-ww_serv_pop)	people	Population whose wastewater is collected but not treated
ww_SL_serv_pop	Resident population serviced with Wastewater Treatment	Output	94	100 * ww_serv_pop/ww_resi_pop	%	Percentage of the resident population that are connected to the sewer systems and which wastewater is treated by the undertaking
ww_SL_treat_m3	Collected wastewater treated	Output	100	100 * ww_serv_pop/ww_conn_pop	%	Percentage of the collected sewage prior to dilution or overflows in the sewer system that are treated in wastewater treatment plants
ww_nrg_cost	Energy costs	Input	0	--	USD	Costs from electric energy consumption for the entire wastewater utility based on the electricity bill during the entire assessment period.
ww_run_cost	Total running costs	Input	0	--	USD	Total operations and maintenance net costs and internal manpower net costs (i.e. not including the capitalised cost of self constructed assets) related to wastewater management within the service area managed by the undertaking during the entire assessment period
ww_SL_nrg_cost	Energy costs percentage	Output	~Missing_inputs	100 * ww_nrg_cost/ww_run_cost	%	Proportion of the utility energy costs referred to the total running costs
ww_nrg_cons	Energy consumed from the grid (Collection+Treatment+Discharge)	Output	7 897 784	wwc_nrg_cons + wwt_nrg_cons + wwd_nrg_cons	kWh	Total electric energy consumed from the grid related to wastewater management within the service area managed by the undertaking during the entire assessment period
ww_vol_fuel	Volume of fuel consumed	Output	0	wwc_vol_fuel + wwt_vol_fuel + wwt_fuel_dig + wwd_vol_fuel	L	Volume of fuel consumed

Code	Name	Type	Current value	Formula	Unit	Description
ww_KPI_GHG_unt_ch4	CH4 from untreated wastewater	Output	0	ww_untr_pop * bod_pday/1000 * Days * ww_ch4_efac_unt * ct_ch4_eq;	kg CO2eq	CH4 from untreated wastewater
ww_KPI_GHG_unt_n2o	N2O from untreated wastewater	Output	0	ww_untr_pop * prot_con * Years * ct_fra_np * ct_fac_nc * ct_fac_ic * ct_ef_eff * ct_n2o_co * ct_n2o_eq;	kg CO2eq	N2O from untreated wastewater
ww_KPI_GHG_unt	Untreated wastewater	Output	0	ww_KPI_GHG_unt_ch4 + ww_KPI_GHG_unt_n2o;	kg CO2eq	GHG emissions in CO2 eq from untreated wastewater
ww_SL_ghg_unc_ch4	CH4 from uncollected wastewater	Calculated variable	1 043 237	ww_uncl_pop * bod_pday/1000 * Days * ww_ch4_efac_unc * ct_ch4_eq;	kg CO2eq	CH4 from uncollected wastewater. 0.3 is kgCH4/kgBOD
ww_SL_ghg_unc_n2o	N2O from uncollected wastewater	Calculated variable	605 877	ww_uncl_pop * prot_con * Years * ct_fra_np * ct_fac_nc * ct_fac_ic * ct_ef_eff * ct_n2o_co * ct_n2o_eq;	kg CO2eq	N2O from uncollected wastewater
ww_SL_ghg_unc	Uncollected wastewater	Output	1 649 114	ww_SL_ghg_unc_ch4 + ww_SL_ghg_unc_n2o;	kg CO2eq	GHG emissions from uncollected wastewater
ww_GHG_avoided	Total GHG emissions avoided	Output	~Missing_inputs	wwt_SL_GHG_avoided + wwt_wr_C_seq_slu + wwd_wr_GHG_avo_d + wwd_SL_ghg_non + wwd_wr_GHG_avo + fst_SL_GHG_avoided + fsr_ghg_avoided_reuse + fsr_ghg_avoided_land + 0;	kg CO2eq	Total GHG emissions avoided
wwc_KPI_GHG	Total GHG Wastewater Collection	Calculated variable	1 191 205	wwc_KPI_GHG	kg CO2eq	Total GHG Wastewater Collection
wwt_KPI_GHG	Total GHG Wastewater Treatment	Output	2 572 378	wwt_KPI_GHG	kg CO2eq	Total GHG Wastewater Treatment
wwd_KPI_GHG	Total GHG Wastewater Discharge/Reuse	Output	4 612 690	wwd_KPI_GHG	kg CO2eq	Total GHG Wastewater Discharge/Reuse
ww_KPI_GHG	Total GHG Wastewater	Output	8 376 273	wwc_KPI_GHG + wwt_KPI_GHG + wwd_KPI_GHG + ww_KPI_GHG_unt	kg CO2eq	GHG Emissions from non-electricity and electricity consumption

ANNEX X

*Table A. XIII. Summary of abbreviations and nomenclature used in the ECAM code and calculations in the **collection** stage (Water and Wastewater Companies for Climate Mitigation, 2020)*

Code	Name	Type	Current value	Formula	Unit	Description
wwc_nrg_cons	Energy consumed from the grid	Calculated variable	1 184 668	--	kWh	Energy consumed during the assessment period by each pumping station for conveying wastewater to treatment managed by the undertaking
wwc_conn_pop	Population connected to sewers	Calculated variable	550 251	--	people	Number of permanent residents within the service area managed by the undertaking which are connected to the sewer system at the reference date
wwc_vol_conv	Volume of wastewater conveyed to treatment	Calculated variable	48 546 535	--	m3	Collected wastewater corresponding to the volume of domestic commercial and industrial outputs to the sewer system which reaches the treatment plant or an outfall during the assessment period (pumped or not). At sub-stage level if the volume is pumped only enter in this line if it is pumping directly to the plant or the discharge. In case of multiple stage pumping do not include the volume in this line. This input should equal value reported in global assessment for volume wastewater treated by default.
wwc_SL_conn_pop	Population connected to sewers	Calculated variable	94	100 * wwc_conn_pop/ww_resi_pop	%	Population connected to sewers
wwc_KPI_nrg_per_m3	Energy consumption per wastewater conveyed to treatment	Calculated variable	0.054	wwc_nrg_cons/wwc_vol_conv	kWh/m3	Amount of energy consumed to bring 1 m3 of wastewater from the sources to the wastewater treatment plant
ww_ch4_efac_unt	CH4 emission factor (untreated wastewater)	Calculated variable	0.06	--	kgCH4/kgBOD	CH4 emission factor (untreated wastewater)
ww_ch4_efac_unc	CH4 emission factor (uncollected wastewater)	Calculated variable	0.06	--	kgCH4/kgBOD	CH4 emission factor (uncollected wastewater)
wwc_fuel_typ	Fuel type	Calculated variable	0	--	Fuel type	Fuel type
wwc_vol_fuel	Volume of fuel consumed	Calculated variable	0	--	L	Volume of fuel consumed
wwc_wet_flow	Average daily wet weather flow	Calculated variable	0	--	m3/day	Average daily wet weather flow
wwc_dry_flow	Average daily dry weather flow	Calculated variable	0	--	m3/day	Average daily dry weather flow
wwc_rain_day	Number of rain days	Calculated variable	0	--	day	Number of rain days during the assessment period
c_wwc_vol_infl	Infiltration and inflow volume	Calculated variable	0	wwc_rain_day/86400 * (wwc_wet_flow-wwc_dry_flow)	m3	Infiltration and inflow volume
wwc_SL_GHG_ii	From Infiltration and Inflow	Calculated variable	0	wwc_KPI_nrg_per_m3 * c_wwc_vol_infl * conv_kwh_co2	kg CO2eq	From Infiltration and Inflow

Code	Name	Type	Current value	Formula	Unit	Description
wwc_SL_fratio	Wet weather flow to dry weather flow ratio	Calculated variable	~Missing_inputs	wwc_wet_flow/wwc_dry_flow	ratio	Wet weather flow to dry weather flow ratio
wwc_SL_GHG_inf	GHG in wastewater collection due to infiltration/inflow	Calculated variable	0	wwc_KPI_GHG_elec * c_wwc_vol_infl / wwc_vol_conv	kg CO2eq	GHG in wastewater collection due to infiltration/inflow
wwt_SL_GHG_inf	GHG in wastewater treatment due to infiltration/inflow	Output	0	wwt_KPI_GHG_elec * c_wwc_vol_infl / wwc_vol_conv	kg CO2eq	GHG in wastewater treatment due to infiltration/inflow
wwd_SL_GHG_inf	GHG in wastewater discharge/reuse due to infiltration/inflow	Output	0	wwd_KPI_GHG_elec * c_wwc_vol_infl / wwc_vol_conv	kg CO2eq	GHG in wastewater discharge/reuse due to infiltration/inflow
wwc_SL_inf_emis	Total GHG emissions attributable to infiltration/inflow	Calculated variable	0	wwc_SL_GHG_inf + wwt_SL_GHG_inf + wwd_SL_GHG_inf	kg CO2eq	Total GHG emissions attributable to infiltration/inflow
wwc_vol_pump	Volume of pumped wastewater	Calculated variable	0	--	m3	Volume of pumped wastewater
wwc_nrg_pump	Energy consumed from the grid (pumping)	Calculated variable	0	--	kWh	Energy consumed from the grid (pumping)
wwc_pmp_head	Pump head	Calculated variable	0	--	m	Pump head
wwc_sta_head	Static head	Calculated variable	0	--	m	Static head
wwc_coll_len	Collector length	Calculated variable	0	--	km	Collector length
wwc_pmp_flow	Measured pump flow	Calculated variable	0	--	L/s	Measured pump flow
wwc_pmp_volt	Measured pump voltage	Calculated variable	0	--	V	Measured pump voltage
wwc_pmp_amps	Measured pump current	Calculated variable	0	--	A	Measured pump current
wwc_pmp_exff	Expected electromechanical efficiency of new pump	Calculated variable	0	--	%	Expected electromechanical efficiency of new pump

Code	Name	Type	Current value	Formula	Unit	Description
c_wwc_pmp_pw	Calculated water power	Calculated variable	0	wwc_pmp_flow * wwc_pmp_head * ct_gravit/1000;	kW	Calculated water power
wwc_KPI_std_nrg_cons	Standardized Energy Consumption	Calculated variable	~Missing_inputs	wwc_nrg_pump/(wwc_vol_pump * wwc_pmp_head/100)	kWh/m3/100m	Percentage of energy consumed in wastewater collection with regards to the Total energy consumed from the grid and self produced in the water and wastewater systems
wwc_KPI_un_head_loss	Unit head loss	Calculated variable	~Missing_inputs	1000 * (wwc_pmp_head-wwc_sta_head)/wwc_coll_len	m/km	Unit energy friction loss in the conveyance system
wwc_pmp_pf	Power factor	Calculated variable	0.9	--	ratio	Power factor
wwc_KPI_nrg_elec_eff	Electromechanical efficiency of existing pump	Calculated variable	~Missing_inputs	100 * c_wwc_pmp_pw/(wwc_pmp_volt * wwc_pmp_amps * Math.sqrt(3) * wwc_pmp_pf/1000)	%	Electromechanical efficiency of existing pump
wwc_KPI_std_nrg_newp	Standardized energy consumption of new pump	Calculated variable	~Missing_inputs	wwc_KPI_nrg_elec_eff/wwc_pmp_exff * wwc_KPI_std_nrg_cons	kWh/m3/100m	Standardized energy consumption of new pump
wwc_KPI_nrg_cons_new	Energy consumption with expected new pump efficiency	Calculated variable	~Missing_inputs	wwc_vol_pump * wwc_KPI_std_nrg_newp/100 * wwc_pmp_head	kWh	Energy consumption with expected new pump efficiency
wwc_KPI_nrg_estm_sav	Estimated electricity savings	Calculated variable	~Missing_inputs	wwc_nrg_cons-wwc_KPI_nrg_cons_new	kWh	Estimated electricity savings
wwc_KPI_ghg_estm_red	Estimated GHG reduction per assessment period	Calculated variable	~Missing_inputs	conv_kwh_co2 * wwc_KPI_nrg_estm_sav	kg CO2eq	Estimated GHG reduction per assessment period
wwc_KPI_GHG_elec	Electricity	Calculated variable	1 191 205	wwc_nrg_cons * conv_kwh_co2	kg CO2eq	GHG emissions from electricity
wwc_KPI_GHG_fuel	Fuel engines (total emissions)	Calculated variable	0	wwc_KPI_GHG_fuel_co2 + wwc_KPI_GHG_fuel_n2o + wwc_KPI_GHG_fuel_ch4;	kg CO2eq	Fuel engines (total emissions)
wwc_KPI_GHG_fuel_co2	Fuel engines (CO2)	Calculated variable	0	fuel=Tables['Fuel types'][Tables.find('wwc_fuel_typ' wwc_fuel_typ)]; wwc_vol_fuel * fuel.FD * fuel.NCV/1000 * fuel.EFCO2;	kg CO2eq	Fuel engines (CO2)
wwc_KPI_GHG_fuel_n2o	Fuel engines (N2O)	Calculated variable	0	fuel=Tables['Fuel types'][Tables.find('wwc_fuel_typ' wwc_fuel_typ)]; wwc_vol_fuel * fuel.FD * fuel.NCV/1000 * fuel.EFN2O.engines * ct_n2o_eq;	kg CO2eq	Fuel engines (N2O)
wwc_KPI_GHG_fuel_ch4	Fuel engines (CH4)	Calculated variable	0	fuel=Tables['Fuel types'][Tables.find('wwc_fuel_typ' wwc_fuel_typ)]; wwc_vol_fuel * fuel.FD * fuel.NCV/1000 * fuel.EFCH4.engines * ct_ch4_eq;	kg CO2eq	Fuel engines (CH4)
wwc_KPI_GHG	Total GHG Wastewater Collection	Calculated variable	1 191 205	wwc_KPI_GHG_elec + wwc_KPI_GHG_fuel	kg CO2eq	Total GHG Wastewater Collection

ANNEX XI

*Table A. XIV. Summary of abbreviations and nomenclature used in the ECAM code and calculations in the **treatment** stage (Water and Wastewater Companies for Climate Mitigation, 2020)*

Code	Name	Type	Current value	Formula	Unit	Description
wwt_nrg_cons	Energy consumed from the grid	Input	5 528 549	--	kWh	Total energy consumed during the assessment period by all wastewater treatment plants managed by the undertaking
wwt_serv_pop	Serviced population	Input	550 251	--	people	Serviced population is referred to the number of inhabitants (or inhabitant equivalents) within the area of service managed by the utility which are connected to a sewer system and which wastewater are receiving treatment in a WWTP.
wwt_vol_trea	Volume of treated wastewater	Input	48 546 535	--	m3	Volume of treated wastewater over the assessment period
wwt_type_tre	Type of treatment	Input	1	--	Technology	Type of treatment
wwt_bod_infl	Influent BOD5 load	Input	11 941 338	--	kg	BOD5 load entering the WWTP during the assessment period. It can be estimated by multiplying the average BOD concentration in the influent by the volume entering the plant. If this is done daily and summed over the duration of the assessment period the value will be most accurate
wwt_bod_effl	Effluent BOD5 load	Input	1 194 134	--	kg	BOD5 load at the effluent of the WWTP during the assessment period. It can be estimated by multiplying the average BOD5 concentration in the effluent by the effluent volume the plant. If this is done daily and summed over the duration of the assessment period the value will be most accurate
wwt_bod_slud	BOD removed as sludge	Input	5 539 989	--	kg	BOD removed from the wastewater though the process of removing primary or secondary sludge from the aerobic treatment process. This value is used to estimate the Methane emissions from poorly aerated biological treatment of wastewater
c_wwt_bod_rmvd	BOD5 mass removed	Calculated variable	10 747 204	wwt_bod_infl-wwt_bod_effl	kg	This is calculated from the difference in BOD mass from the influent with BOD mass from the effluent over the assessment period.
wwt_KPI_nrg_per_m3	Energy consumption per treated wastewater	Output	0.054	wwt_nrg_cons/wwt_vol_trea	kWh/m3	Energy consumption per treated wastewater
wwt_KPI_nrg_per_kg	Energy consumption per BOD5 mass removed	Output	0.24	wwt_nrg_cons/c_wwt_bod_rmvd	kWh/kg	Percentage of energy consumed in wastewater treatment with regards to the Total energy consumed from the grid and self produced in the water and wastewater systems
wwt_SL_vol_pday	Treated wastewater per person per day	Output	242.4	1000 * wwt_vol_trea/wwt_serv_pop/Days	L/serv.pop./day	Volume of treated wastewater per serviced person in the service area managed by the undertaking divided by the duration of the assessment period
wwt_KPI_capac_util	Capacity utilization	Calculated variable	~Missing_inputs	100 * wwt_vol_trea/wwt_trea_cap	%	Percentage of dry weight of sludge that comes out from the WWTP to disposal
wwt_SL_qual_com	Percentage of quality compliance	Output	~Missing_inputs	100 * wwt_tst_cmpl/wwt_tst_cond	%	Percentage of water quality tests carried out in wastewater treatment plants that comply with discharge consents
wwt_KPI_nrg_per_pump	Energy consumption for wastewater pumping to treatment	Output	~Missing_inputs	wwt_nrg_pump/wwt_vol_pump	kWh/m3	Energy consumption for wastewater pumping to treatment

Code	Name	Type	Current value	Formula	Unit	Description
wwt_pmp_amps	Measured pump current	Input	0	--	A	Measured pump current
wwt_pmp_exff	Expected electromechanical efficiency of new pump	Input	0	--	%	Expected electromechanical efficiency of new pump
c_wwt_pmp_pw	Calculated water power	Calculated variable	0	wwt_pmp_flow * wwt_pmp_head * ct_gravit/1000;	kW	Calculated water power
wwt_KPI_nrg_elec_eff	Electromechanical efficiency of existing pump	Calculated variable	~Missing_inputs	100 * c_wwt_pmp_pw/(wwt_pmp_volt * wwt_pmp_amps * Math.sqrt(3) * wwt_pmp_pf/1000)	%	Electromechanical efficiency of existing pump
wwt_KPI_std_nrg_newp	Standardized energy consumption of new pump	Output	~Missing_inputs	wwt_KPI_nrg_elec_eff/wwt_pmp_exff * wwt_KPI_std_nrg_cons	kWh/m3/100m	Standardized energy consumption of new pump
wwt_KPI_nrg_cons_new	Energy consumption with expected new pump efficiency	Output	~Missing_inputs	wwt_vol_pump * wwt_KPI_std_nrg_newp/100 * wwt_pmp_head	kWh	Energy consumption with expected new pump efficiency
wwt_KPI_nrg_estm_sav	Estimated electricity savings	Output	~Missing_inputs	wwt_nrg_cons- wwt_KPI_nrg_cons_new	kWh	Estimated electricity savings
wwt_KPI_ghg_estm_red	Estimated GHG reduction per assessment period	Output	~Missing_inputs	conv_kwh_co2 * wwt_KPI_nrg_estm_sav	kg CO2eq	Estimated GHG reduction per assessment period
wwt_biog_pro	Biogas produced	Input	2 563 706	--	m3	Biogas produced during the assessment period by each wastewater treatment plant managed by the undertaking
wwt_biog_fla	Biogas flared	Input	2 563 706	--	m3	Biogas flared is calculated with the difference between biogas produced minus biogas valorised. If biogas produced is 0 (unknown) biogas flared is estimated using ww_serv_pop*bod_pday*ct_bod_kg*ct_biog_g*Days/1000
wwt_mass_slu	Sludge produced in WWTPs (total weight)	Input	2 798 221	--	kg	Sludge produced during the assessment period by each wastewater treatment plant managed by the undertaking
wwt_dryw_slu	Dry weight in sludge produced	Input	111 929	--	kg	Average of dry total weight of sludge produced as dry weight during the assessment period by each wastewater treatment plant managed by the undertaking. If sludge is processed with centrifuges or chemicals a good estimation is 20% of Sludge produced in WWTP (total weight)
wwt_slu_disp	Sludge type disposed of	Input	1	--	Sludge type disposed of	Sludge type disposed of

Code	Name	Type	Current value	Formula	Unit	Description
wwt_KPI_sludg_prod	Sludge production (total weight)	Output	0.058	wwt_mass_slu/wwt_vol_trea	kg/m3	Sludge production per treated wastewater
wwt_KPI_dry_sludge	Dry weight in sludge production	Output	4	100 * wwt_dryw_slu/wwt_mass_slu	% DW	Dry sludge production per treated wastewater in wastewater treatment plants
wwt_KPI_ghg_inc_co2eq	Total CO2 eq emissions due to sludge incineration	Calculated variable	0	wwt_slu_inciner_ch4 + wwt_slu_inciner_n2o	kg CO2eq	Amount of CO2 eq emissions due to sludge incineration
wwt_soil_typ	Soil typology	Input	0	--	Soil type	Soil typology the sludge is applied on. Note: if you don't know the soil typology leave it as 'Fine-textured'
wwt_slu_la_N_cont	Total Nitrogen (% of dry weight)	Input	4	--	%	Total Nitrogen (% of dry weight)
wwt_slu_landapp_n2o	N2O emissions due to sludge for land application	Output	48 222	sludge_type=Tables.find('wwt_slu_disp' wwt_slu_disp); soil_type=Tables.find('wwt_soil_typ' wwt_soil_typ); ratio_CN=content_C(wwt_mass_slu_app sludge_type)/content_N(wwt_mass_slu_app sludge_type); if(ratio_CN>=30){0;} if(soil_type=="Fine-Textured (>30% clay)"){wwt_mass_slu_app * wwt_slu_la_N_cont/100 * 0.023 * ct_n2o_co * ct_n2o_eq} if(soil_type=="Coarse-Textured (<30% clay)"){wwt_mass_slu_app * wwt_slu_la_N_cont/100 * 0.005 * ct_n2o_co * ct_n2o_eq}	kg CO2eq	Amount of N2O emissions due to sludge applied to land
wwt_KPI_GHG_tre_n2o	N2O from treatment process	Output	654 102	ActiveStages.wasteTre * wwt_serv_pop * ct_fac_ic * ct_n2o_efp * Years * 1e-3 * ct_n2o_eq + wwt_GHG_tre_n2o;	kg CO2eq	N2O (CO2 eq) emitted in wastewater treatment plants.Eq 6.9 2006 IPCC Guidelines for National Greenhouse Gas Inventories
wwt_KPI_GHG_dig_fuel_ch4	Fuel employed for digester (CH4)	Output	0	fuel=Tables['Fuel types'][Tables.find('wwt_dige_typ' wwt_dige_typ)]; wwt_fuel_dig * fuel.FD * fuel.NCV/1000 * ct_ch4_eq * fuel.EFCH4.engines	kg CO2eq	Amount of CH4 (CO2 eq) emissions due to fuel employed for digester
wwt_KPI_GHG_biog	Biogas	Output	678 849	(wwt_biog_pro-wwt_biog_val-wwt_biog_fla + wwt_biog_fla * ct_ch4_lo/100) * wwt_ch4_biog/100 * ct_ch4_m3 * ct_ch4_eq;	kg CO2eq	GHG emissions from biogas
wwt_KPI_GHG	Total GHG Wastewater Treatment	Output	2 572 378	wwt_KPI_GHG_elec + wwt_KPI_GHG_fuel + wwt_KPI_GHG_tre + wwt_KPI_GHG_dig_fuel + wwt_KPI_GHG_biog + wwt_KPI_GHG_slu;	kg CO2eq	Total GHG Wastewater Treatment

ANNEX XII

Table A. XV. Summary of abbreviations and nomenclature used in the ECAM code and calculations in the ***discharge/reuse*** *stage (Water and Wastewater Companies for Climate Mitigation, 2020)*

Code	Name	Type	Current value	Formula	Unit	Description
wwd_wr_nrg_sav	Net electricity savings due to reuse displacing potable water	Output	~Missing_inputs	wwd_wr_vol_d * (wsa_nrg_per_abs_watr + wst_KPI_nrg_per_m3 + wsd_KPI_nrg_per_vd)- wwd_wr_adnrg;	kWh	Net electricity savings due to reuse displacing potable water
wwd_wr_GHG_avo_d	GHG emissions avoided due to reuse displacing potable water use	Output	~Missing_inputs	wwd_wr_nrg_sav * conv_kwh_co2;	kg CO2eq	GHG emissions avoided due to reuse displacing potable water use
wwd_nrg_cons	Energy consumed from the grid	Input	1 184 668	--	kWh	Sum of energy consumed (from the grid or self-produced) during the assessment period by all each pumping stations for discharged wastewater managed by the undertaking
wwd_KPI_nrg_per_m3	Energy consumption per discharged/reused wastewater	Output	0.061	wwd_nrg_cons/wwd_vol_disc	kWh/m3	Unit energy consumption per discharged/reused water
wwd_KPI_std_nrg_cons	Standardized Energy Consumption	Output	~Missing_inputs	wwd_nrg_pump/(wwd_vol_pump * wwd_pmp_head/100)	kWh/m3/100m	Standardized Energy Consumption
wwd_pmp_pf	Power factor	Input	0.9	--	ratio	Power factor
wwd_KPI_un_head_loss	Unit head loss	Output	~Missing_inputs	1000 * (wwd_pmp_head- wwd_sta_head)/wwd_coll_len	m/km	Unit head loss
wwd_KPI_nrg_elec_eff	Electromechanical efficiency of existing pump	Calculated variable	~Missing_inputs	100 * c_wwd_pmp_pw/(wwd_pmp_volt * wwd_pmp_amps * Math.sqrt(3) * wwd_pmp_pf/1000)	%	Electromechanical efficiency of existing pump
wwd_KPI_std_nrg_newp	Standardized energy consumption of new pump	Output	~Missing_inputs	wwd_KPI_nrg_elec_eff/wwd_pmp_exff * wwd_KPI_std_nrg_cons	kWh/m3/100m	Standardized energy consumption of new pump

Code	Name	Type	Current value	Formula	Unit	Description
wwd_KPI_nrg_cons_new	Energy consumption with expected new pump efficiency	Output	~Missing_inputs	wwd_vol_pump * wwd_KPI_std_nrg_newp/100 * wwd_pmp_head	kWh	Energy consumption with expected new pump efficiency
wwd_KPI_nrg_estm_sav	Estimated electricity savings	Output	~Missing_inputs	wwd_nrg_cons- wwd_KPI_nrg_cons_new	kWh	Estimated electricity savings
wwd_KPI_ghg_estm_red	Estimated GHG reduction per assessment period	Output	~Missing_inputs	conv_kwh_co2 * wwd_KPI_nrg_estm_sav	kg CO2eq	Estimated GHG reduction per assessment period
wwd_KPI_GHG_elec	Electricity	Output	1 191 205	wwd_nrg_cons * conv_kwh_co2	kg CO2eq	GHG emissions from electricity
wwd_vol_disc	Volume of discharged effluent to water body	Input	43 478 410	--	m3	Volume of wastewater discharged by each wastewater treatment plant that are the responsibility of the undertaking during the assessment period. This includes all the wastewater collected whether it is conveyed to treatment or discharged untreated
wwd_bod_effl	Effluent BOD load	Input	852 306	--	kg	Effluent BOD load
wwd_n2o_effl	Total Nitrogen concentration in the effluent	Input	16.53	--	mg/L	Total Nitrogen concentration in the effluent during the assessment period
wwd_ch4_efac	CH4 emission factor	Input	0.06	--	kgCH4/kgBOD	CH4 emission factor
wwd_KPI_GHG_tre_n2o	N2O from effluent discharge	Output	1 682 780	wwd_n2o_effl/1000 * wwd_vol_disc * ct_n2o_eq * ct_ef_eff * ct_n2o_co;	kg CO2eq	Indirect CO2 emitted in receiving waters due to nitrogen in wastewater effluent. Based upon nitrogen in the WWTP effluent multiplied by default emission factor
wwd_KPI_GHG_tre_ch4	CH4 from effluent discharge	Output	1 738 704	wwd_bod_effl * wwd_ch4_efac * ct_ch4_eq;	kg CO2eq	CH4 from effluent discharge
wwd_KPI_GHG_tre	Effluent discharge	Output	3 421 485	wwd_KPI_GHG_tre_ch4 + wwd_KPI_GHG_tre_n2o;	kg CO2eq	Effluent discharge
wwd_total_m3	Total volume discharged and reused effluent	Output	43 478 410	wwd_vol_disc + wwd_vol_nonp;	m3	Total volume discharged and reused effluent
wwd_KPI_GHG	Total GHG Wastewater Discharge/Reuse	Output	4 612 690	wwd_KPI_GHG_elec + wwd_KPI_GHG_fuel + wwd_KPI_GHG_trck + wwd_KPI_GHG_tre;	kg CO2eq	Total GHG Wastewater Discharge/Reuse

ANNEX XIII

Equations for input estimations based on other inputs:

1. Estimations performed when answering biogas questions (produced and valorized)

Biogas produced → wwt_biog_pro = wwt_serv_pop * bod_pday * Days * ct_bod_kg * ct_biog_g/1000;

Percentage of methane in biogas → wwt_ch4_biog = 59

Biogas valorised as heat and/or electricity → wwt_biog_val = wwt_biog_pro

2. Estimations performed when the main treatment type is chosen

CH_4 emission factor → wwt_ch4_efac = type_tre=Tables.find('wwt_type_tre',wwt_type_tre);
Tables.wwt_type_tre[type_tre].ch4_efac;

Influent BOD_5 load → wwt_bod_infl = bod_pday/1000 * ww_serv_pop * Days

Effluent BOD_5 load → wwt_bod_effl = 0.10 * wwt_bod_infl

BOD removed as sludge → wwt_bod_slud =
type_tre=Tables.find('wwt_type_tre',wwt_type_tre);
percent=Tables.wwt_type_tre[type_tre].bod_rmvd_as_sludge_estm;
percent * wwt_bod_infl;

Effluent BOD load → wwd_bod_effl = wwt_bod_effl

3. Estimations performed when the sludge disposal method is chosen

Sludge produced in WWTPs (total weight) → wwt_mass_slu = if(wwt_producing_biogas){
b=0.6;
}else{
b=1;
}
b * 0.55 * bod_pday * ww_serv_pop * 0.9 * 1e-3 * 1.176 * Days;

Dry weight in sludge produced → wwt_dryw_slu = 0.04 * wwt_mass_slu

Fluidized Bed Reactor Temperature → wwt_temp_inc = 1023

Total Nitrogen (% of dry weight) → wwt_slu_lf_N_cont = slu_disp=Tables.find('wwt_slu_disp',wwt_slu_disp);
Tables.wwt_slu_disp[slu_disp].la_N_cont;

Total Volatile Solids (% of dry weight) → wwt_slu_lf_TVS = slu_disp=Tables.find('wwt_slu_disp',wwt_slu_disp);
Tables.wwt_slu_disp[slu_disp].TVS;

Total Nitrogen (% of dry weight) → wwt_slu_la_N_cont = slu_disp=Tables.find('wwt_slu_disp',wwt_slu_disp);
Tables.wwt_slu_disp[slu_disp].la_N_cont;

FSM

Source: (Water and Wastewater Companies for Climate Mitigation, 2020)