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Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional Oaxaca

Análisis de indicadores indirectos de disponibilidad y contaminación hídrica, mediante modelado en zonas agrícolas

Analysis of indirect indicators of availability and water pollution, through modeling in agricultural areas

T E S I S

Que para obtener el grado académico de:

Doctor en Ciencias en Conservación y Aprovechamiento de Recursos Naturales

Presenta:

M.C Edwin Antonio Ojeda Olivares

Asesores:

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ACTA DE REVISIÓN DE TESIS

En la Ciudad de Oaxaca siendo las 13:30 horas del día 14 del mes de octubre del 2019 se reunieron los miembros de la Comisión Revisora de la Tesis, designada por el Colegio de Profesores de Estudios de Posgrado e Investigación de CIIDIR OAXACA para examinar la tesis titulada:

Análisis de indicadores indirectos de disponibilidad y contaminación hídrica mediante modelado en zonas agrícolas.

Presentada por el alumno:

Ojeda	Olivares
Apellido paterno	Apellido materno

Nombre(s): Edwin Antonio

Con registro: | B | 1 | 5 | 0 | 6 | 7 | 2 |

aspirante de:

Doctorado en Ciencias en Conservación y Aprovechamiento de Recursos Naturales

Después de intercambiar opiniones los miembros de la Comisión manifestaron ***APROBAR LA TESIS***, en virtud de que satisface los requisitos señalados por las disposiciones reglamentarias vigentes.

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En la Ciudad de Oaxaca el día 14 del mes de octubre el año 2019, el (la) que suscribe Edwin Antonio Ojeda Olivares alumno(a) del Programa de Doctorado en Ciencias en Conservación y Aprovechamiento de Recursos Naturales con número de registro B150672, adscrito a Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional Unidad Oaxaca, manifiesta que es autor (a) intelectual del presente trabajo de Tesis bajo la dirección del Dr. Sadoth Sandoval Torres y Dr. Salvador Isidro Belmonte Jiménez y cede los derechos del trabajo titulado: Análisis de indicadores indirectos de disponibilidad y contaminación hídrica mediante modelado en zonas agrícolas al Instituto Politécnico Nacional para su difusión, con fines académicos y de investigación.

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ABSTRACT

Water resources, especially groundwater, play a crucial role in economic and social development, and the population is so dependent on water to produce goods and services. Dependence that can derive in a susceptible situation and in two possible scenarios, the reduction of the water supplies (water scarcity) and pollution of the water sources. The availability of groundwater resources (quantity), will depend on two essential parameters, abstraction volumes, and water recharge ratios. This study, evaluate the main stressors for water depletion and pollution, climate change, population growth and land use/land cover change and how they are related and proposes the implementation of two simple models to evaluate groundwater resource. The first considers abstraction, water recharge, runoff, pollution, and marginalization as indicators of groundwater vulnerability, while the second additionally considers the wastewater treatment capacity to evaluate water availability in terms of quantity and quality. For the generation, management and validation of data tools have been used such as remote sensing techniques, geographic information systems, general circulation models, climate change scenarios, analytical hierarchy process, fuzzy logic, sensitivity and uncertainty analysis with Monte Carlos simulations. Results indicate the increase of impervious surface and climate change effects are reducers of water recharge, and the corresponding scenarios indicate dangerous changes that could drive exhaust the aquifer and led to a total scarcity in the next years. While aquifer depletion is a product of the combination of population growth, land use and land cover change, climate change and other factors, give rise to water stress and boosts unstainable resource use. Groundwater is vulnerable and susceptible to overexploitation and pollution, mainly because of the intense agricultural activities and the precarious treatment capacity of the wastewater. Future water management strategies should incorporate an integral plan to preserve the groundwater resource, and water policies should implement regulation that permits reductions in groundwater abstraction, identification of water recharge areas, promoting of induced water recharge, protection of the forest cover and an increase of the water treatment capacity, avoiding water bodies pollution and giving an alternative source of water, making the water 100% recyclable, improving water availability, especially when scenarios predict reduction in the recharge due to climate change affectations, in the near and medium future.

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Chapter 1: Research approach
1. Introduction

In recent years the stress to which the water resource has been subjected is very high, so much that many communities have restricted access to the water resource, due to overexploitation and the reduction of the amount of water available due to the decrease in rainfall and of storage supplies (Parish et al., 2012). In 2010 80% of the world's water supplies were exposed to significant stressors that jeopardized the safety of drinking water for the respective populations (Vörösmarty et al., 2010), is the population increase and Climate Change (Cch) the main stressors. Climate change can directly or indirectly affect hydrological processes and groundwater resources in ways that have not yet been sufficiently explored (Dettinger and Earman, 2007, Green et al., 2011). The larger amount of climate data and predictions provide enough evidence that water resources are vulnerable to climate change, a situation that represents a risk to society and ecosystems (Bates et al., 2008).

Water is a highly susceptible and vulnerable resource to anthropogenic factors and changes in the conditions of the hydrogeological media since they affect its availability and quality. Water availability is linked to abstraction for different uses, recharge rates, climatological conditions, population, and aquifer features while water quality is related to the contamination rates, water treatment capacity, economic activities, which altogether generate water stress in any aquifer system.

For water management it is necessary to evaluate the effects of the different water stressors. The evaluation of water systems is a complicated issue, especially the groundwater, which is an intricate component of the hydrological system of any region since the information for its evaluation is usually minimal, incomplete and uncertain. The relationship with social, economic, and environmental systems is another factor to take into account, since they are complicated systems to predict, increasing the complexity. This complexity of groundwater makes them even more susceptible since once degraded; it is hard to restore a system (Jakeman et al., 2016).

Groundwater is a vital source of fresh water for residential consumption and agriculture uses (Siebert et al., 2010, Shahid et al., 2015), and it plays a fundamental role in economic and food security (Sharma, 2009). Agriculture uses more freshwater than any other sector or economic activity. It represents approximately 70% of global groundwater withdrawals and 90% of total freshwater consumption. Irrigation consumes 545 km3 of groundwater per year (Siebert et al., 2010). In terms of availability and water pollution, three significant stressors were identified for water security in the Central Valleys of Oaxaca: The Climate Change, Population, and Land Use/Land Cover Change. Therefore, in this work, these indicators will be analyzed in order to develop a water availability model. The contribution of this research work allows a better understanding of the dynamic of the groundwater resource.

1.1 Study Area

The study area comprises the Alto Atoyac sub-basin and it is located between 16°30’ and 17°25’ north latitude, and 96°15’ and 97°00’ west longitude, and includes the Central Valleys Region of the State of Oaxaca, including Etla, Tlacolula, and Zaachila valleys (see Figure 1.1). It is limited to the west by the Mixteca Region, to the northeast by the Cañada Region, to the north by the Sierra de Juarez, to the east by the Tehuantepec Isthmus Region, and to the south by the Sierra Madre del Sur. In the Central Valleys, 100% of drinking water is derived from the underground. Of the water used in agriculture in the entire region 87.6 % also has its origin in the sub-soil. This dependence and the fact that groundwater is the only water resource in a surface of 3,744.64 km2 with an exploitation surface of 1,130 km2, explain why it is imperative to assess the possible impacts of climate change on the groundwater.

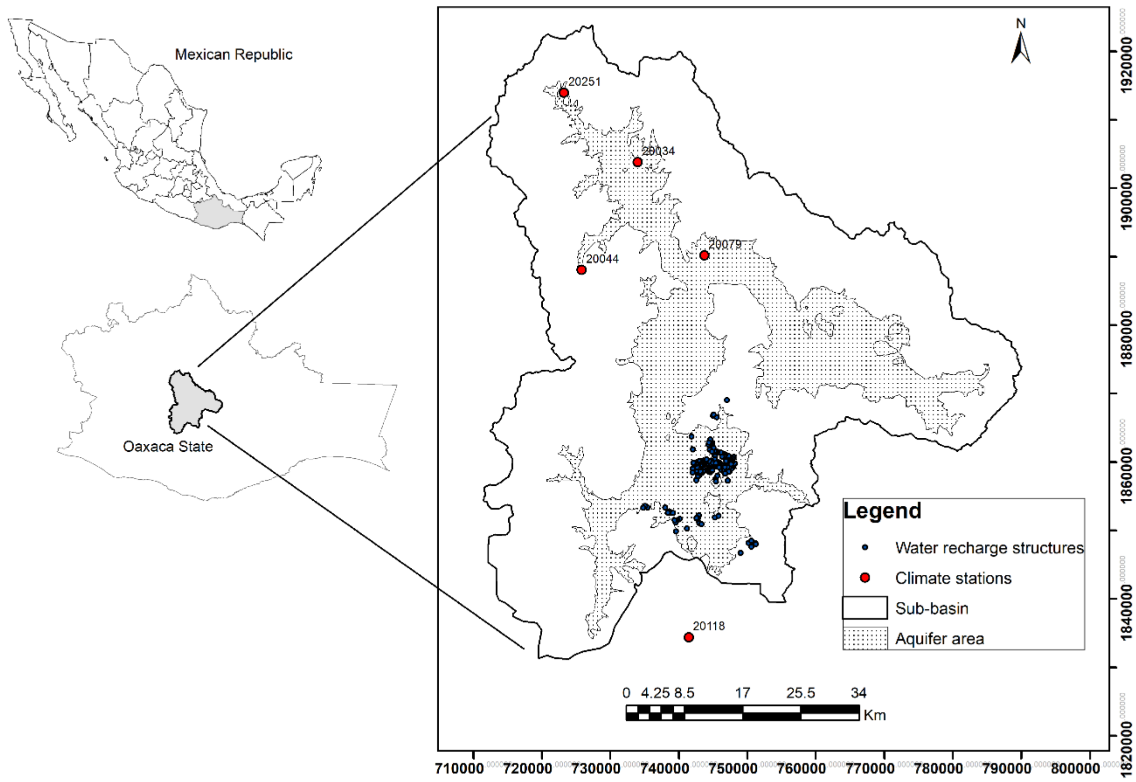

Figure 1. 1 Location of the study area

1.2 Hydrological and geological features

Figure 1. 2, shows the simplified geologic map of the study area according to Secretary of Economy (SE, 1997, SE, 2007, SE, In press). It can be noted the presence of rocks of Precambrian, Cretaceous, and Tertiary ages that point to a complex geological history.

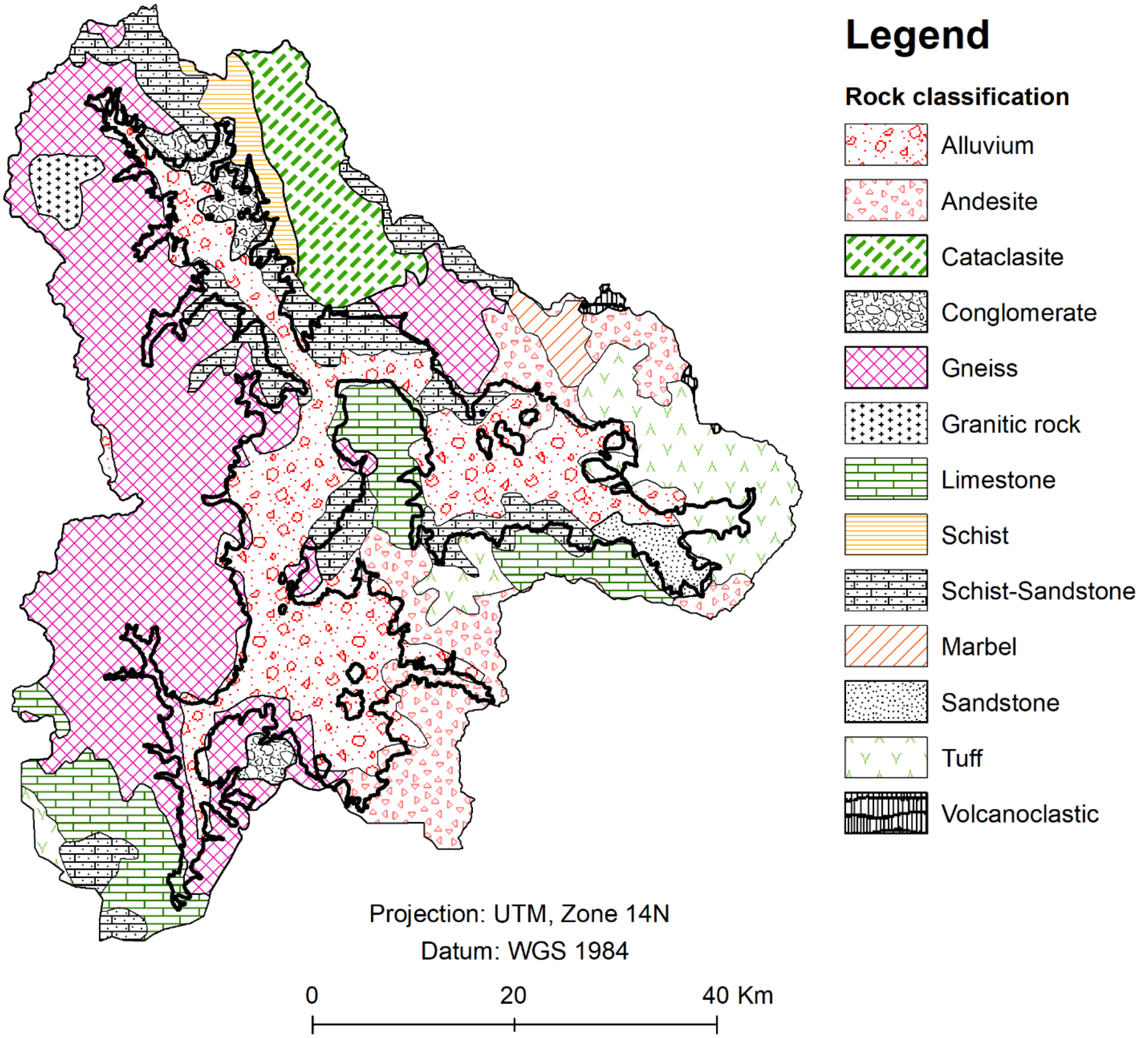

Figure 1. 2 Geology of the study area

The study area straddles the boundary between the Oaxaca (Zapoteco, Oaxaquia) and Juarez (Cuicateco) terranes (Campa and Coney, 1983, Sedlock et al., 1993, Alaniz-Álvarez et al., 1994). The Oaxaca Fault is a major Tertiary fault located along the western boundary of the 10–15 km wide, polyphase mylonitic, Juarez shear zone that forms the boundary between the above mentioned tectonostratigraphic terranes. Most of the sub-basin is located on the Oaxaca terrain, whose basement is constituted by the Oaxaca Complex.

The metamorphic Oaxaca complex comprises paragneisses and arc volcanic rocks intruded by within-plate, rift-related orthogneisses at P1140 Ma, and intruded by a 1012 ± 12 Ma anorthosite-charnockite-granite suite. Polyphase deformation under granulite-facies metamorphic conditions occurred during the Zapotecan orogeny at 1004 ± 3–979 ± 3 Ma (Keppie et al., 2003, Solari et al., 2003).This was followed by intrusion of the 917 ± 6 Ma, arc-related, Etla granitoid pluton (Ortega-Obregon et al., 2003). These Precambrian rocks are unconformably overlain by latest Cambrian–earliest Ordovician (Tremadocian) clastic and carbonate rocks (Tiñu Formation) containing a Gondwanan faunal assemblage (Landing et al., 2007). These are overlain by Carboniferous-Permian clastic and carbonate rocks, which are overstepped by Upper Jurassic and Cretaceous continental- shallow marine clastic and carbonate rocks, and Cenozoic red shallow marine clastic and carbonate rocks, and Cenozoic red beds and volcanic arc rocks.

The aquifer is unconfined and constituted by an alluvial material that includes, unconsolidated sediments such as pebbles, gravels, sand, clay, and silt, which constitutes a heterogeneous mixture with thicknesses that vary between 10 to 100 m, thinning toward its edges. The basement consists of metamorphic rocks, and in some zones, limestone, and rhyolites (that have been cut in boreholes). Laterally, the aquifer is delimited by impermeable material composed of metamorphic rocks (gneiss and schist), and extrusive volcanic rocks that bound the Central Valleys. The saturated thickness ranges between 15 and 100 m.

2. Background

Some models have been developed to evaluate the availability and pollution of water resources, they are known as WGHM (WaterGAP Global Hydrology Model), which model the water availability on a global scale (Globally water balance). They calculate time series of surface runoff and groundwater runoff, recharge, and river discharge, as well as variations of canopy storage, snow, soil, subsoil, lakes, wetlands, and rivers (Figure 1.3).

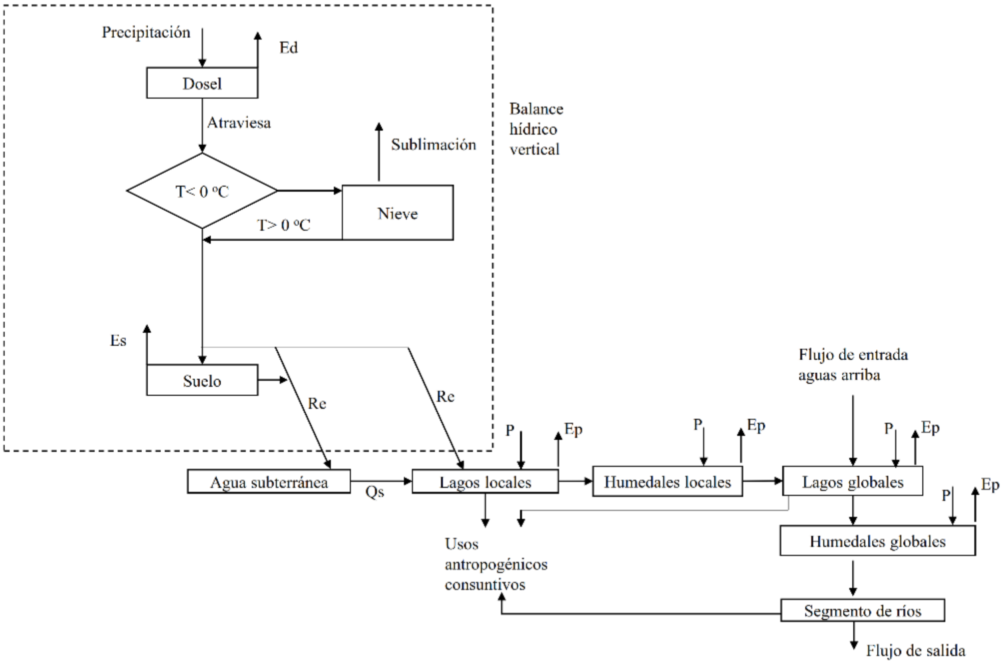

Figure 1. 3 Globally water balance to calculate water availability (Döll et al., 2003), Ed, Es, Ep Dosel, Soil, Potential Evapotranspiration, P Precipitation, Rc Recharge, Qs Groundwater flow.

These model take into account the storage capacity of the soil, soil cover, climate, vegetation, soil humidity, runoff and recharge in a spatial resolution of 0.5 degrees (Yates, 1997; Klepper and Van Drecht, 1998; Vörösmarty et al., 1998; Arnell, 1999).

The global water availability models do not give us a local perspective of the water resource, due to their spatial resolution. The effects of population increase, land-use change and local effects of climate change are not included, and another important aspect that any model takes into account is the pollution or potential sources of water pollution as a stressor of water availability.

Nevertheless, water availability can be evaluated through models that analyze indexes and indicators. Depending on the availability of information, each index is useful to predict the evolution. Table 1.1 shows the different approaches and indexes applied by other researchers.

Table 1. 1 Methodologies to evaluate the water availability.

Index	Methodology to calculate water availability	References
Falkenmark index (Water stress index)	WEI =WA/P WEI: Water stress index (m^3/pop/year) WA: Water availability P:population	(Falkenmark et al., 1989; Savenije, 2000)
Critically rate	CR =W/WA CR: Critically rate W: water extraction W: water availability	(Alcamo et al., 2000; Vörösmarty et al., 2000; Oki and Kanae, 2006)
Indicator IWMI	WS =PWS/UWS UWS: Usable Water Supply PWS: Primary Water Supply	(Seckler et al., 1998)
Water poverty index	$\mathrm{WPI} = \frac{\sum_{i=1}^{n} \mathrm{wi\ Xi}}{\sum_{i=1}^{N} \mathrm{wi}}$ WPI: Water poverty index Xi: component i of the structure of the WPI (Evaluated as percentage) Wi: weight apply to the i component	(Sullivan, 2002; Sullivan et al., 2003)

2.1 Problem statement

The scarcity of the water resource and the
deterioration of its quality have been increasing in recent years in the Central Valleys of Oaxaca. Piezometric data since 1984 shows high levels of depletion (in the range of 10 to 25 m) in the last 33 years. The aquifer is unconfined, shallow, with an alluvial area constituted of permeable material, which makes it vulnerable to contamination and overexploitation (Belmonte-Jiménez et al., 2003; Belmonte-Jimenez et al., 2005; Ramos Leal et al., 2012). The pressure of population increase, the spread of urban areas that change the local dynamics of the hydrological cycle, coupled with the effects of climate change, are the main problems that face the water resource. The lack of information for this region is a concern. A growing problem related to exploitation and water pollution must be studied. Therefore, it is necessary to identify the relationship between water stressors and methodologies to evaluate the water system.

2.2 Justification

A lack of information difficult the monitoring and analysis of groundwater systems. Approaches related to water availability or scarcity do not consider combined effects of stressors such as climate change, population increase, and land use/land cover change that put at risk water security; moreover, the evaluation of water pollution becomes a complex parameter challenging its assessment. Most studies and methodologies require physical sampling; unfortunately, this kind of procedures are expensive, then they are not affordable, and water pollution assessment cannot be conducted. Therefore, a methodology that allows us to evaluate the effects of water pollution and the stress factors mentioned above on water availability is required.

In the Central Valleys of Oaxaca, groundwater plays a vital role in the economy and development of the region. The annual water availability is estimated to be 169x106 m3 per year, where 87.6% of the groundwater is used for agricultural purposes while 9.5% is used for public-urban services (Pérez et al., 2010). Annually 142x106 m3 are used for agriculture purpose and 15.8x106 m3 for human consumption, in a region with 1,033,884 inhabitants that grows at a rate of 1.2% per year. The water availability must be assessed in order to predict the groundwater depletion.

3. Objectives

3.1 General

- Propose a methodology to evaluate the impact of water stressors on water availability and pollution in agriculture areas.

3.2 Specific

1. Analyzed the effects of climate change and, impervious surface in groundwater recharge of the Alto Atoyac sub-basin.
2. Asses how climate change, urban growth and, land use/land cover play an important role in groundwater depletion of the Alto Atoyac sub-basin.
3. Create a model to assess groundwater vulnerability in agricultural areas
4. Develop a methodology to evaluate water availability by considering water quantity and quality

4. Methods and data

The study is divided into four chapters (see Table 1.2). Every chapter comprises a research paper; the methodology followed in everyone is described in its respective chapter. Some of the mentioned papers have already been published in JCR journals while the last two are under revision.

Table 1. 2 Outline of the Thesis. Chapters and status of the paper.

Chapter name	Status
1. Decrease of the water recharge and identification of water recharge zones in the Alto Atoyac sub-basin, Oaxaca, as a result of climate change (published)	Accepted in: Journal of water and climate change, JCR, IF 1.009. https://doi.org/10.2166/wcc.2017.033
2. Climate Change, Land Use/Land Cover Change, and Population Growth as Drivers of Groundwater Depletion in the Central Valleys, Oaxaca, Mexico (published)	Accepted in: Remote Sensing, JCR, IF 4.118. https://doi.org/10.3390/rs11111290
3. A hierarchical model for assessing groundwater vulnerability in agricultural areas in the Central Valleys of Oaxaca, Mexico	Submited to the Journal: Science of the Total Environment, JCR, IF 5.589. (Under revision)
4. Methodology approach to include potential water pollution in water availability studies	Under the revision by the Co-authors

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Chapter 2: Decrease of the water recharge and identification of water recharge zones in the Alto Atoyac, Sub-Basin, Oaxaca, as a result of climate change

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Decrease of the water recharge and identification of water recharge zones in the Alto Atoyac, Sub-Basin, Oaxaca, as a result of climate change

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ABSTRACT

This study analyzes effects of climate change (CCh) and of the increase of impervious surfaces on the groundwater recharge in the Alto Atoyac sub-basin (Oaxaca, southern Mexico). Water recharge was modeled based on HELP 3.95D; temperature and precipitation were derived, for a near (2015-2039) and a far distant future scenario, from GFDL-CM3 global circulation model (GCM), which describes the climate of Mexico under the RCP8.5 scenario. Potential recharge loss zones for the period of 1979-2013 were estimated through a remote sensing analysis. The actual estimated mean annual recharge of 169 million cubic metres could be reduced by 17.97% and 65.09% according to the analyzed CCh scenarios, and the loss of 135 km^2 of permeable soil would represent additionally 2.65x10^6 m^3 of non-infiltrated water. This study indicates three sites, with high recharge potential, and it can be used to propose local adaptations to guarantee the availability of the water resource in the studied sub-basin.

Keywords: climate change, groundwater recharge, remote sensing, watershed management

1 INTRODUCTION

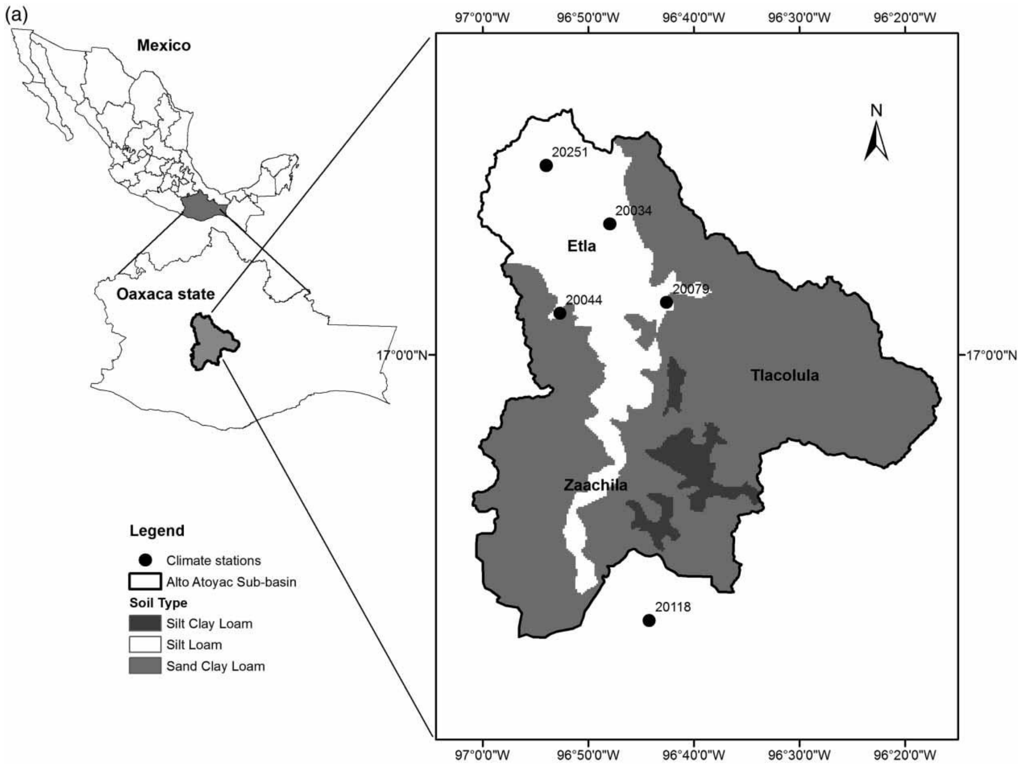
Water resources in Mexico are under such high stress that several communities do not have access to drinking water, and it is a matter of national security. Although the states in southern Mexico, such as Oaxaca, have larger water resources in comparison with the northern states, there are still zones at risk due to overexploitation and contamination, limiting the population's access to drinking water. According to recent studies, almost 80% of the Earth's population is exposed to significant stress factors that put the security of drinking water at risk (Vörösmarty et al. 2010). Water stress may result from the overexploitation of groundwater resources as well as the reduction in precipitations and decreases in stored water supplies (Parish et al. 2012), the latter one being a consequence of climate change (CCh). In this context, the population is directly affected due to the lack of sufficient drinking water per capita. It is important to understand that CCh represents a challenge, particularly with regard to groundwater which can be affected both directly and indirectly by CCh in ways that today have yet to be explored (Dettinger & Earman 2007; Green et al. 2011).

A great amount of data and climatic predictions provide evidence that water resources are vulnerable to CCh and easily affected by it, which puts society and ecosystems at risk (Bates et al. 2008). The most obvious CCh impacts on water resources are changes in phreatic levels and in the surficial water quality (Leith & Whitfield 1998) but potential effects on the amount and quality of groundwater should also be considered (Bear & Cheng 1999).

CCh could affect water recharge and put water security at risk, giving rise to agriculture production problems and possibly food security (Aguilera & Murillo 2009). Some of these studies have predicted a recharge reduction due to these phenomena (Herrera-Pantoja & Hiscock 2008). Contrastingly, Jyrkama and Sykes (2007) consider that these effects may not always be negative throughout time. The objective of this study is to analyze the effects of the increase of impervious surface and of the CCh on the water recharge inside the Alto Atoyac sub-basin, a region with poor agriculture practices, growing urbanization, and deforestation. Its main economic activity is based on water resource, with 87.6% of the groundwater withdrawals used for agriculture, and 9.5% of withdrawals for public and urban services (Pérez et al. 2010). Remote sensing techniques and geographic information systems (GIS) were used to estimate permeable soil loss. This information was used to evaluate recharge using the Hydrology Evaluation of Landfill Performance (HELP 3.95D) software. Assuming soil properties remain unchanged through time, water recharge in the sub-basin was evaluated under the RCP8.5 scenario, for two time horizons, 2015-2039 and 2075-2099. In particular, precipitation was provided by two global circulation models (GCMs), GFDL-CM3 and HADGEM2-ES, but GFDL-CM3 was taken as a reference for this study.

1.1 Study area

The Alto Atoyac sub-basin is located between 16°30' and 17°25' north latitude, and 96°15' and 97°00' west longitude. It comprises the Central Valleys Region of the State of Oaxaca, which includes the Etla, Tlacolula, and Zaachila valleys as shown in Figure 2.1a. It is limited to the west by the Mixteca Region, to the northeast by the Cañada Region, to the north by the Sierra de Juarez, to the east by the Tehuantepec Isthmus Region, and to the south by the Sierra Madre del Sur (Figure 2.1b). In the Central Valleys, 100% of drinking water is derived from underground. A total of 87.6% of the water used in agriculture in the entire region also has its origin in the sub-soil. This dependence and the fact that groundwater is the only water resource in a surface of 3,744.64 km^2 with an exploitation surface of 1,130 km^2 explains why it is really important to assess the possible impacts of climate change on groundwater.



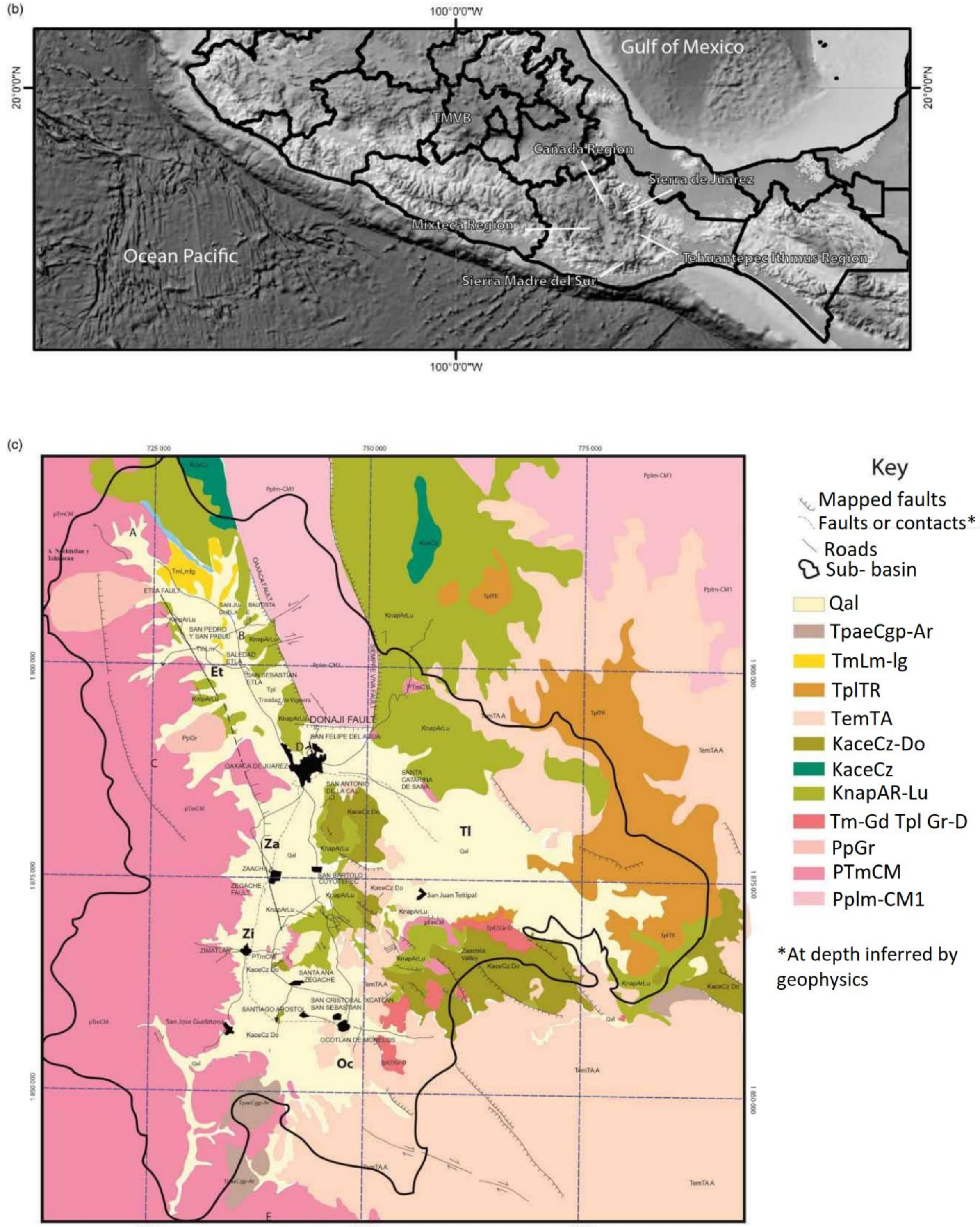


Figure 2. 1 (a) Location of the study area, climate stations and soil type distribution. (b) Regional location of the study area (TMVB: Trans-Mexican Volcanic Belt). (c) Simplified geological map of the study area according to Secretary of Economy (SE 1997, 2007), and Secretary of Economy (in press). Las leyendas no son legibles.

1.2 Hydrological and geological features

Figure 2.1c, shows the simplified geologic map of the study area according to the Secretary of the Economy (SE 1997, 2007), and the Secretary of the Economy (in press) and also Campos-Enriquez et al. (2010, 2013). The presence of rocks of Precambrian, Cretaceous, and Tertiary ages that point to a complex geologic history can be noted.

The study area straddles the boundary between the Oaxaca (Zapoteco, Oaxaquia) and Juarez (Cuicateco) tectonostratigraphic terranes (Campa & Coney 1983; Sedlock et al. 1993; Alaníz-Alvarez et al. 1994) (Figure 1c). The Oaxaca Fault is a major Tertiary fault located along the western boundary of the 10–15 km wide, polyphase mylonitic, Juarez shear zone that forms the boundary between the above-mentioned tectonostratigraphic terranes. Most of the sub-basin is located on the Oaxaca terrane, whose basement is constituted by the Oaxaca Complex.

The metamorphic Oaxaca Complex comprises paragneisses and arc volcanic rocks intruded by within-plate, rift-related orthogneisses at P1140 Ma and intruded by a 1012 ± 12 Ma anorthosite-charnockite-granite suite. Polyphase deformation under granulite-facies metamorphic conditions occurred during the Zapotecan orogeny at 1004 ± 3–979 ± 3 Ma (Keppie et al. 2003; Solari et al. 2003). This was followed by intrusion of the 917 ± 6 Ma, arc-related, Etla granitoid pluton (Ortega-Obregón et al. 2003). These Precambrian rocks are unconformably overlain by latest Cambrian–earliest Ordovician (Tremadocian) clastic and carbonate rocks (Tiñu Formation) containing a Gondwanan faunal assemblage (Landing et al. 2007). These are overlain by Carboniferous-Permian clastic and carbonate rocks, which are overstepped by Upper Jurassic and Cretaceous continental shallow marine clastic and carbonate rocks, and Cenozoic red shallow marine clastic and carbonate rocks, and Cenozoic red beds and volcanic arc rocks.

The aquifer under study is unconfined and constituted by alluvial material that includes unconsolidated sediments such as pebbles, gravels, sand, clay and silt, which constitutes a heterogeneous mixture with thicknesses that vary between 10 and 100 m, thinning toward its edges. The basement consists of metamorphic rocks and, in some zones, limestone, and rhyolites (that have been cut in boreholes). Laterally, the aquifer is delimited by impermeable material composed of metamorphic rocks (gneiss and schist) and extrusive volcanic rocks that bound the central valleys. The saturated thickness ranges between 15 and 100 m.

1.3 General circulation models (GCMs) for Mexico

There are several coupled atmosphere-ocean general circulation models selected by the United Nations Framework Convention on CCh that provide reliable results for the area of Mexico (Conde et al. 2011; Fernandez-Eguiarte et al. 2014). Among them, MPI-ESM-LR (Max-Plank Institute), GFDL-CM3 (Geophysical Fluid Dynamics Laboratory), and HADGEM2-ES (Met Office Hadley) provide good resolutions for Mexico (Conde et al. 2011). However, for southern Mexico, the performance of the models in the precipitation and the Reliability Ensemble Averaging (REA) presents a high variability. HADGEM2 and MPI-ESM-LR are models with a high standard deviation (STD). GFDL-CM3 and HADGEM2 are models with high mean absolute error (MAE) and root mean square error (RMSE) in Maximum temperature which significantly reduces their REA. For the Minimum temperature all the mentioned models have low MAE, RMSE and similar STD (Cavazos et al. 2013).

2 METHOD AND DATA

Temperature and precipitation in our study area, for a near (2015-2039) and far time horizon (2075-2099), respectively, were obtained from the RCP8.5 scenario (Riahi et al. 2011) based on GFDL-CM3 and HADGEM2-ES atmosphere-ocean coupled general circulation models (GCMs) (Conde et al. 2011; Intergovernmental Panel on Climate Change [IPCC] 2013; Fernandez-Eguiarte et al. 2014).

The 3.95 version of the hydrologic model HELP enabled us to estimate recharge rates, both for the historical climate data and for the two mentioned time horizons. HELP is a hydrological model that allows one to analyze the water balance. This model performs a quasi-two-dimensional analysis and simulates the daily water flow in the subsoil, as well as the amounts of water movement in each of its forms (surficial storage, flow, evapotranspiration, vegetation interception, vegetative growth). It considers the effects of temperature on the water balance (Schroeder et al. 1994;

Berger & Schroeder 2013). This model has been rigorously tested and constitutes a user-friendly program. It uses accessible parameters (soil types, hydraulic conductivity, land use, runoff, etc.). Several studies (Berger 2000; Gogolev 2002; Risser et al. 2005; Jyrkama & Sykes 2007) report that it provides accurate results. The estimation of recharge zone loss was based on a supervised analysis of the available Landsat images (Berger & Schroeder 2013).

Soil type, recharge zone information, water table depths, hydraulic conductivity, runoff, and the normal climates corresponding to the climate stations, and those resulting from the GCMs were integrated into a Geographic Information System to estimate the water recharge according to the methodologies of Jyrkama et al. (2002).

2.1 Climate information

Climate stations with time series of more than 30 years were selected. Five climate stations in the study area were appropriate for our analysis (Figure 2.1a). The respective climatic information was obtained from the National Meteorological System (SMN 2010). The analyses comprise a database of 60 years. Table 2.1 indicates the climate station names together with their mean climatic parameters, as well as coordinates. Figures 2.2a to 2.2e show the behavior of the climate normal for these five stations located in the Alto Atoyac sub-basin.

Table 2. 1. Climate stations located in the Alto Atoyac sub-basin (locations in Figure 1a).

Climate station	Name	Average rainfall (mm/year)	Average temperature (°C)	Coordinates (lat/long)
20151	San Francisco Telixtlahuaca	774.4	19	17º18’00”N, 96º54’00”W
20034	Etla	753.5	19.7	17º12’26”N, 96º47’59”W
20079	Oaxaca	746	21.3	17º04’59”N, 96º42’35”W
20044	Jalapa del Valle	761.6	18.9	17º03’57”N, 96º52’42”W
20118	San Miguel Ejutla	671.9	20.9	16º34’46”N, 96º44’14”W

2.2 General circulation models and CCh scenarios

The information used in this study comprises a climatology database spanning from 1950 to 2000 developed by Hijmans et al. (2005). These data series were modeled under given scenarios. This information has an original spatial resolution of 0.5° x 0.5° (55x55 km approximately). The calculated anomalies were downscaled by spline interpolation resulting in grids of 30" x 30" (926 x 926 m approximately). Later, the downscaled anomalies were added to the climatology database and high spatial resolution scenarios resulted that include the topographic effect (Fernandez-Eguiarte et al. 2014).

The assessment of the effects of CCh on the water recharge was based on two GCMs. After a comparison of the climate anomalies, GFDL-CM3 and HADGEM2-ES models were selected. Considering that significant differences between simulation results and reality can occur, and that the effectiveness of a particular linear system may be drastically overestimated, analysis of the effects on water recharge arising from a very pessimistic CCh scenario based on the actual state of knowledge, will help to realize and asses the degree of the affectations that would occur in such a situation (Berger 2000). This analysis considers the RCP8.5 scenario which represents an extreme situation corresponding to the pathway with a large population and a relatively slow income growth with modest rates of technological change and energy intensity improvement, leading to a long-term high energy demand and the highest Greenhouse Gas (GHG) emission in the absence of climate change policies, and it does not include any specific climate mitigation target (Riahi et al. 2011). This extreme case scenario might help to sensitize politicians on the problems of water preservation.

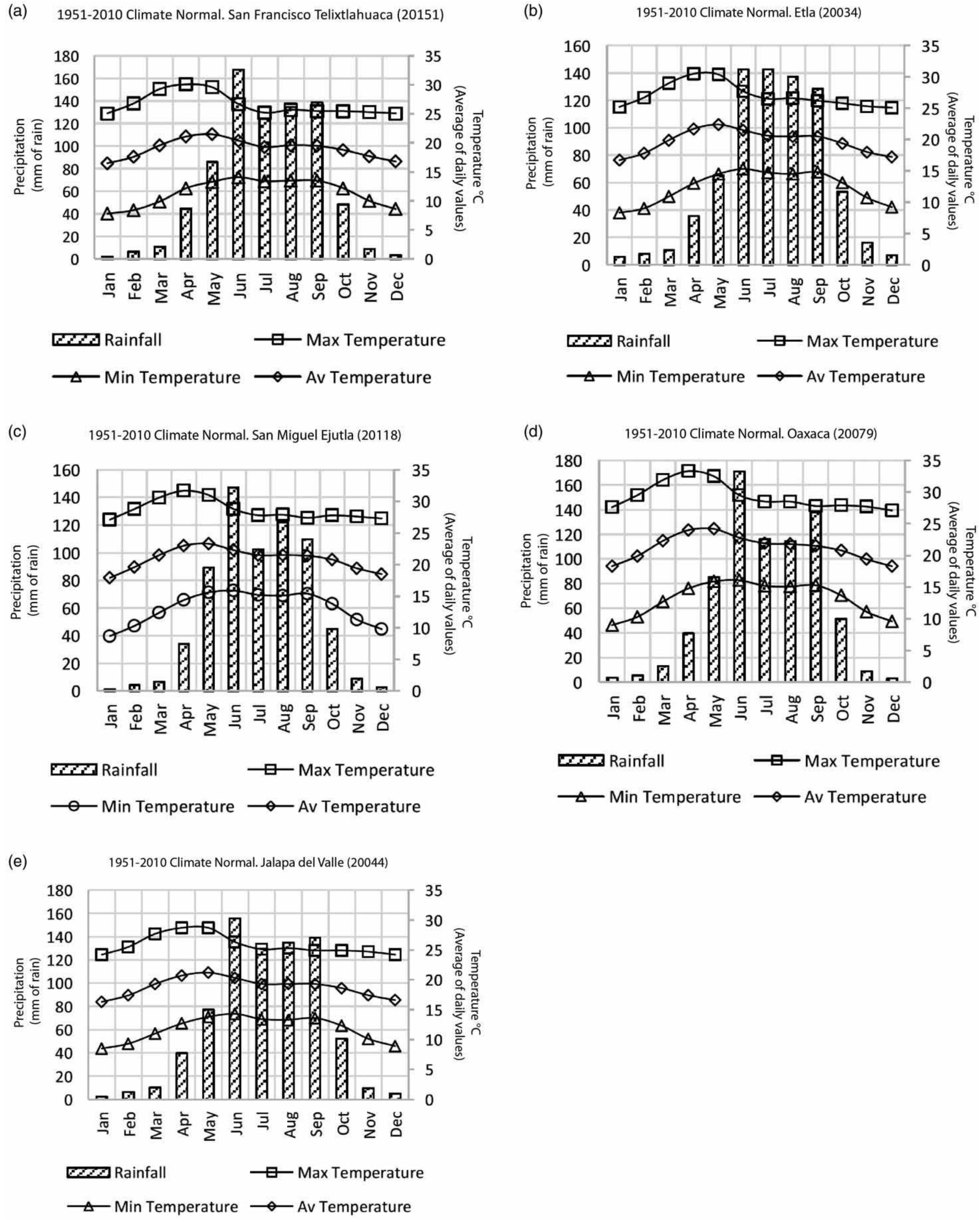


Figure 2. 2 (a)–(e) Climate normal (rainfall and temperature) of the local climate stations located in the study area (Alto Atoyac sub-basin). Locations of the climate stations in Figure 1(a).

2.3 HELP parameters

The HELP model, used for predicting landfill hydrologic processes, can also be used to estimate groundwater recharge rates, requiring the following input: (1) weather (precipitation, solar radiation, temperature, and evapotranspiration), (2) soil (porosity, field capacity, wilting point, and hydraulic conductivity), and (3) engineering design data (liners, leachate and runoff collection systems, and surface slope) (Schroeder et al. 1994; Allen et al. 2004; Berger & Schroeder 2013).

The numerical solution accounts for the effects of runoff, infiltration, evapotranspiration, vegetation grown, soil moisture storage, surface storage, and some engineering parameters. The components of the simulated water balance are precipitation, interception of rainwater by leaves, evaporation by leaves, surface runoff, evaporation from soil, plant transpiration and percolation of water through the soil profile (Schroeder et al. 1994; Allen et al. 2004; Berger & Schroeder 2013).

2.4 Profile structure

The profile structure can be multi-layered, consisting of a combination of natural (soil) and artificial materials (Schroeder et al. 1994; Allen et al. 2004; Berger & Schroeder 2013). In the current HELP application, only natural geological materials found in the central valleys of Oaxaca were used. A homogeneous stratigraphy was considered in every analyzed profile. Soil type information was provided by the National Institute of Statistics and Geography (INEGI 2010).

Hydraulic conductivity, K, is a measure of how easily water can pass through subsurface: high values indicate permeable material; low values indicate impermeable material and it is defined by Darcy's law. K-values were assigned according to the soil textures following the methodology of the US Department of Agriculture (USDA 1985). Table 2.2 indicates the soil classification and respectively adopted hydraulic conductivities.

Table 2. 2 Soil Classification and hydraulic conductivity (USDA, 1985) (Distribution see Figure 1a)

Soil textures	Saturated hydraulic conductivity (cm/s)
Silt clay loam	$1.9x10^{-6}$
Sand clay loam	$2.7x10^{-6}$
Silt loam	$9.0x10^{-6}$

Figure 2.3 presents the average depth distribution of the water level from 2001 to 2013 based on field monitoring during the past years. Depths between 1 and 10 meters to the water level are predominant.

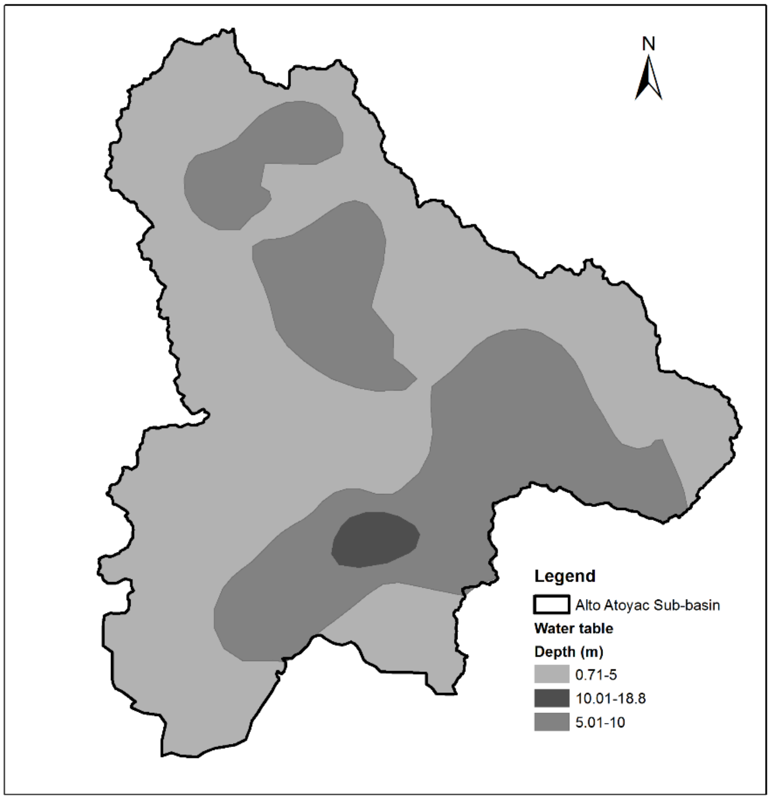


Figure 2. 3 Water table depths (m) obtained from a 12-year field monitoring (2001–2013).

2.5 Runoff

The rainfall-runoff process is modeled in HELP by using the USDA Soil Conservation Service curve-number method (USDA 1985). The curve-number method is a procedure amply used for four reasons: (1) it is widely accepted, (2) it is computationally efficient, (3) the required input is generally available, and (4) it can conveniently handle a variety of soil types, land uses and management practices (Schroeder et al. 1994).

The curve number (CN) is defined with respect to the runoff-retention parameter (S), which is a measure of the maximum retention of rainwater after runoff starts (in length units). HELP uses different procedures to adjust the CN value to the surface slope, soil texture, and vegetation class. The maximum value of CN (100) occurs when there is no infiltration. A smaller CN value indicates more rainwater infiltrating into the soil. A previous work conducted in the study area permitted the CN values to be established (Reyes-López et al. 2009).

2.6 Evapotranspiration

The input parameters for HELP to calculate the evapotranspiration include evaporative depth zone, maximum leaf-area index, start and end day of growing season, average wind speed and quarterly relative humidity. For this study a depth of 100 cm was used (maximum depth where water can be removed by evapotranspiration), which corresponds to the average plant root length in the area.

2.7 Land change analysis

Three Landsat images from the Global Land Cover Facility (GLCF) and of the United States Geological Survey (USGS) from 1979 to 2013 were used to analyze land use changes (LUC) along 34 years to quantify impervious surface increase. Table 2.3 indicates the different satellites used, with respective bands, sensors, and spatial resolutions. A total of five land covers (urban areas, coniferous, agriculture areas, rangeland and deciduous forest) were selected according to the IV map series published by the National Institute of Statistics and Geography of Mexico (INEGI for its abbreviation in Spanish). Table 2.4 reports the land uses considered for this analysis. Figures 2.4 and 2.5 show the calculated land uses for 1979 and 2013.

Table 2. 3 Landsat image characteristics. Source; GLCF and USGS.

Satellite	Date	Bands	Sensor	Spatial Resolution	Source
LandSat4	08/11/1979	1,2,34	MSS	60 m	GLCF
LandSat8	02/02/2013	1,2,3,4,5,6,7,8,9,10,11	OLIS/TIRS	30 m	USGS

Table 2. 4 Land use and covers selected for the supervised classification analysis of the satellite images of the alto Atoyac sub basin.

Land cover	Observations
Urban areas	Urban areas, roads
Coniferous	Pine oak forest
Agriculture areas	Rainfed and irrigated agriculture
Rangeland	Induced grassland, pasture-farming
Deciduous forest	Secondary forest

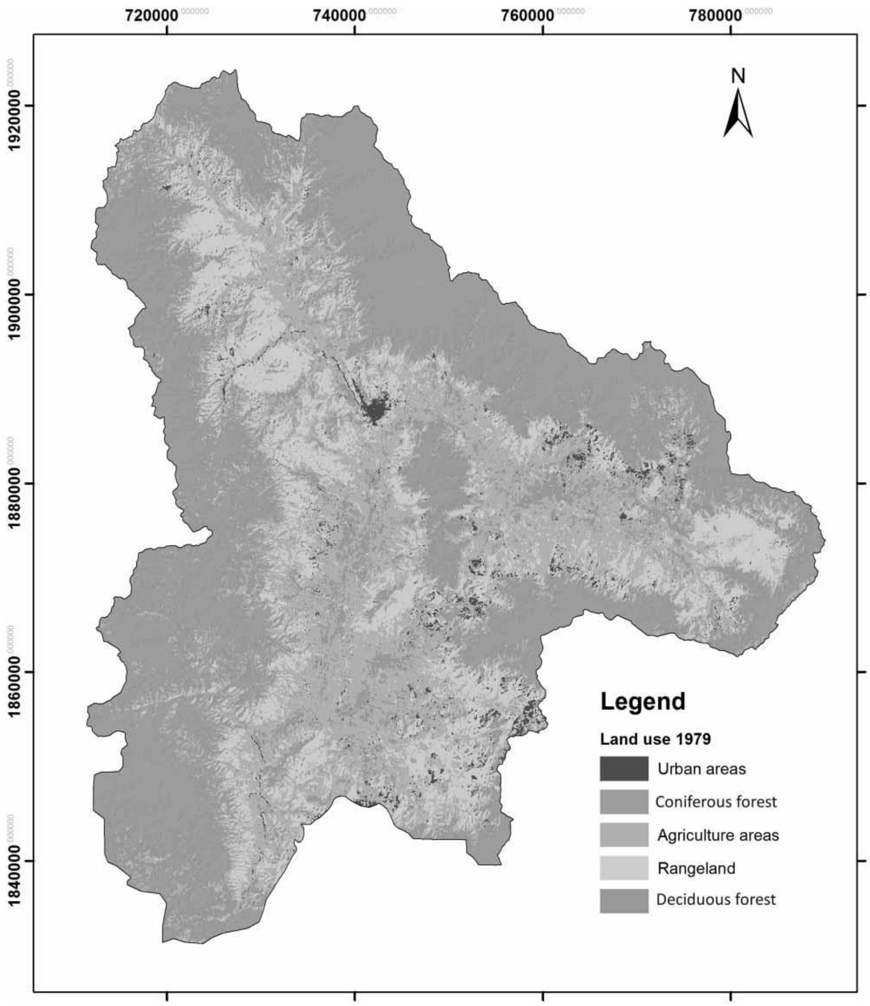


Figure 2. 4 Land use for 1979, in the Alto Atoyac sub-basin.

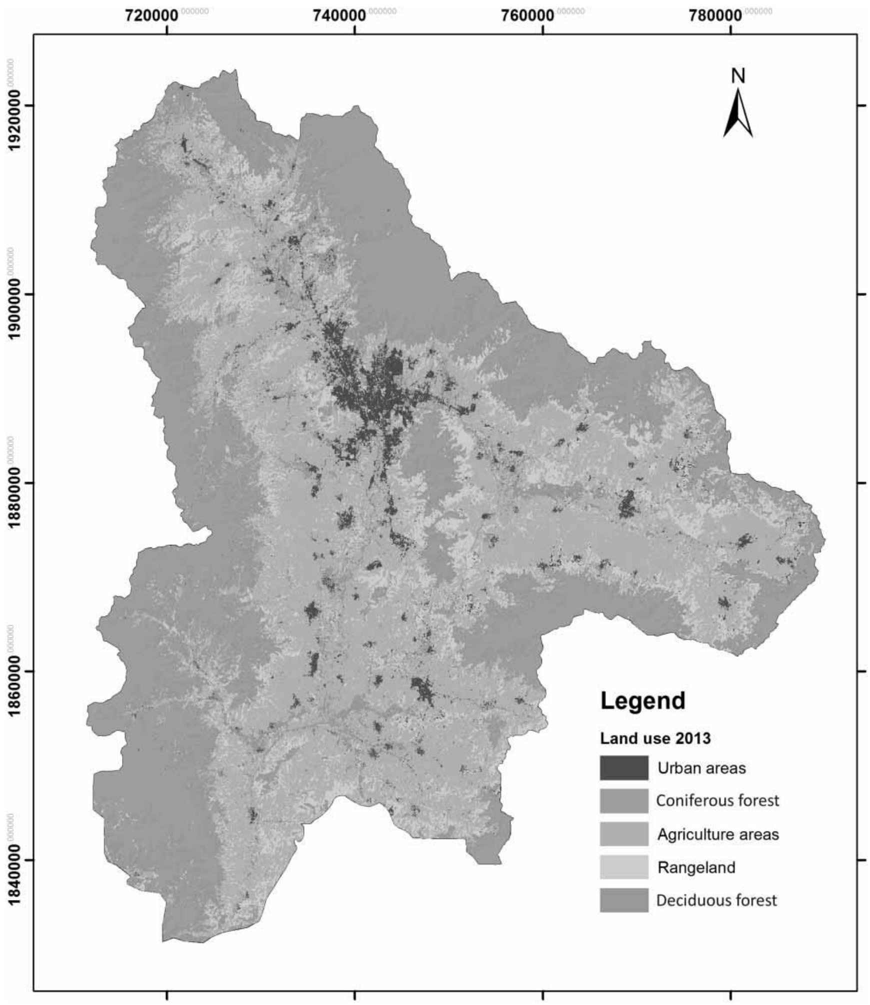


Figure 2. 5 Land use, for 2013 in the Alto Atoyac sub-basin.

2.8 Imagery correction: atmospheric correction and resample

The atmospheric correction transformed the sensor digital data into radiance values to avoid errors of atmospheric spreading and energy absorption. The input parameters for the atmospheric correction are the available imagery data, wavelength, digital values, gain, offset, and sun elevation. Since imagery was produced by sensors, and at different dates, they have a different spatial resolution, so they needed to be matched by means of a GIS resample tool (IDIRISI in this case).

2.9 Band composite, supervised classification and class validation

The selected RGB (Red, Green and Blue) composite for the imagery classification comprises a false color composition of the MSS (Multispectral Scanner System) sensor RGB321 and of the OLI (Operational Land Imager) sensor RGB543. Field work, INEGI land use GIS layer, and Google Earth allow to delineate training polygons, in the study area, to conduct the supervised classification. The agreement kappa index enables validation of the reliability among calculated classes (López de Ullibarri & Pita 2001).

2.10 Identification of potential recharge zones

Use of GIS and HELP allowed one to delimit the recharge zone and estimate groundwater recharge rates by combining GIS layers of land use, soil type, daily weather data (precipitation, temperature, solar radiation), and evapotranspiration data (evaporative zone depth, leaf area index, curve numbers, average wind speed, relative humidity, and growing season) (Jyrkama et al. 2002; Jyrkama & Sykes 2007).

3 RESULTS AND DISCUSSION

3.1 Climate scenarios and model uncertainty

Model performance comparison indicates that differences between the normal and the RCP8.5 scenario projections are small, as presented in Figure 2.6. In the first period (2015-2039), the GFDL-CM3 indicates small but noticeable precipitation reductions from April to August (planting season in the Alto Atoyac sub-basin) (see Table 5), with annual accumulative reductions of 69.15 mm and of 105.24 mm. Contrastingly, the HADGEM2-ES based scenario indicates an annual increase of 21 mm for the near time horizon (2015-2039) and a decrease of 86.81 mm for the far time horizon (2075-2099). According to the GFDL-CM3 the average annual temperature would increase by 1.5 °C and 5.13 °C for the 2015-2039 horizon and for the 2075-2099 horizon, respectively, while HADGEM2-ES indicates increases of 1.21 °C and 5.38 °C, respectively, for the near and far time horizons as shown in Table 2.5. Precipitation data from the GFDL-CM3 have a lower STD in comparison to the HADGEM2-ES based values. Concerning the average temperature data, the HADGEM2-ES data seems to have a better correlation and a lower STD.

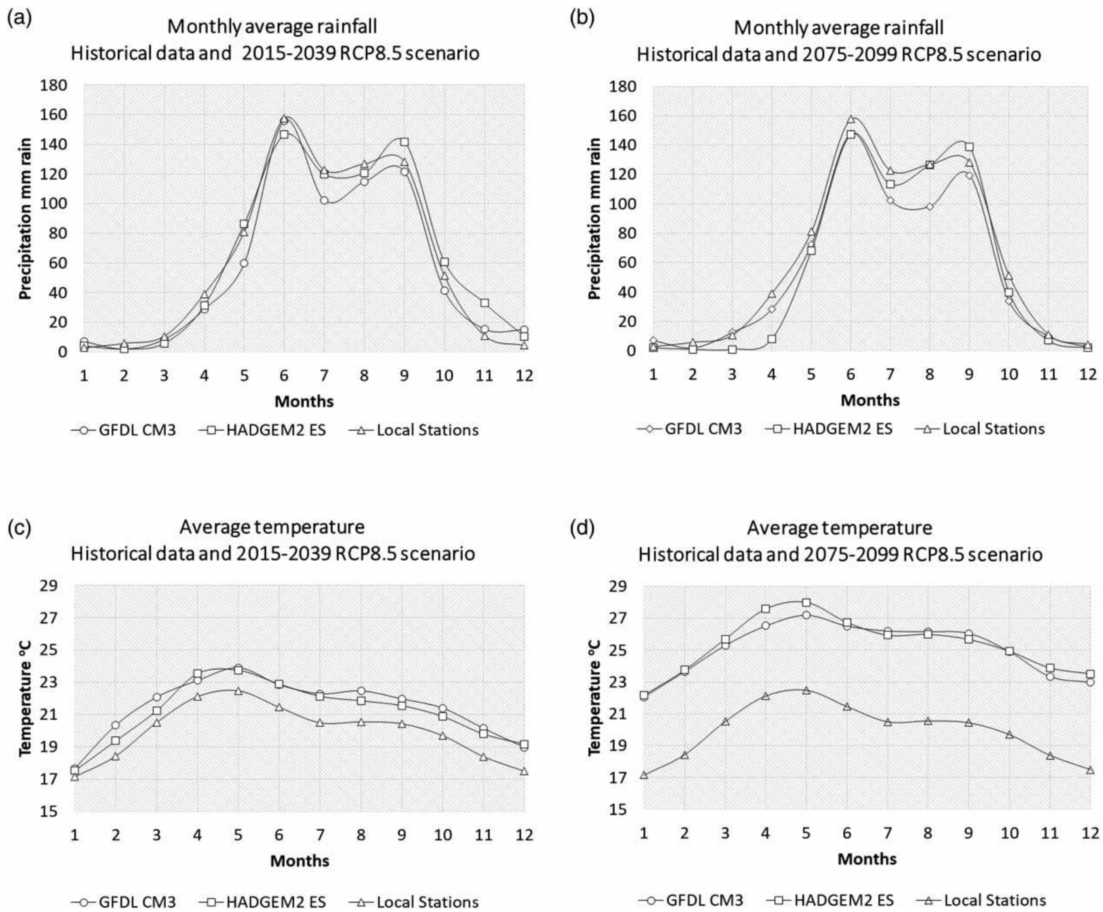


Figure 2. 6 Historical climate normal obtained from the local climate stations and climate normal from RCP8.5, 2015–2039 and 2075–2099 horizons, modeled by GFDL-CM3 and HADGEM2-ES GCMs (Fernandez-Eguiarte et al. 2014).

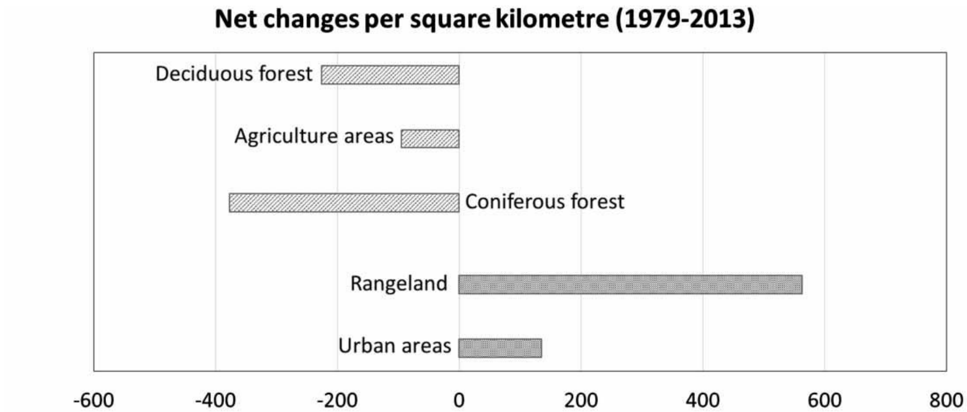
Table 2. 5 GCMS Climate anomalies respect to the historical climate normal.

Months	GFDL CM3 (2015-2039) Anomalies R(mm/month)	Anomalies T(°C)	GFDL CM3 (2075-2099) Anomalies R(mm/month)	Anomalies T(°C)	HADGEM2-ES (2015-2039) Anomalies R(mm/month)	Anomalies T(°C)	HADGEM2-ES (2075-2099) Anomalies P(mm/month)	Anomalies T(°C)
January	-4.16	-0.51	-4.16	-4.91	-1.16	-0.37	0.84	-5.01
February	3.8	-1.91	3.8	-5.21	3.8	-0.94	4.8	-5.31
March	2.12	-1.57	-1.88	-4.77	4.79	-0.72	9.62	-5.17
April	10.37	-1	10.62	-4.4	7.92	-1.42	31.12	-5.47
May	21.21	-1.43	8.88	-4.71	-5.46	-1.27	12.87	-5.52
June	1.6	-1.4	9.85	-5.05	11.1	-1.44	10.35	-5.28
July	20.41	-1.8	20.41	-5.7	2.91	-1.64	9.41	-5.44
August	12.07	-1.92	28.49	-5.6	6.07	-1.3	0.32	-5.43
September	6.76	-1.54	8.76	-5.61	-13.49	-1.12	-10.49	-5.23
October	10.05	-1.71	17.55	-5.21	-9.45	-1.19	11.55	-5.23
November	-4.46	-1.75	1.04	-4.94	-21.96	-1.4	4.04	-5.49
December	-10.62	-1.48	1.88	-5.48	-6.12	-1.68	2.38	-6.01
STD	9.72	0.40	9.62	0.41	9.79	0.38	9.93	0.25
R accumulative/ T Average	69.15	-1.50	105.24	-5.13	-21.05	-1.21	86.81	-5.38

The model and scenarios do not intend to reproduce or predict the future. Their purpose is to provide possible scenarios under some assumptions and conditions in order to analyze CCh challenges to natural resources, groundwater in this case, in such conditions.

3.2 Decrease of water recharge areas

Impervious surfaces are features of anthropogenic origin. They include roads, buildings, and parking lots for which water cannot infiltrate through the soil (Flanagan & Civco 2001). The decrease of pervious surfaces leads to an increase of surface runoff during a given storm and reduces lag-time and time of concentration, contributing to much greater peak flows. The natural storage along the stream channels is reduced, while the downstream discharge is increased (Micklin & Hodler 1983). Overflow and high runoff can clog soil interstices, reducing the aquifer water recharge. Assuming urban areas as impervious zones, a reduction of 135 km^2 of permeable soil was obtained for the 34-year analysis, which amounts to $2.65x10^6$ m^3 of non-infiltrated water. This estimation considers that this amount of water will not infiltrate somewhere else. As already mentioned, in the Alto Atoyac sub-basin, the urban growth is disordered (no urban planning exists). Consequently, it is inferred that this loss presents a big challenge that water resources will be facing in the future because high potential recharge zones will be lost, which in turn will lead to an increase in surface runoff and overflows. Water availability and resource quality will be put at risk. Figure 2.7 summarizes the results of the analysis of land change in the sub-basin from 1979 up to 2013.



	Urban areas	Rangeland	Coniferous forest	Agriculture areas	Deciduous forest
Losses	0	0	-377.18	-94.27	-226.39
Gains	135.32	562.52	0	0	0

Figure 2. 7 Net gains and losses in the Alto Atoyac sub-basin between 1979 and 2013 according to the remote sensing analysis.

Another land use change is represented by deciduous and coniferous forest losses, which have been largely reduced. A mean annual forest loss of 0.29% is estimated, which together with the urban area growth will increase pressure on the natural resources.

Forests influence climate through physical, chemical, and biological processes that affect the hydrologic cycle and atmospheric composition. These complex and nonlinear forest-atmosphere interactions can dampen or amplify anthropogenic climate change since they can attenuate global warming through carbon sequestration. However, the evaporative effect of temperate forests is yet unclear (Bonan 2008). Studies indicate that the loss of forest decreases the evapotranspiration as well as the rainfall. Nevertheless, the calculated reductions in precipitation are larger than the calculated decrease in evapotranspiration, indicating a reduction in the regional moisture convergence and also an increase in the length of the dry season (Nobre et al. 1991). The decrease in rainfall and increase in temperature will result in an increase in evapotranspiration (Abtew & Melesse 2013).

3.3 Water recharge

Based on the 60-year period database, the obtained mean annual recharge associated with the vertical flow is 45.2 mm per year. In an area of 3,744.64 km^2, this corresponds to 169 million cubic metres annually. It was not possible to compare this estimation with results from other studies, as suggested by Jyrkama and Sykes (2007) and Risser et al. (2005), because of the costs and difficulty in accessing data from other numerical models. Nevertheless, it was possible to compare our results with other studies on water availability and recharge. Table 2.6 summarizes the recharge estimated from the HELP analysis and results from other studies on water availability conducted in the study area by different institutions (Pérez et al. 2010). It is important to note that previous recharge studies are based on other methodologies and did not take into account the increase of impervious surfaces or the future

CCh affectation. The good correlation observed add reliability to the recharge water estimated in this study.

Table 2. 6 Comparison of water recharge studies carried out in the Alto Atoyac sub-basin (Pérez et al., 2010).

Institution	Water recharge in millions of cubic meters
COPEI 2001	162.8
CONAGUA 2003	153.6
CONAGUA 2009	153.6
UACH 2010	153.6
Mean	155.9
Standard deviation	4.6

Figure 2.8 represents water recharge, runoff and real evapotranspiration for the historical period. Water recharge for two time horizons (2015-2019 and 2075-2099) based on: 1) the RCP8.5 scenario as modeled with the GFDL-CM3 GCMs (i.e., Conde et al. 2011; Fernandez-Eguiarte et al. 2014), and 2) the HELP based water balance (water recharge and real evapotranspiration) are shown in Figures 2.9 and 2.10. These figures enable a comparison of the water recharge, runoff, and real evapotranspiration between the historical period and the 2015-2019 and 2075-2099 time horizons.

According to Figures 2.8 and 2.9, water recharge already shows a decrease in the first time horizon (2015-2039).

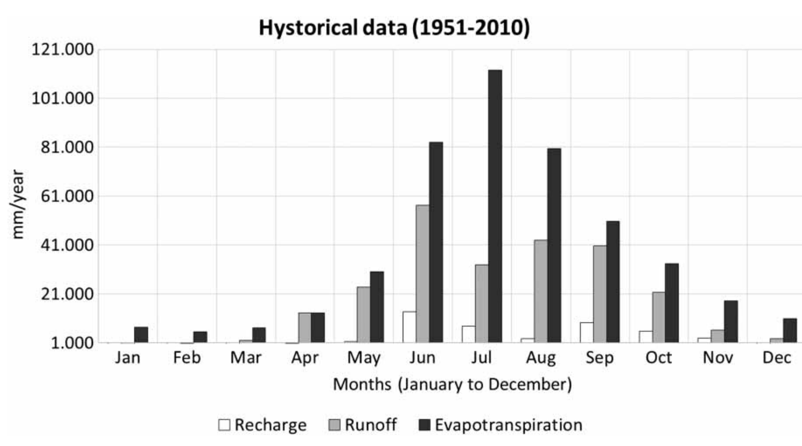


Figure 2. 8 Water balance variables for the Alto Atoyac sub-basin for the historical period 1951–2010.

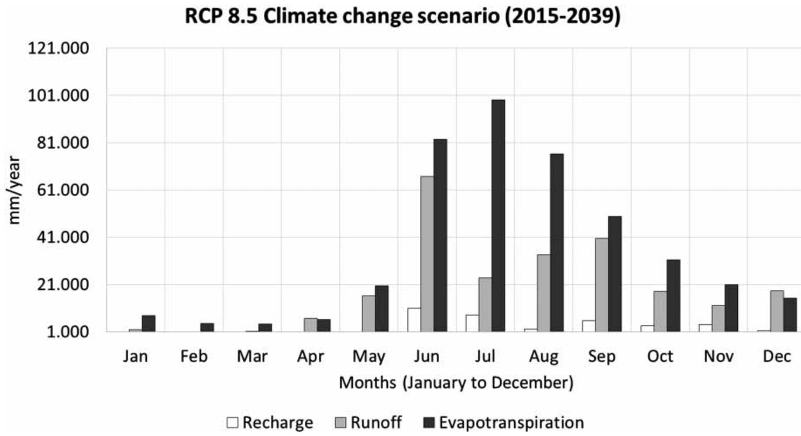


Figure 2. 9 Water balance variables for the Alto Atoyac sub-basin for the period 2015–2039.

The recharge decreases notoriously for the 2075-2099 time horizon (Figure 2.10). As temperature increases and precipitation decreases, water recharge diminishes in a proportional way. Contrastingly, the real evapotranspiration increases together with runoff, which is also increased by the reduction of recharge zones.

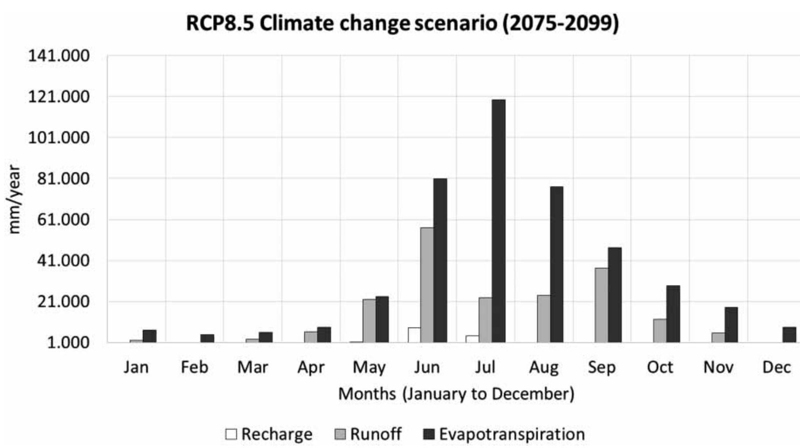


Figure 2. 10 10 Water balance variables for the Alto Atoyac sub-basin for the period 2075–2099.

Figures 2.11 and 2.12 show, respectively, the monthly and total water recharge for the analyzed periods. Figure 2.11 presents the mean monthly recharge. A sequential recharge decrease from the present up to the 2075-2099 time horizon can be observed. During June and July, recharge rates are relatively high, but in August a notable decrease is observed. In the 2075-2099 time horizon, from June to August the recharge is already very low, which can endanger the agricultural activities in the study area.

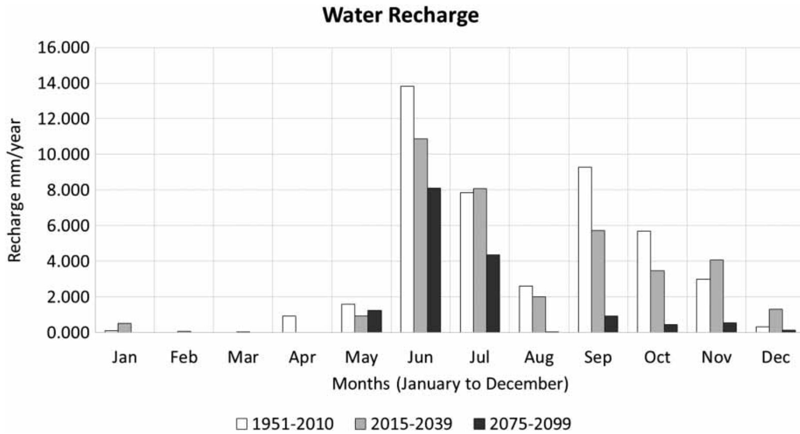


Figure 2. 11 Monthly historical water recharge compared to water recharge for the two climate horizons 2015–2039 and 2075–2099.

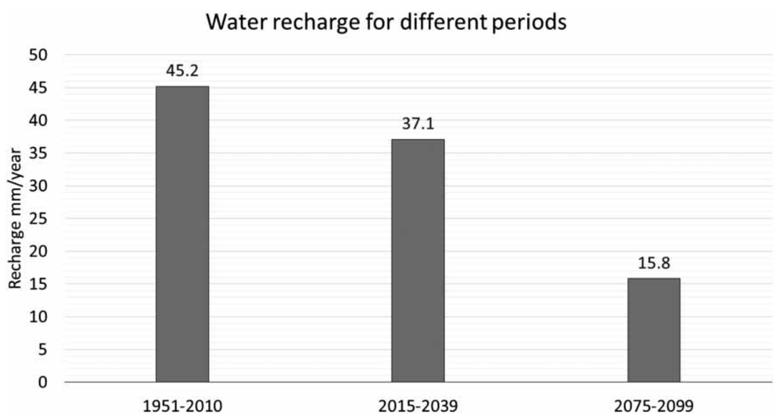


Figure 2. 12 Historical water recharge compared to water recharge for the two climate horizons 2015–2039 and 2075–2099.

In Figure 2.12 it can be noted how the water recharge in the near and far climate horizons tends to decrease in comparison to the historical recharge relatively by 17.97% and 65.09 %, respectively. Figures 2.13, 2.14, and 2.15 show the water recharge in the Alto Atoyac sub-basin for the historical period as well as for the climate horizons of 2015-2019 and 2075-2099, as obtained from the RCP8.5 scenario.

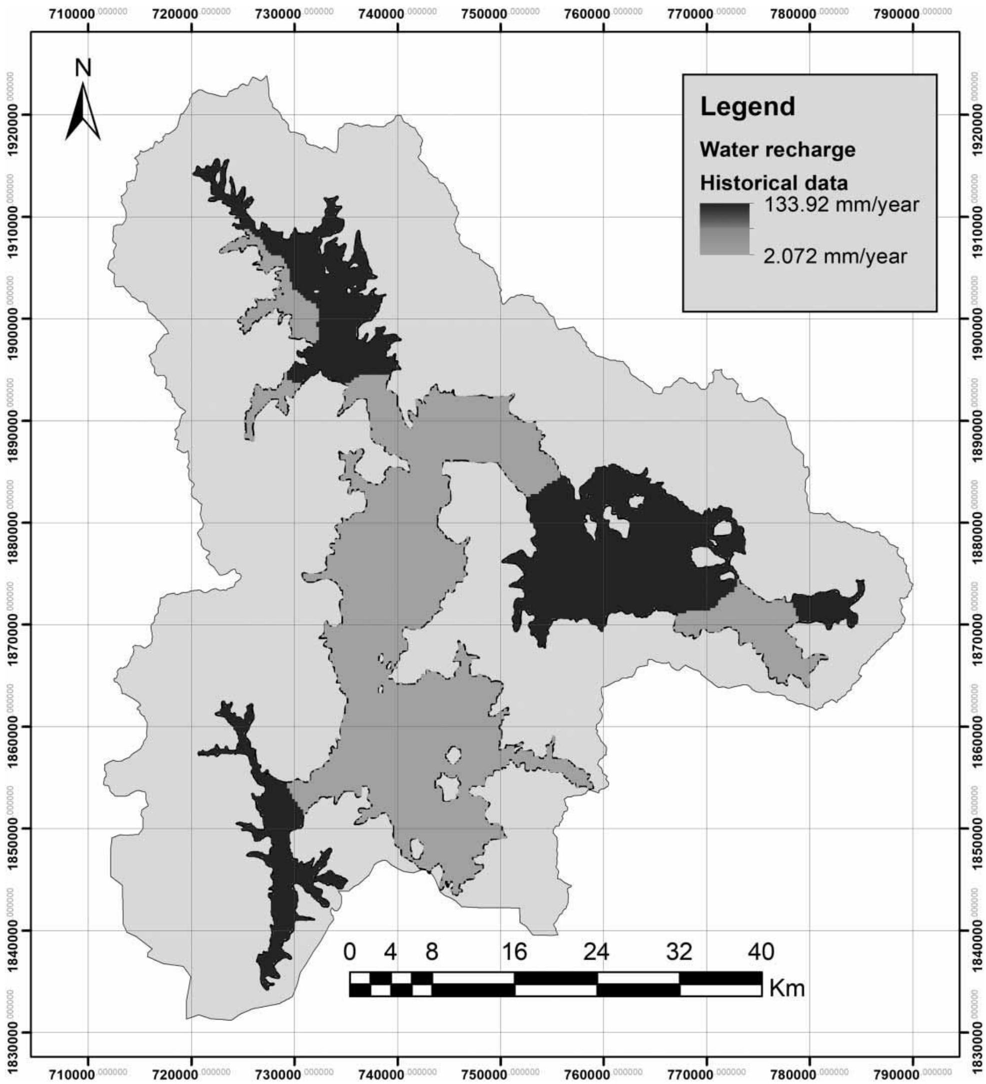


Figure 2. 13 Water recharge for the historical period 1951–2010.

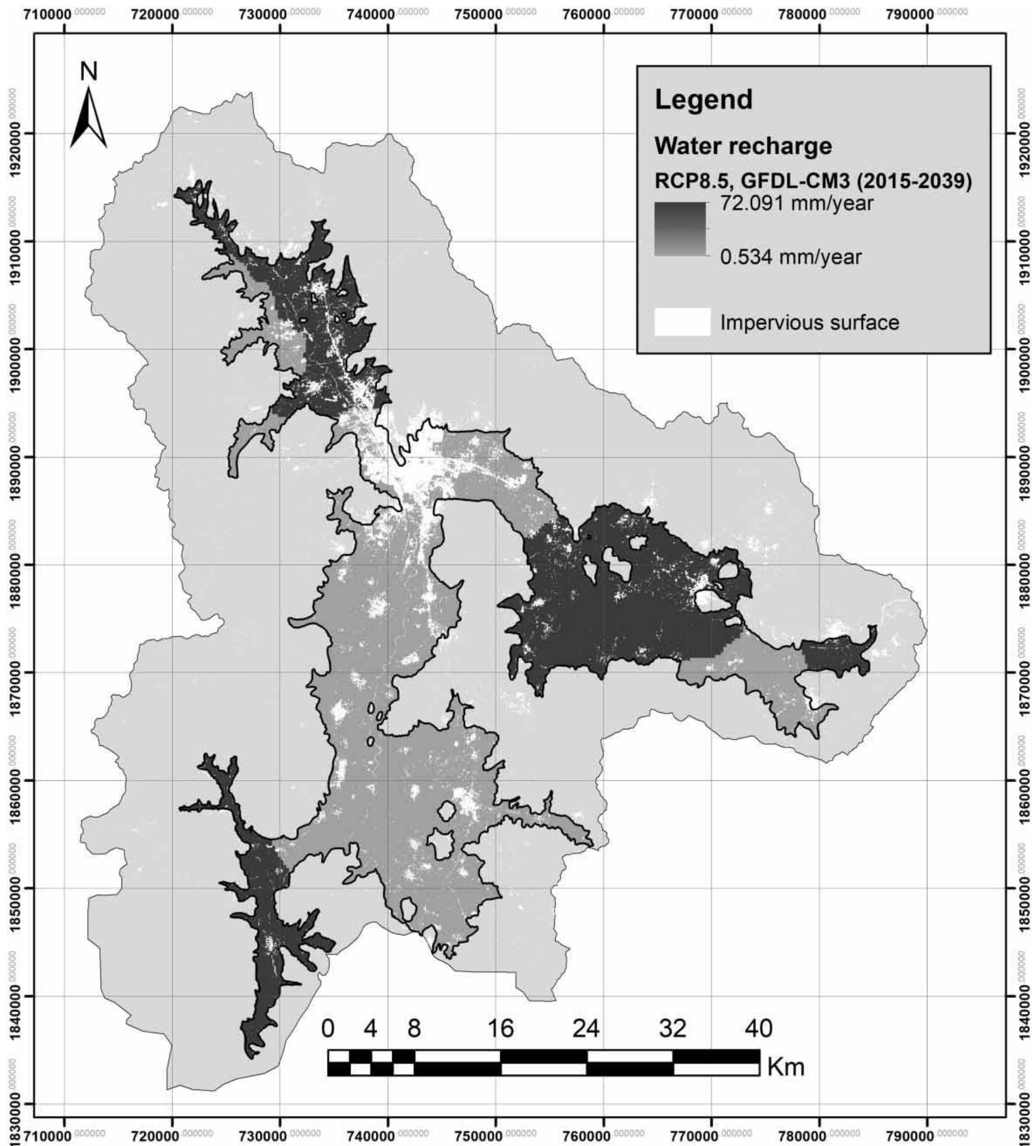


Figure 2. 14 Water recharge in the Alto Atoyac sub-basin for the horizon 2015–2039.

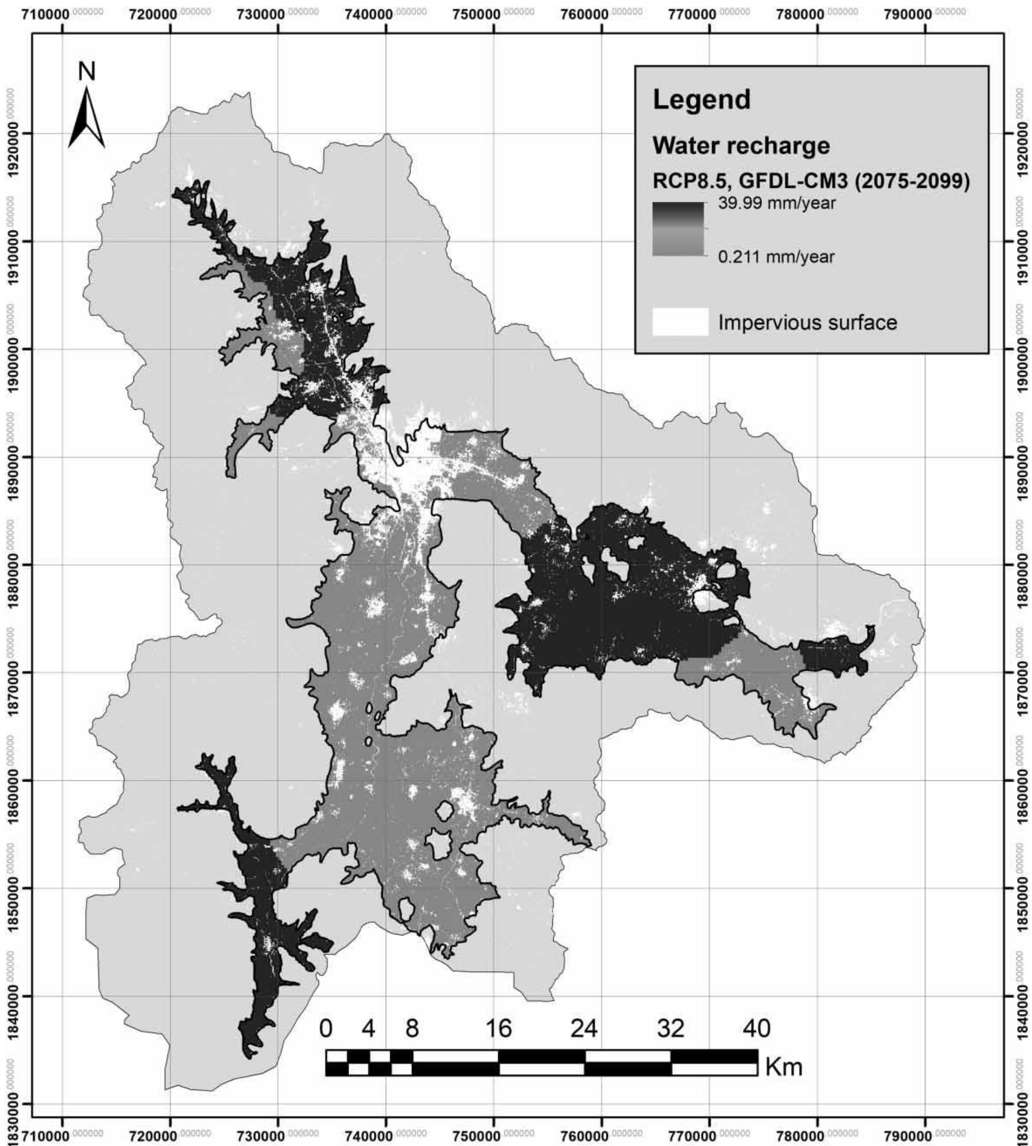


Figure 2. 15 Water recharge in the Alto Atoyac sub-basin for the horizon 2075–2099.

There are three main recharge sites. The first one is hosted in the northeastern part of the Etla Valley. The second one is located in the southern part of the study area, in the Tlacolula Valley. The third one is comprised in the southwestern part of the Zaachila Valley. This last recharge site presents a lesser infiltration potential.

Areas with high water recharge ratios represent zones where the aquifer is potentially vulnerable to contamination, and in fact the studies indicate that this aquifer presents a high vulnerability to vertical contamination, due to the permeability of soils and the shallow water levels (Belmonte-Jiménez et al. 2003; Belmonte-Jiménez et al. 2005; Ramos-Leal et al. 2012).

3.4 Adaptation strategies in the Alto Atoyac sub-basin

To better appreciate the reality of the study area it is necessary to emphasize that Oaxaca is Mexico's second poorest state, with highest marginalization indices, and affected by an increasing environmental deterioration, mainly of its water resources. Pollution of the mainsrivers that cross the city is large, while many municipalities suffer water scarcity.

In the Alto Atoyac sub-basin, the challenges for water security are associated with: 1) the agriculture production systems, 2) land use changes (LUC), 3) the growing population, 4) the lack of interest of the people in the conservation of natural resources, and 5) the lack of consideration by local and federal governments of the corresponding risks. The identification of measures to be implemented in the near future represents challenges to the stakeholders (local institutions, non-governmental organizations [NGOs], and farmers). The spectra of adaption strategies range from no regret (generating other benefits to the economy or to the environment), reversibility, minimizing environmental impacts, reducing vulnerability or at least not increasing it (De Loë et al. 2001). Cost effectiveness, equity, ease of implementation (feasibility) and effectiveness must be considered in choosing the best adaption strategies.

Conditions in the Alto Atoyac sub-basin region result in negative impacts on the crops. As already mentioned, 87.6% of exploited groundwater resource is allocated to irrigation. Agriculture technology is not well developed despite this economic sector representing the main economic activity. Irrigation itself is considered an adaptation strategy to climate change and variability (De Loë et al. 2001); however, inefficient irrigation methods can put the groundwater system at risk. Farmers need to switch from low- to high-efficiency irrigation methods, to reduce wastage. This can be achieved by irrigation management techniques, such as irrigation scheduling and by considering the water demand of different crops. Appropriate advice, training programs and monitoring of the corresponding achievements would be key in enabling assimilation of the knowledge and respective technologies. Rainwater harvesting and water recharge works represent good strategies that are being implemented by farmers in the Zaachila Valley and providing positive results for them.

LUC and growing population are closely related and both stress the groundwater resources. Reduction of forest and increase of urban areas may result in less water recharge areas and larger water demand for different uses. Effects associated with these items are already being experienced. Government must implement an urban planning policy that limits effects of a growing population and associated LUC. Government must fund studies to identify and assure the preservation of the potential recharge zones, and to plan a re-forestation campaign in the watershed upstream.

The challenge is to make the government aware of the risk to water supply. This can be done by presenting the government with the possible scenarios if no action is taken. Studies like this one can be a large contribution. A collaboration with research centers is necessary and also the establishment of sustainable water conservation policies. This requires more research in the study area since at the moment there are few studies concerning the water resource. Studies about the water degradation and its effect on the poorest communities are necessary.

The lack of interest of the people in the conservation of natural resources, can only be overcome through the education of the future generations, and awareness campaigns to explain the importance of the conservation of water resource. The people need to understand that water is a highly vulnerable resource, mainly in the Alto Atoyac sub-basin, and that probably in future years they will not have access to water.

4 CONCLUSIONS

Land use changes along a 34-year period in the Alto Atoyac sub-basin were established by means of a classification analysis of Landsat imagery. Hydraulic conductivities were assigned to soil types as classified by INEGI by following the USDA (1985) methodology.

Water balance analysis together with land use made it possible to estimate water runoff and the loss of infiltration surface due to urban growth. This information made it possible to further conduct a water balance to estimate the water recharge based on a temperature and rainfall 60-year database from five climate stations located in the study area. The HELP3.95D program was used.

By assuming that the soil properties will not change over time and using the soil temperature and precipitation from the climate change RCP8.5 scenario, the recharge at the time horizons of 2015-2019 and 2075-2099 was estimated. According to the CCh RCP8.5 scenario in the Alto Atoyac sub-basin, there will be a direct reduction of precipitation and an increase in soil temperatures in these two horizons.

From 1979 to 2013, the urban areas in the Alto Atoyac sub-basin increased by 135 square kilometres. That amounts to a loss of a 135 km^2 caption surface and of $2.65x10^6$ m^3 of water infiltration into the subsoil. Assuming that this water amount does not infiltrate somewhere else, this infiltration surface loss represents a significant water recharge loss. According to the HELP based water balance, this will result in a reduction of water recharge into the aquifer of the Alto Atoyac sub-basin. In the case of future urban growth continuing, additional water recharge reductions might result.

Near and far horizons analyzed under the CCh RCP8.5 scenario indicate that reductions of 17.97% and 65.09% of water recharge would take place in the short and long term within the watershed respectively, this represents a challenge to the management of water resources for the future, as farming and human consumption are the most important uses of water.

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Chapter 3: Climate Change, Land Use/Land Cover Change, and Population Growth as Drivers of Groundwater Depletion in the Central Valleys, Oaxaca, Mexico

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Climate Change, Land Use/Land Cover Change, and Population Growth as Drivers of Groundwater Depletion in the Central Valleys, Oaxaca, Mexico

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ABSTRACT

Groundwater depletion is an important problem driven by population growth, land use and land cover (LULC) change, climate change, and other factors. Groundwater depletion generates water stress and encourages unstainable resource use. The aim of this study is to determine how population growth, LULC change, and climate change relate to groundwater depletion in the Alto Atoyac sub-basin, Oaxaca, Mexico. Twenty-five years of dry season water table data from 1984 to 2009 are analyzed to examine annual groundwater depletion. Kriging is used to interpolate the region's groundwater levels in a geographic information system (GIS) from mapped point measurements. An analysis of remotely sensed data revealed patterns of LULC change during a 34-year (1986–2018) period, using a supervised, machine-learning classification algorithm to calculate the changes in LULC. This analysis is shown to have an 85% accuracy. A global circulation model (GFDL-CM3) and the RCP4.5 and RCP8.5 scenarios were used to estimate the effects of climate change on the region's groundwater. Estimates of evapotranspiration (using HELP3.5 code) and runoff (USDA-SCS-CN), were calculated. Since 1984, the region's mean annual temperature has increased 1.79 °C and urban areas have increased at a rate of 2.3 km^2/year. Population growth has increased water consumption by 97.93 × 10^6 m^3/year. The volume of groundwater is shrinking at a rate of 284.34 × 10^6 m^3/year, reflecting the extreme pressure on groundwater supply in the region. This research reveals the nature of the direct impacts that climate change, changing LULCs, and population growth have in the process of groundwater depletion.

Keywords: climate change; groundwater depletion; land use and land cover change; population growth; runoff; evapotranspiration; water recharge

1. INTRODUCTION

Groundwater is a complex component of any region's hydrological system. Detailed information and descriptive data of the volumes, extent, and quality of groundwater supplies is usually very limited. What is known about the groundwater resources of a region is often sketchy and uncertain. Groundwater is storage of fresh water in aquifer systems which are subterranean layers of water-bearing permeable rock or unconsolidated materials. According to Arnell [1], the processes that control the recharge (R_e) ratios in aquifers are climate, topography, and the geological structure. Precipitation (P) provides the input into the aquifer system. Hydrological soil conditions control infiltration of water to the water table. However, the geological framework determines the capacity for water to flow at depths and can slow recharge rates. If the climatic and soil conditions generate R_e in excess of the capacity of the saturated matrix to transmit the R_e, then the permeability of the geological characteristics controls R_e rates [2]. The water balance (aquifer inflows and outflows) can be defined as the volume that is required to sustain groundwater use and groundwater-dependent ecosystem services for a region of interest, which could be delimited as an aquifer, a watershed, or a community [3]. Many social, economic, and environmental processes influence groundwater quantity and quality, and these systems are often difficult to predict. They therefore increase the complexity of groundwater management. Populations of every region of the world rely to some extent on groundwater. Due to its complexity, groundwater is a system that, once degraded, is very difficult to repair [4]. Groundwater is a vital source of fresh water for residential uses and for agriculture [5–7], and it plays a fundamental role in economic and food security [8]. Agriculture uses more freshwater than any other economic sector or activity. It accounts for about 70% of global freshwater withdrawals and 90% of freshwater consumption. Irrigation consumes 545 km^3 of groundwater per year. Groundwater provides 43% of water consumed (1277 km^3) for irrigation ever year [5].

Water scarcity is a widespread and challenging problem in Mexico, regularly presenting moderate and severe scarcity from February to May or June [9]. The problem has worsened dramatically over the last three decades. In the Central Valleys of Oaxaca, two forces are the main drivers of increasing groundwater demand: agriculture, the main economic activity using groundwater (more than 80% of groundwater is used for agriculture), and population, which has increased by about 76% since the 1980s. Agriculture in Oaxaca has experienced abandonment due to poverty, and rural-to-urban migration has increased the pressure of urban water demand on rural groundwater supplies. Changing consumption habits and low-tech irrigation infrastructure have also intensified the pressures on groundwater. Climate change (CC) is now an additional stress. In combination with population growth and redistribution, and land-use and land-cover (LULC) changes, shifts in weather patterns and increasingly unanticipated shifts in components of climate magnify stresses on freshwater supplies [10–15]. The pressures are so great that some parts of the Central Valleys of Oaxaca are experiencing significant pollution problems due to overexploitation, poor waste management infrastructure, and shrinking aquifers.

New tools and techniques are needed to extract and analyze data to evaluate present and future groundwater conditions. Probabilistic tools to determine the sensitivity and uncertainty of the analytical innovations can provide some insight. LULC changes can be used to assess the trends in groundwater supplies. Remote sensing can be used to determine where those changes are greatest in order to fill in data gaps. Water table monitoring at wells provides instantaneous assessments of the effects of R_e and extraction. Water table point data must be spatially extrapolated to visualize regional change. Therefore, geostatistical methods are vital for data analysis. The distribution and quality of field data dictates the best methods to use. Kriging, for example, is an interpolation method that has been used in many groundwater studies [16–21]. Kriging can be applied to a small and sparsely distributed observation sample and yields error estimates to characterize the accuracy of its output.

Assessing the hydrological effects of climate change, LULC, and population growth is of vital importance for land use planning and water resource management. Especially because groundwater supports drinking water for the population and irrigation for agriculture in the Central Valleys of Oaxaca. This research combines empirical data from a network of wells, remotely sensed data, groundwater models, and a geographic information system (GIS) for data management and analyses of historical patterns of groundwater uses, demands, and supplies in the Central Valleys of Oaxaca in order to spatially predict the future demands and supplies in the contexts of anticipated growth and change of population, land use and land cover (LULC), and climate. The results can help pinpoint areas that may (or may not) contribute sufficient R_e to meet the future demands for groundwater in the region. Such knowledge can aid planning for engineered R_e infrastructure for selected zones and the use of irrigation management strategies with effective water-consumption policies that achieve water supply goals.

1.1 Study Area

The study area is a basin located between 16°30' and 17°25'N and 96°15' and 97°00'W. Three valleys in the basin, the Etla, the Tlacolula, and the Zaachila (from Zimatlán to Ocotlán), are collectively referred to as the Central Valleys of Oaxaca (Figure 3.1). The Central Valleys border the Mixteca region to the west, the Cañada region to the northwest, the Sierra de Juárez to the north, the Tehuantepec Isthmus region to the east, and the Sierra Madre del Sur to the south. The Alto Atoyac sub-basin has a surface area of 3744.64 km^2, with an approximate aquifer surface of 1130 km^2, the annual R_e ranges from 153.6 to 169 million m^3 [22], with an average annual P (P) of 741 mm/year and annual average temperature (T) of 19.96 °C. The region's bedrock includes metamorphic gneiss and schists, limestones, and rhyolites. The metamorphic rocks and extrusive volcanic rocks constitute the impermeable borders of the sub-basin [22] (for more detail of the geology see [23] and [24]. The 396 km long Atoyac River is the main river course through the Central Valleys.

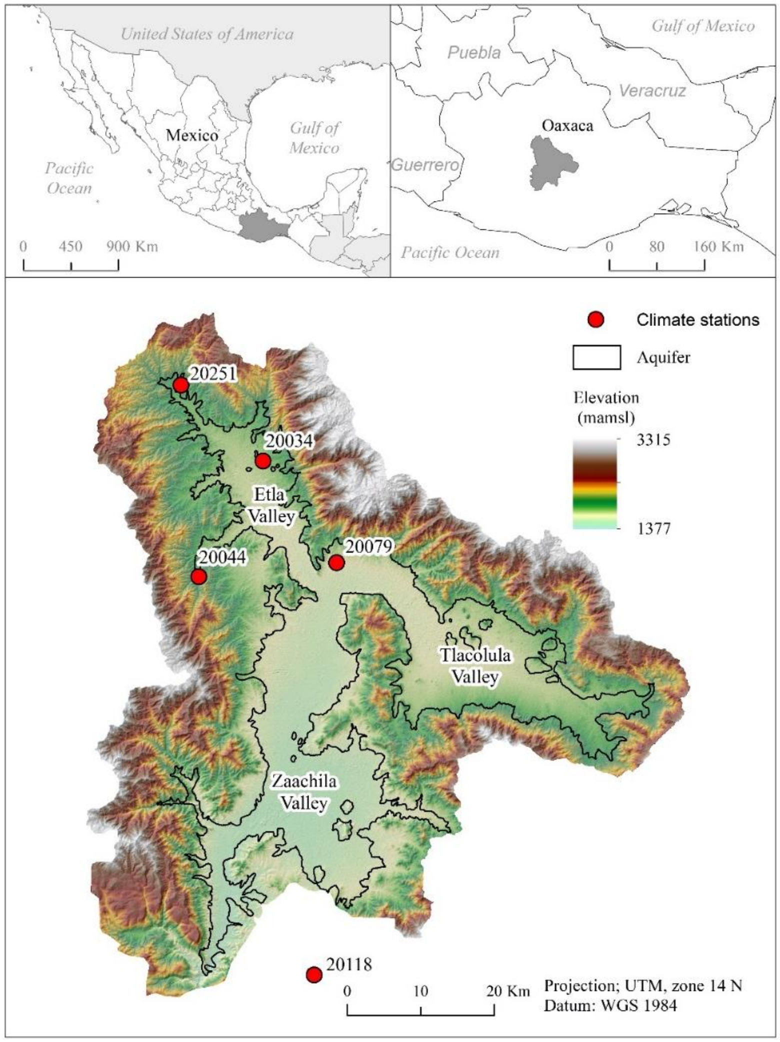

Figure 3. 1 Location of the study area in the Central Valleys of Oaxaca

Agriculture is the main economic activity of the rural portions of the sub-basin, particularly in the Zaachila and Etla Valleys, the two largest agricultural districts. Agriculture is estimated to use 87.6% of the groundwater of the study area [22]. The aquifer of the Central Valleys is unconfined and is composed of alluvium, a heterogeneous mixture of unconsolidated sediments. Its thickness ranges from 15 m to 100 m, thinning toward the basin's edges. The region's water table is shallow (0.2 m to 20 m) and there are areas of high permeability (Figure 3.2). Intensive agriculture in the region has increased the likelihood of overexploitation. A large depletion cone has been identified in the Zaachila Valley.

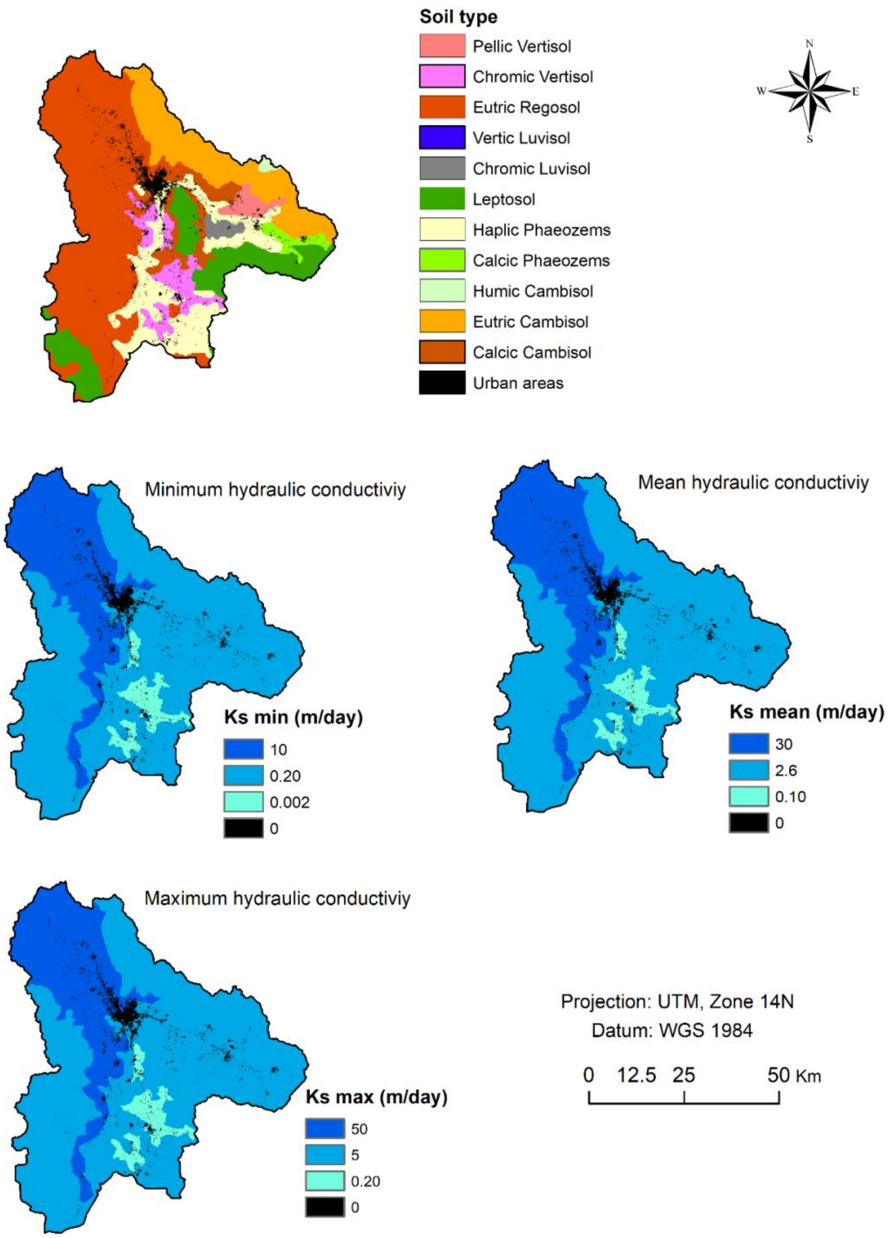

Figure 3. 2 Soil type and hydraulic conductivity distribution

2. Materials and Methods
2.1. Meteorological Stations

Climatological data are limited for the area. Five meteorological stations with time-series records of more than 30 years were selected (Figure 3.3). The climatic information was obtained from Mexico's CLICOM (Climatological Computing) project, Servicio Meteorológico Nacional (National Meteorological Service) through CICESE (available at http://clicom-mex.cicese.mx/) for the period from 1984 to 2012 and the year 2014, to analyze the evolution of P and T (Table 3.1).

Figure 3. 3 Climographs of five meteorological stations in the study area

Table 3. 1 Statistic values of the meteorological stations

Meteorological Station	Mean				STD			
	Tmin (°C)	Tmean (°C)	Tmax (°C)	P (mm/year)	Tmin (°C)	Tmean (°C)	Tmax (°C)	P (mm/year)
20034	11.81	19.24	26.66	589.53	1.04	0.95	1.36	169.67
20079	13.75	22.23	30.71	768.70	0.90	0.91	1.08	188.25
20118	13.10	21.08	29.06	672.18	0.75	1.48	2.60	129.72
20151	12.11	19.42	26.73	780.48	0.89	0.75	1.50	164.69

20044	10.75	18.19	25.62	793.72	1.38	1.11	1.57	101.22

2.2. Climate-Change Scenarios

Two scenarios of CC based on the projections produced by RCP4.5 and RCP8.5 are used to assess the impacts of changing climate on groundwater volumes. The first is a scenario based on stabilizing future climates without thermal overshoot. Total radiative forcing (4.5 W/m^2) is stabilized after 2100. RCP4.5 includes long-term, global emissions of short-lived species of greenhouse gases and LULC in a global economic framework. This scenario was developed by the Global Change Assessment Model (GCAM) modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) [25,26]. The second scenario, RCP8.5, assumes high population growth and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading to long-term high energy demand and unrestricted GHG emissions in the absence of global-warming mitigation policies [27].

A global circulation model (GCM), GFDL-CM3, was chosen from the last update of the Climate Change Scenarios for Vulnerability and Adaptation Impact studies conducted for Mexico and Central America [28]. These scenarios have a high spatial resolution of 30" × 30". Two scenarios were analyzed for RCP4.5 and RCP8.5 conditions in three time-horizons: near (2015–2039), medium (2045–2069) and far (2075–2099) (Figure 3.4a,b, Figure 3.5a,b).

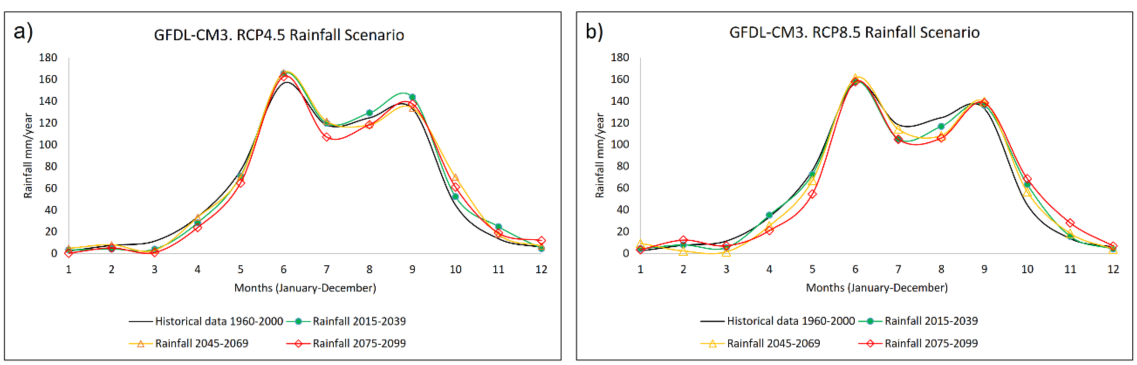

Figure 3. 4 (**a**,**b**) Normal monthly P for historical and future climate projections under RCP4.5 and RCP 8.5 for 2015–2039, 2045–2069, and 2075–2099 horizons modeled by GFDL-CM3

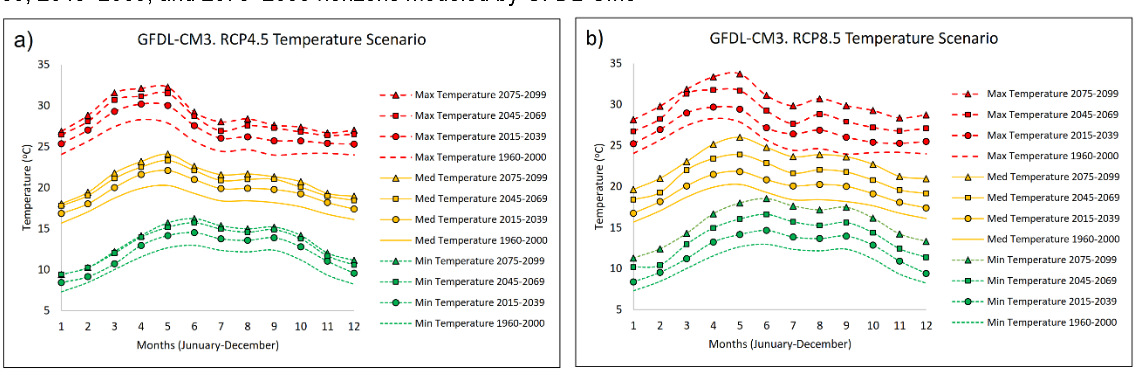

Figure 3. 5 (**a**,**b**) Normal monthly T for historical and future climate projections under RCP4.5 and RCP 8.5 for 2015–2039, 2045–2069, and 2075–2099 horizons modeled by GFDL-CM3

2.3. Calculating Evapotranspiration (ET)

To estimate future groundwater supplies, the balance of the values of the components of the hydrological system, like ET rates, must be calculated for given future T and P scenarios. The HELP model, used for predicting landfill hydrologic processes, can also be used to estimate water-balance parameters, requiring the following inputs: (1) weather (P, solar radiation, T, and ET); (2) soil (porosity, field capacity, wilting point, and hydraulic conductivity), and (3) engineering design data (liners, leachate and runoff collection systems, and surface slope) [29,30].

To calculate ET, the input parameters included in the HELP model were evaporative depth zone, maximum leaf area index, starting and ending dates of growing season, average wind speed, and quarterly relative humidity [30]. A depth of 100 cm was used as the maximum depth at which water can be removed by ET, which corresponds to the average plant root length in the area. ET was calculated for the historical climate data and for the data produced by the RCP4.5 and RCP8.5 climate scenarios for the 2015–2039, 2045–2069, and 2075–2099 horizons.

2.4. LULC Change and Runoff ($\mathbf{R_u}$)

2.4.1. Satellite Imagery Acquisition and Preprocessing

Landsat imagery was used to discern LULC change and to calculate its effects on groundwater supplies over the last three decades as these data span the period of interest. Five temporally equidistant dates were chosen based on data availability, data quality (minimization of cloud coverage), and season (dry season) (Table 3.2). To encompass the study area, two Landsat scenes for each date (024048 and 024049) were acquired. All images have the same spatial resolution (30 m), but data were sensed by distinct satellites and sensors at different times of the year. Therefore, each scene was radiometrically corrected by converting the raw digital numbers (DNs) into top of atmosphere (TOA) reflectance values to enable interannual comparisons. After mosaicking the Landsat scenes by date, the resulting five images were clipped to the study area. The 1986 image was slightly masked by clouds and cloud shadows along the northeastern border. Though only 0.26% of the pixels were affected, they were removed from the analysis to avoid misclassification.

Table 3. 2 Satellite imagery used for the remote sensing analysis

Satellite	Sensor	Date
Landsat 5	TM	20 January 1986
Landsat 5	TM	26 January 1994
Landsat 7	ETM+	13 March 2002
Landsat 5	TM	22 January 2010
Landsat 8	OLI	1 March 2018

2.4.2. Classification and Change Detection

According to the LULC characteristics of the study area and based on the spatial resolution of the images, five classes of LULC were assigned: urban, agriculture, grassland, forest, and water. Following this scheme, samples of each class were collected using visible, near infrared, and short-wave infrared spectral bands, as well as a digital elevation model (DEM) as ancillary data. The samples were used to train a random-forest classifier [31]. This supervised machine-learning classification algorithm is nonparametric and overcomes the issue of individual decision trees overfitting to the training sample data. To determine classification accuracy, reference points were compared to the classification results at the specific locations. The calculation of the sample size for reference points was based on binomial probability theory with an expected accuracy of 85% and allowable error of 5% [32]. Thus, 204 randomly distributed reference points were classified by visual interpretation of finer resolution imagery available on Google Earth. After classifying and assessing the accuracy of the five images, post-classification comparison techniques were used to detect LULC change. Image pairs of subsequent dates were compared by cross-tabulation of the LULC statistics. The resulting four change-detection matrices (1986–1994, 1994–2002, 2002–2010, 2010–2018) reflect conversion of specific LULC types to other classes. The total area assigned to each class at each time node was also calculated to evaluate the changes over the entire 32-year period. The forest class was arbitrarily attributed to all cloud-affected pixels to facilitate a pixel-based comparison to the 1986 image, the only scene affected by clouds. This was justified by the fact that all cloud-covered pixels were surrounded by forest and they remained unchanged over the study period.

2.4.3. R_u Rates by LULC Class

LULC change impacts local water dynamics, either by changing groundwater R_e patterns or runoff due to increased impervious surfaces through urbanization or slowing runoff with revegetation of the surface. Assessing the direct impact of land cover change allows extrapolation to the study region's hydrology. The runoff was calculated with the Soil Conservation Service (SCS) curve number (CN) method which is described in detail in SCS [33]. The curve-number method was used for four reasons: (1) it is widely accepted; (2) it is computationally efficient; (3) the required input is generally available, and (4) it can conveniently handle a variety of soil types, LULCs, and management practices [29]. The runoff equation to be evaluated is:

$$R_u = \frac{(P - 0.2 * S)^2}{(P + 0.8 * S)} \quad (1)$$

where R_u is runoff (inches), P is precipitation (inches), and S is potential maximum retention after R_u begins (inches). S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100; 0 indicates conditions of high permeability and 100 indicates complete impermeability. S can be calculated as:

$$S = \frac{1000}{CN} - 10 \quad (2)$$

There are seven different soil types in the study area, and they can be grouped into two soil types according to their hydrological features (hydraulic conductivity) (Figure 2). The curve number was calculated for the four LULCs in combination with the two soil types.

Urban growth was projected as a linear trend for the study area. It was assumed that agricultural areas would continue to be transformed to urban LULCs, as our change analysis of the Landsat scenes showed. By comparison, the other land cover classes were unaltered. R_u amounts were calculated based on the variations of P under both of the climate-change scenarios and over the three time horizons.

2.5. Water Balance

Water balance was calculated from annual P, ET, and R_u to assess the impacts of various changes on water recharge. P was the only input to the system and R_u, ET, were the outputs to obtain R_e.

2.6. Sensitivity Analysis for the Water Balance

Sensitivity analysis evaluates the impact of changes in a model's parameters, inputs, or (initial) states on the model's output variable of interest [34]. A Monte Carlo method was used to determine the sensitivity of the water balance parameters. This is a stochastic technique based on the use of random numbers and statistics to evaluate the consequences of altered inputs. Multiple evaluations of the model were performed with probabilistically selected model inputs to evaluate and quantify the uncertainty in the predictions of the model, and to identify the input factors that gave rise to the uncertainty [35,36]

Monte Carlo simulations were executed using the software SimLab V2.2 (Simulation Environment for Sensitivity and Uncertainty Analysis) downloaded at https://ec.europa.eu/jrc/en/samo/simlab. It consists of three modules: the statistical preprocessor module, the model specification and execution module, and the statistical postprocessor module. To use SimLab, the user performs the following operations [35]:

1. Select a range and distribution for each input factor.
2. Generate a sample of elements from the distribution of the inputs previously specified.
3. Feed the model with the sample elements and produce a set of outputs.
4. Use the results of the model outputs for uncertainty analysis.

The input variables for the model were P, mean annual T, LULC (urban, agriculture, grassland, and forestland), and the results of modeled calculations for the five meteorological stations (ET, R_u, and recharge). Randomly sampled values were taken to reflect the cardinality of the model's inputs and output.

2.7. Partial Correlation Coefficient (PCC)

Correlation between variables are indicated by partial correlation coefficients. These coefficients are guided by the principles of correlation and partial correlation; however, when relationships between input factors are nonlinear, the correlation coefficient could be low. To solve the problem of nonlinear data, a rank transformation was used. In this process the data are replaced with their corresponding ranks (from 1 for smallest to N for the largest observation) [35].

Variation of rank of partial correlation coefficients are −1 to +1. A value close to the upper or lower limits shows a strong influence of the input factors over the output values. Usually, PRCC values >+0.5 or <−0.5 are considered significant. Positive or negative values indicate the nature of the relationship (direct or inverse) between the input and output variables [36]

2.8. Water Table Change and Calculation of Volume Storage Change

The water table depth was measured as piezometric head (in m) for five years: 1984, 2001, 2003, 2007, and 2009 (Figure 3.6). A geostatistical interpolation technique was used to represent the distributed depth to water table throughout the study area. This technique allowed for scenario-based prediction surfaces that have measurable levels of accuracy [37]. This well-known technique, kriging, denotes interpolators stochastically. Kriging statistically predicts values using an unbiased linear estimator. It is often the best method for interpolation because it factors in the number and spatial configuration of observation points, the positions of the data points within the region of interest, the distances between the data points with respect to the area of interest, and the spatial continuity of the interpolated variable [17]. It also generates an estimate of the error of its calculations.

The changes in depth to water table can be used to calculate the change in volume of the aquifer from one time period to the next. To calculate the change of volume for each period, a triangular irregular network (TIN) model was constructed in GIS to calculate the volume for each of the four intervening periods between the estimates: 1984–2001, 2001–2003, 2003–2007 and 2007–2009 (Figure 3.7). The piezometric surface for 1984 was used as the baseline.

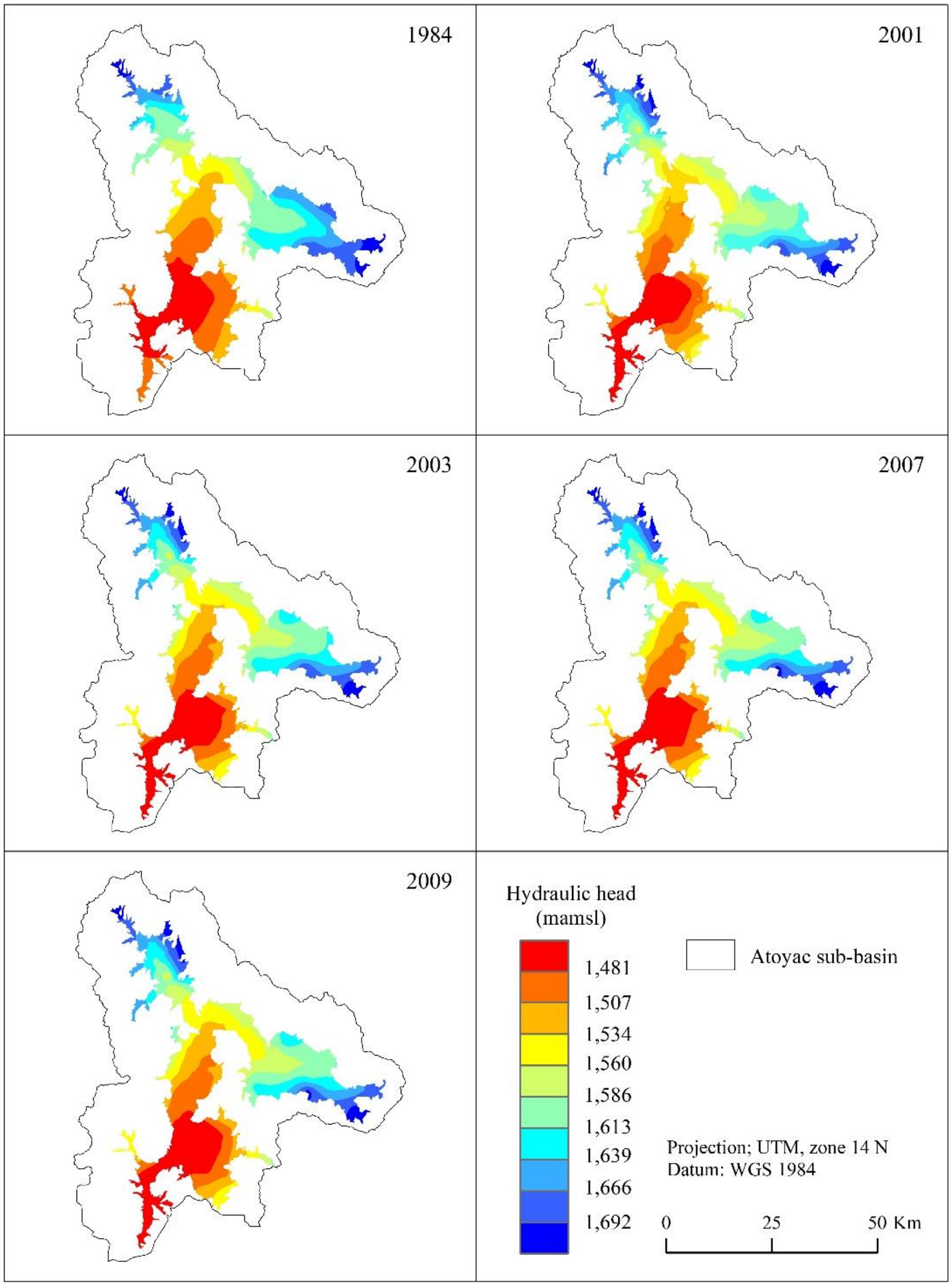

Figure 3. 6 Piezometric head (in m) in the Central Valleys of Oaxaca during the dry seasons of 1984, 2001, 2003, 2007, and 2009

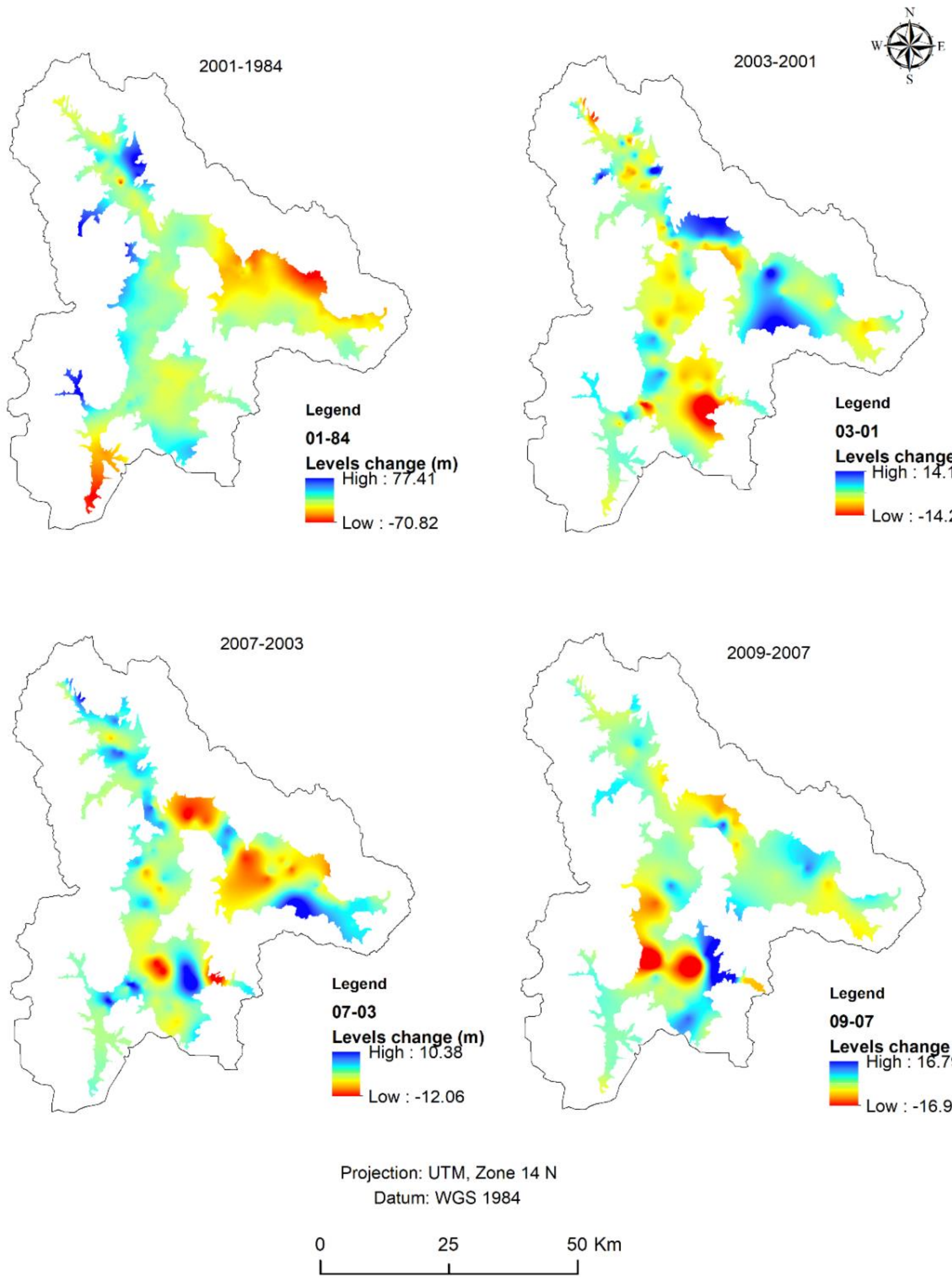

Figure 3. 7 Volume storage change (in m) in the Central Valleys of Oaxaca during the dry seasons of 1984, 2001, 2003, 2007, and 2009

2.9. Population Growth and Water Consumption

According to the Instituto Nacional de Estadística Geografía e Informática (INEGI—the National Institute of Geographic Statistics and Information), the population of the Central Valleys of Oaxaca has grown at a rate of 2.32% per year from 1980 to 2010 [38,39]. Population growth trends since 1980 were projected to 2039, 2045, 2069, 2075, and 2099 to estimate future water needs. Projected needs translate to groundwater extraction and must be set into the context of CC to determine the predicted impacts on future supplies. Historically, water consumption in the study area ranged from 48 to 384 liters per person per day (LPD) [40]. The average of 216 LPD was used as a constant on which future consumption projections could be made.

3. RESULTS

3.1. Climatology, Cclimate-Change Scenarios and ET

Five meteorological stations provided P and T records for the Central Valleys. Water resources are dynamic yet examining meteorological data climatologically can enable examination of the changing patterns of water supplies in a region. Over the last 30 years, empirical measurements indicate that there have been changes in annual P amounts. Empirical data reveals an increase in annual T_{mean} in the Central Valleys. Annual T_{mean} has increased by 1.76 °C over the past 30 years, while the annual T_{min} and T_{max} have increased 1.109 °C and 2.4 °C, respectively (Table 3.3).

Table 3. 3 Changes in Annual T_{mean} from 1984 to 2014

Meteorological Station	T_{min} (°C)	T_{mean} (°C)	T_{max} (°C)
20034	1.877	2.297	2.662
20079	1.439	2.560	3.681
20118	1.668	1.597	1.531
20151	1.414	2.286	3.158
20044	−0.854	0.058	0.970
Average	1.109	1.760	2.400

The RCP4.5 projects P will increase in the near term and medium term (2015–2039 and 2045–2069) of 23.03 mm/year and 26.56 mm/year, respectively. In the long term (2075–2099), P will diminish at a rate of 15.58 mm/year compared to the contemporary average. The RCP8.5 scenario projects that the annual average P will diminish by 3.58, 20.59, and 19.04 mm/year in the near, medium, and distant periods (Table 3.4).

Table 3. 4 Projections of P based on RCP4.5 and RCP8.5 scenarios using the GFDL-CM3 global circulation model

Scenario	P (mm/year) 2015–2039	P (mm/year) 2045–2069	P (mm/year) 2075–2099
RCP4.5	751.34	754.87	712.73
RCP8.5	724.73	707.72	709.27
Historical *	728.31		

* 1984–2014.

The CC scenarios indicate that annual T_{mean} and average T_{max} will increase each year. Rising global T_{mean} of up to 2 °C followed by stabilization and of 4 °C indicate that water scarcity will increase exponentially as a product of warming in many parts of the world [41] (Table 3.5). In the first climate scenario (RCP4.5) T_{mean} will increase by 1.46, 2.49, and 3.02 °C, and in the second (RCP8.5) the increases will be 1.49, 3.21, and 4.95 °C for 2015–2039, 2045–2069 and 2075–2099, respectively.

Table 3. 5 Projected changes of annual T_{mean}, T_{min}, and T_{max} under the RCP4.5 and RCP8.5 scenarios

Scenario	T_{mean} (°C) 2015–2039	T_{mean} (°C) 2045–2069	T_{mean} (°C) 2075–2099	T_{min} (°C) 2015–2039	T_{min} (°C) 2045–2069	T_{min} (°C) 2075–2099	T_{max} (°C) 2015–2039	T_{max} (°C) 2045–2069	T_{max} (°C) 2075–2099
RCP4.5	19.49	20.52	21.05	12.04	13.07	13.39	26.97	28.16	28.82
RCP8.5	19.52	21.24	22.98	12.16	13.83	15.60	26.92	28.72	30.41
Historical *	18.03			10.71			25.36		

* 1984–2014.

ET rates are calculated using annual P and T_{mean}. ET projections under both scenarios show a trend that is increasing from historical rates (Table 3.6). However, under RCP4.5, the trend peaks in the medium-term future and diminishes as T_{mean} diminishes after overshoot. Under RCP8.5, increasing rates of ET continue into the distant future. The increase of 1.46 °C above the current annual T_{mean} (scenario RCP4.5 in Table 3.4) for the near term translates to a rate of increase of 3.9% above the present rate of ET. An increase of 2.49 °C for the medium time horizon (scenario RCP4.5) yields an expected increase of 6.49% above the contemporary rate of ET.

Table 3. 6 Historical and projected ET rates under both scenarios and the percentages of increase from the present

Evapotranspiration (mm/year)						
	2015–2039	%Increase	2045–2069	%Increase	2075–2099	%Increase
RCP4.5	472.673	3.895	484.088	6.405	468.128	2.896
RCP8.5	460.920	1.312	467.018	2.652	479.798	5.462
Historical *	454.95					

* Calculated as the annual average of all meteorological stations for the period of study.

3.2. LULC Change and R_u

LULC change affects the water balance by changing R_u and infiltration and contributes to water supply problems. Another connection to water scarcity is the linkage of LULC and activities to water demand. For example, the growth and intensification of agriculture increases water extraction [42]. Industrial development tends to demand more water than does residential development, but lifestyles and culture (private swimming pools, lawns, golf courses, for instance) certainly distinguish water-heavy LULCs from water-light LULCs.

Historical LULC change in the Central Valleys has been dramatic over the thirty-year study period. From 1986 to 2018, urban land has increased from 0.85% of the sub-basin surface to 2.86% of the area (Table 3.7). Agricultural land has decreased slightly from 31.39% to 30.28%. Forestland increased slightly from 48.14% to 48.2%. Grassland diminished from 19.53% to 18.63%. Surface water decreased from 0.09% to 0.04%. The trend of the agricultural decline, however, has been neither constant nor consistent. Between 1986 and 1994, agricultural land increased by 11.2 km^2 and from 1994 to 2002 it grew another 7.57 km^2. However, from 2002 to 2010, farmlands decreased by 62.95 km^2, and from 2010 to 2018, 0.64 km^2 were converted to agriculture. Similarly, forested lands had gained 60.02 km^2 between 1994 to 2010; however, after 2010, 45.96 km^2 were changed to other uses.

Table 3. 7 LULC in the Alto Atoyac sub-basin for five years

Class	**Area (km^2)**				
	1986	**1994**	**2002**	**2010**	**2018**
Urban	33.16	48.94	63.82	94.95	111.65
Agriculture	1227.45	1238.67	1246.24	1183.29	1183.93
Grassland	763.78	749.62	689.18	694.60	728.37
Forest	1882.57	1870.63	1909.67	1930.65	1884.69
Water	3.42	2.52	1.47	6.89	1.74
Total	3910.37	3910.37	3910.37	3910.37	3910.37

A trend line for urban LULC follows a direct linear relationship in the study region and can be approximated with the equation:

$$U = 2.5374 * Y - 5009.3 \; R^2 = 0.9823 \quad (3)$$

Where U is the area of urban LULC in km^2 and Y is the period (in years) of projected increase to be calculated.

The other LULC classes don't exhibit a linear trend. Changes in the other LULC categories over the last 32 years have been relatively minor. For example, forestland was nearly stable from 1986 to 2018. Forest cover increased by only 2.12 km^2. Agriculture covers less land in 2018 than it did in 1984, as

43.52 km^2 were lost to urbanization. The result is that because urban LULC increased, R_u has increased from urban land by 7.58 mm/year (Table 3.8). Even though R_u from urban areas is greatest and though there has been an increase of urban LULC, it seems to not have had much of an impact in total R_u since 1986. Agriculture accounts for 45.03% of all runoff. Urban LULC is only a small portion (2.89%) of the sub-basin.

Table 3. 8 R_u values for the historical climate normal and for the five LULC categories

R_u (mm/year) for the Historical Climate Normal					
LULC	**1986**	**1994**	**2002**	**2010**	**2018**
Urban	3.21	4.73	6.17	9.18	10.79
Agriculture	104.07	105.02	105.66	100.32	100.38
Grassland	49.20	48.29	44.39	44.74	46.92
Forest	64.76	64.34	65.69	66.41	64.83
Water	0.00	0.00	0.00	0.00	0.00
Total R_u	221.23	222.38	221.91	220.65	222.92

Projecting changes in R_u due to projected LULC change and changing climates using the two scenarios reveals that by the end of the century, urban R_u may nearly double during the period 2018 to 2099 (Table 3.9). This is projected to happen despite decreasing P. By contrast, R_u for the other LULCs should diminish over the 81-year projection in both the RCP4.5 and RCP8.5 scenarios, largely because of diminishing P. Thus, due to urbanization of rural (particularly agricultural) lands, water supply will be diminished at a rate that is greater than is the effect of CC.

Table 3. 9 R_u values for the climate-change scenarios by LULC

R_u (mm/year) in the RCP4.5 Climate-Change Scenario					
LULC	**2039**	**2045**	**2069**	**2075**	**2099**
Urban	16.40	18.00	24.10	24.20	29.96
Agriculture	98.93	98.06	92.71	86.27	81.22
Grassland	48.40	48.63	48.63	45.91	45.91
Forest	66.88	67.19	67.19	63.44	63.44
Water	0.00	0.00	0.00	0.00	0.00
Total R_u	230.61	231.88	232.63	219.82	220.53

R_u (mm/year) in the RCP8.5 Climate-Change Scenario

LULC	2039	2045	2069	2075	2099
Urban	15.82	16.88	22.60	24.08	29.81
Agriculture	95.43	91.94	86.92	85.85	80.82
Grassland	46.69	45.59	45.59	45.69	45.69
Forest	64.51	63.00	63.00	63.13	63.13
Water	0.00	0.00	0.00	0.00	0.00
Total R_u	222.44	217.40	218.10	218.76	219.46

3.3. Water Balance

The potential for R_e has been changing since 1986 (Table 3.10). This has been due to the interactions between increasing annual $T_{mean,}$ rainfall variations and urbanization in the study region. R_e potential has increased by 72.29 mm/year.

Table 3. 10 Water balance in Alto Atoyac sub-basin from the climate record

Water Balance	1986	1994	2002	2010	2013
Mean Annual P * (mm/year)	629.42	666.36	583.23	935.62	794.80
ET (mm/year)	405.98	434.07	391.15	405.98	498.45
Runoff (mm/year)	221.23	222.38	221.91	220.65	221.5
Potential R_e (mm/year)	2.21	9.91	−29.83	308.99	74.5

* From the all five meteorological stations.

There appear to be reductions of groundwater R_e by 2039 (26.44 mm, 35.48%) under the RCP4.5 scenario compared to the 2013 rate. However, there would be a reduction of 44.47% by 2039 under the RCP8.5 scenario (Table 3.11). At the most distant horizons of both scenarios, potential R_e is projected to decrease 67.69% (RCP4.5) and 86.56% (RCP8.5), indicating that there would be groundwater availability problems in the future.

Table 3. 11 Water balance for RCP4.5 and RCP8.5 CC scenarios

RCP4.5 CC Scenario					
Water Balance	**2039**	**2045**	**2069**	**2075**	**2099**
Mean Annual P (mm/year)	751.34	754.87	754.87	712.73	712.73
ET (mm/year)	472.67	484.09	484.09	468.13	468.13
R_u (mm/year)	230.61	231.88	232.63	219.82	220.53
Potential R_e (mm/year)	48.06	38.90	38.15	24.78	24.07
RCP8.5 CC Scenario					
Water Balance	**2039**	**2045**	**2069**	**2075**	**2099**
Mean Annual P (mm/year)	724.73	707.72	707.72	709.27	709.27
ET (mm/year)	460.92	467.02	467.02	479.8	479.8
R_u (mm/year)	222.44	217.40	218.10	218.76	219.46
Potential R_e (mm/year)	41.37	23.30	22.60	10.71	10.01

3.4. Sensitivity Analysis

Sensitivity indices represent the sensitivities of RU, ET, and Re values to changes in P, T_{mean}, and changes in urban, agricultural land, grassland, and forestland proportions. Probability distribution of the input factors have to be chosen (Table 3.12), and the correlation among the parameters have to be calculated (Table 3.13). A total of 10,000 random values were generated to determine the implications of the LULC assuming significant changes of the values which varied from 0 to 3910.38 km^2 with uniform distributions and the changes in Rainfall and Temperature with a triangular distribution.

Table 3. 12 Probability distribution and range of values

Input Factors	**Probability Distribution**	**Range**	**Most Probable Number (MPN)**
Rainfall	Triangular	[200, 1300 mm/year]	568
Temperature	Triangular	[5, 35 °C]	15
Urban	Uniform	[0, 3910.38 km^2]	600
Agriculture	Uniform	[0, 3910.38 km^2]	490
Grassland	Uniform	[0, 3910.38 km^2]	1792
Forest	Uniform	[0, 3910.38 km^2]	3724

Table 3. 13 Correlation matrix for the input parameters

	Rainfall	T_{mean}	Urban	Agriculture	Grassland	Forest
Rainfall	1	−0.0395	0.119	−0.101	−0.074	0.020
T_{mean}		1	0.201	−0.114	−0.138	0.132
Urban			1	−0.709	−0.860	0.879
Agriculture				1	0.394	−0.707
Grassland					1	−0.819
Forest						1

The sensitivity index of Ru is positive (direct) for P, urban, and agriculture, which indicates that increases in these variables leads to increases in Ru. In contrast, the sensitivity index of R_e is negative (inverse) with respect to T_{mean}, urban, and agricultural areas. (Table 3.14 and Figure 3.8).

P is the most sensitive output variable to input factors with its indices significantly larger than +0.5 and reaching the highest value of 0.98 and 0.92 for R_u and ET. T_{mean} is sensitive to ET with and index of 0.798 and for Re with and index of −0.864, representing an inverse relationship. Urban, agriculture, grassland, and forest are significant in the increase and decrease of R_u with and index higher than 0.5. T_{mean}, Urban, Forest areas seem to cause significant changes in R_e with indices of −0.86, −0.52, 0.457, but they show an inverse relationship (T_{mean}, urban), indicating that increases in these inputs could reduce R_e.

Table 3. 14 Partial rank correlation coefficient and ranks for the input factors

	Sensitivity Indices					
	R_u		ET		R_e	
Input factors	PRCC	Rank	PRCC	Rank	PRCC	Rank
P	0.986	1	0.920	1	0.784	2
T_{mean}	−0.010	6	0.789	2	−0.868	1
Urban	0.761	2	0.011	3	−0.523	3
Agriculture	0.614	5	0.007	5	−0.367	6
Grassland	−0.644	4	0.017	4	0.410	5
Forest	−0.678	3	0.005	6	0.457	4

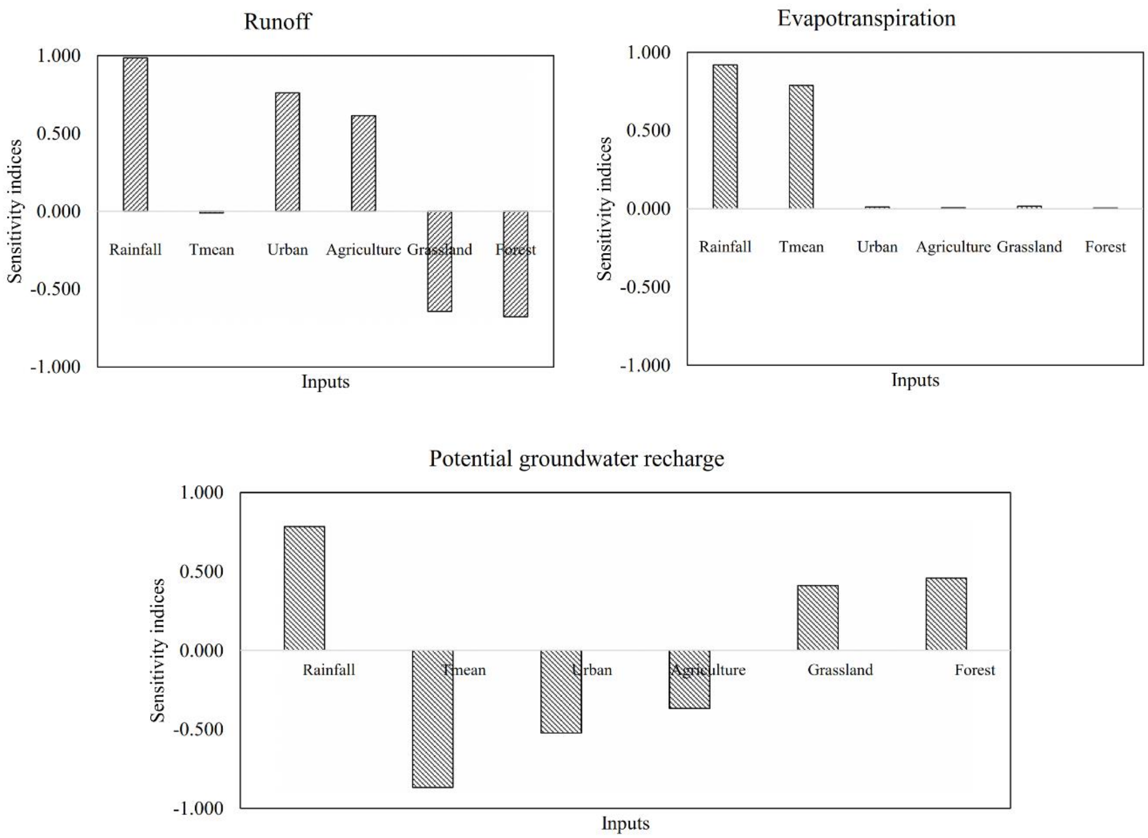

Figure 3. 8 Sensitivity indices for water balance variables in the study area

If sensitivity analysis is conducted with the empirical values measured at the five meteorological stations, a total of 139 inputs are generated. The model based on empirical data is not sensitive to changing forest area because it has not changed much in the study area. The analysis will evaluate only the empirical contribution of forestland to the region's runoff. It will not evaluate extreme reductions of any of the LULC categories. Forest area represented 48.2% of the total area and accounts for 21.04% of the total runoff (in 2018). The area of change in forest area has been very small—a STD of 24.18 km^2 and average coverage of 1895 km^2. This forest dynamic is probably due to conservation efforts in the region, the ejido and communal land ownership regimes, the indigenous tenants, and decreased farming and less cultivation. In Oaxaca, this is evident by a resurgence of forests [43,44]. Similar results to Minnig et al. [45] can be found, indicating that urban increases and forest decrease can decrease ET and increases the likelihood of R_e, but these results are not significant with PRCC values of −0.122 and 0.002, respectively.

Accuracy in input factors is important in estimation of R_u, R_e, and ET, but the results of the MC sensitivity analysis reveal that accuracy of measurements particularly with P, T, and urban and forest areas is critical. Indicating the CC and human impacts in the area will affect the area in the future.

3.5. The Impacts of Population Growth on Groundwater

Population growth has contributed to raising rates of groundwater extraction by increasing consumption for different uses. CC is projected to decrease R_e due to climate change [22]. The region's population growth rate has been 2.32% annually. The population nearly doubled between 1984 and 2010, from 603,009 to 1,033,884 (Table 3.15). This growth increased consumption by 50.39 Mm^3 (from 47.54 Mm^3 in 1984 to 97.93 Mm^3 in 2018 (average water consumption rate of 216 LPD), which is nearly a two-fold growth (94.33%) over 34 years. This trend, if it continued unabated, is not sustainable.

Table 3. 15 Water consumption in the Alto Atoyac sub-basin

Year	Population	Water Consumption 48 LPD (Mm^3)	Water Consumption 216 LPD (Mm^3)	Water Consumption 384 LPD (Mm^3)
1984	603,009	10.56	47.54	84.52
1986	649,293	11.38	51.19	91.00
1990	718,942	12.60	56.68	100.77
1994	773,122	13.55	60.95	108.36
2001	877,946	15.38	69.22	123.05
2003	910,426	15.95	71.78	127.61
2007	979,037	17.15	77.19	137.22
2009	1,015,257	17.79	80.04	142.30
2010	1,033,884	18.11	81.51	144.91
2018	1,242,099	21.76	97.93	174.09
2039	2,010,607	35.23	158.52	281.81
2045	2,307,227	40.42	181.90	323.38
2069	4,000,766	70.09	315.42	560.75
2075	4,590,990	80.43	361.95	643.47
2099	7,960,844	139.47	627.63	1115.79

LPD: Liters per person per day, Mm^3: Millions of cubic meters.

The connection between water consumption and urbanization is apparent when one plots water consumption rates against the changing areal extent of urban LULCs (Figure 3.9). The direct linear relationship demonstrates the greater pressure that per unit area urban LULCs and the systems of cities put on water resources.

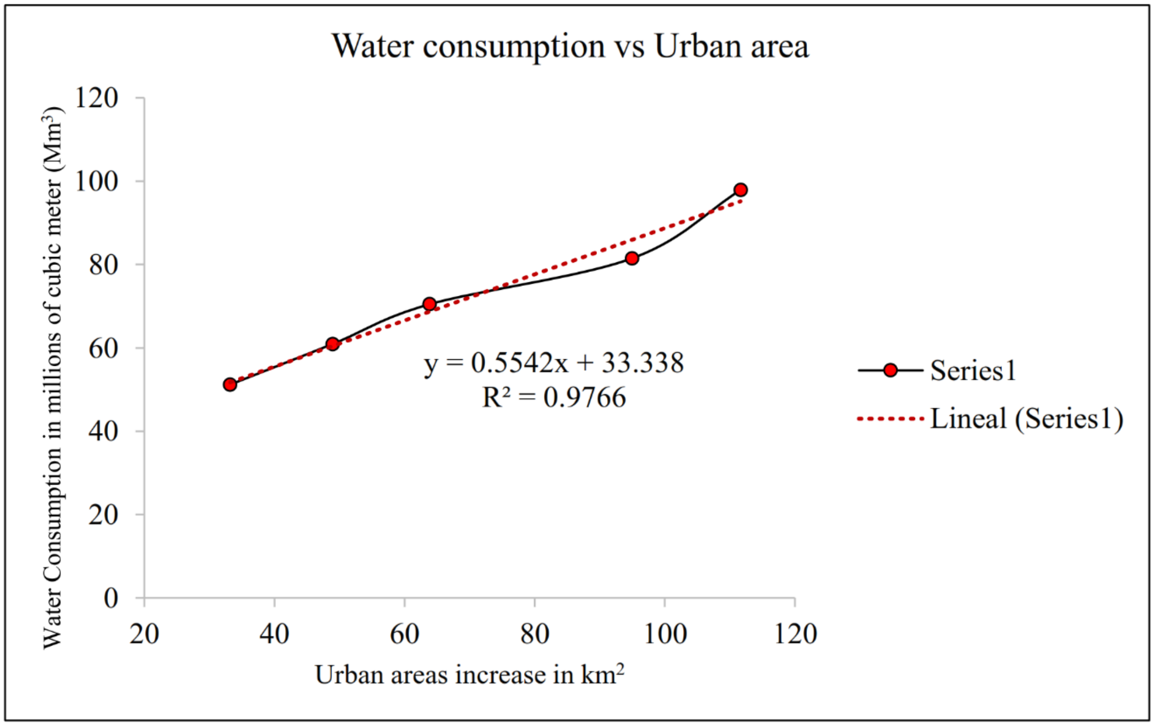

Figure 3. 9 Relationship between urban growth and water consumption (Mm³)

3.6. Groundwater Volume Storage Change

A water table evaluation allows us to examine the evolution of groundwater extraction rates through the period of record (Table 3.16). Groundwater extraction is closely related to the intrinsic and extrinsic conditions of the sub-basin, the anthropogenic effects on weather conditions, the increasing area of impervious surfaces, agriculture water demand, and population growth. Together, they can accelerate the rate of groundwater extraction.

Table 3. 16 Extracted volume in different periods (volume storage change)

Period	Volume Storage Change in the Period (m^3)	Annual Average Change (m^3)	Annual Average Human Consumption (m^3)	Agriculture/other Uses (m^3)	Annual Average Recharge (m^3)
1984–2001	1964×10^6	115.53×10^6	$47.54–69.22 \times 10^6$	57.15×10^6	$138.910–158.77 \times 10^6$
2001–2003	695.1×10^6	347.5×10^6	$69.22–71.78 \times 10^6$	277×10^6	$158.77–160.491 \times 10^6$
2003–2007	1370×10^6	342.5×10^6	$71.78–77.19 \times 10^6$	325.95×10^6	$160.491–170.89 \times 10^6$
2007–2009	663.6×10^6	331.8×10^6	$77.19–80.04 \times 10^6$	253.185×10^6	$170.89–171.75 \times 10^6$

Our analysis of the spatial and temporal nature of the water table in the Alto Atoyac sub-basin from 1984 to 2009 reveals growing groundwater depletion, especially in zones of agricultural activities. The areas of the aquifer with the most decline are the areas that have the greatest need for water conservation efforts. Comparing the mapped 1984 water table to the water table of 2009 reveals the areas with substantial groundwater depletion (Figures 3.6 and 3.7). Abatements of up to 20 m have developed over only 25 years over an area of 1130 km^2. Roughly 4692.7 × 10^6 m^3 of groundwater were extracted from the aquifer during the study period. This amounts to an annual extraction rate of 284.34 × 10^6 m^3, 115 × 10^6 m^3 more than the average annual recharge. This extraction distributed over the aquifer area (1130 km^2) represents an annual decline of 0.1 m per year of the water table.

4. DISCUSSION

P and T are two important aspects of the water cycle that dictate the condition of water resources. They link local environmental conditions and changing climate to regional water resources. Changes in P and T patterns will affect the distribution of water over space and time [46]. Many studies have projected increased water demand due to CC, increasing water scarcity in many regions over the next several decades, and enhancing the intensities of extreme events (like droughts and floods) in the water cycle. Weather extremes are expected to increase every year [46–50]. Even without a clear linear relationship between T and P in the climate models, increasing T is believed to promote P [51–54]. However, there is a significant amount of uncertainty in these relationships.

Increasing P extremes and increasing T can be related to the absence of a moisture-limitation in the Clausius—Clapeyron relationship [54,55], which calculates the water-holding capacity of the atmosphere. In the study area, since 1984, the variation of T and the frequency of extreme P events in the study region have both increased. These changes directly influence the water cycle and the water balance. Increasing T augments ET, so increases of mean annual T from 2 °C to 4.95 °C can be extremely impactful on groundwater resources by reducing the rate of recharge. Even if P increases, flooding can overwhelm a soil's infiltration capacity.

Since 2013, it has been evident that the effects of LULC change should be incorporated into climate-change studies [56]. The water in a basin is controlled by climatic factors and features of the basin (LULC and soil type, hydrogeological conditions). To quantify the combined effects of LULC and CC on water resources is a challenge because LULC affects water availability by altering hydrological processes through modifications of ET, soil moisture dynamics [57,58], and R_u.

The impervious surfaces of urban land use can cause land degradation and increase R_u [57,59] in a region, even if the R_u is primarily dictated by agricultural land (which represents 38.28% of the study area). Because water demand for crops is usually high, the increase of urban cover is a challenge for water resource management. As both water consumption and R_u rates are increasing, augmenting water demand intensifies pressure on the resource. Urban areas represent a small percentage of the total area but are still a major influence and determine supply by increasing R_u in the sub-basin. R_u has increased 1.69 mm from 1986 to 2018. From 1984 to 2002, agriculture land area increased, but from 2002 to 2010, the total farmland area decreased. Farms were converted to urban use. The same process occurred throughout Mexico during this period due to socio-political conditions that caused abandonment of farms between 2000–2006. Many farmers migrated northward and into cities (to cities in Mexico and the United States) for better economic opportunities.

The increase of impervious surfaces (urban areas) doesn't allow soil infiltration of P or R_u. Streets, channels, and drainages funnel storm water into waterways, and leads to a decrease in infiltration and an increase of runoff [60]. Urban environments significantly alter the recharge [61]. The effect of urbanization on water recharge is complex and the impact will depend on the features of the area, construction density, infrastructure to manage storm water, sewage systems, and water supply infrastructure [62]. However, the effect of urban growth can be mitigated by reducing evapotranspiration rates, and other, maybe new, matters may consequentially enhance recharge in some urban environments, such as leaks from sewage and water distribution systems and directing runoff into recharge infrastructure [45,63]. Unfortunately, urban growth is usually caused by population growth, which increases groundwater abstraction to meet the increasing water demand, and this can lead to increasing groundwater depletion. Another problem is that decreasing ET reduces consumption of latent heat. Therefore, more energy is available as sensible heat, which results in higher land surface temperatures [64], which can decrease precipitation, and increase the length of the dry season [65–68]. In the long term, increased urban land use can diminish the size of the recharge area, increase potential evaporation rates, and increase the length of the dry season.

Water balance is sensitive to the changes in climatological data and basin conditions, which is, in this case, changing LULC. Increasing urban and agricultural LULC accelerates the rate at which R_u is rising. Because the percentage of the region that has urbanized is small compared to the other LULC categories, the R_u contribution of urban areas is small. T_{mean}, urban, and agricultural covers are inversely related to R_e, indicating that increases of this factors could lead to reductions in R_e in the study area. Considering that ET is one of the parameters with a higher weighting in the water balance and LULC changes, it also induce changes in ET rates. For every LULC category, changes are inversely related to ET: increasing urban areas can decrease ET and decreasing forestland also decreases ET, as mentioned above. Less ET means more R_u and increases the likelihood of Re [46]. ET was not calculated for forest, urban, and grassland land uses and was not included in the analysis. This a limitation of the method because it is a limited consideration of the impacts of the other three LULCs. This underestimates the real effect of LULC on ET in the study. This could be the basis for future research that more closely examines the relationships between LULCs and ET in the study area.

Sensitivity analysis with the empirical values measured at the five meteorological stations (139 inputs) is not sensitive to changing forest area because it has not changed much in the study area, and results will indicate that increases in forest will produce increases in runoff. Nevertheless, ET sensitivity analysis indicate that increase in urban areas and decrease in forestland can promote R_e (PRCC values of −0.1222 and 0.002 for urban and forestland), but these values are not significant. Similar values are found in Minnig, et al. [45] and it can most likely explain the R_e trend from 1986 to 2013, which increases by 72.29 mm/year.

4.1 Changing Water Tables and Depleting Aquifers

Since 1984, depletion cones have become apparent throughout the sub-basin. Over the last 25 years, the Tlacolula Valley's water table has fallen 38 m. In the Etla Valley, the aquifer has fallen between 29 m and 44 m. In the Zaachila Valley, the depletion is 25 m. There is constant pressure upon the groundwater, which is evident by what the annual extraction volume has done to the hydraulic head. The extracted volume in 1984 was 115.53×10^6 m^3 and in 2009 it was 331.8×10^6 m^3. By 2009, the extraction rate surpassed the annual R_e rate of 169×10^6 m^3 [22]. Over the same period, consumption nearly doubled from 47.54×10^6 m^3 in 1984 to 80.04×10^6 m^3 in 2009 (a calculation based on an average water demand of 216 LPD). This depletion is due to CC, intensified T, urbanization, and the increasing extent of impervious surfaces. Consumers of water in the study area are extracting more water from the aquifer than is available to R_e due to increasing R_u and higher ET.

There is relationship between urbanization and water consumption since the latter is tied to population growth. The negative effects of population on water resources are numerous [10], as the water input into the aquifer has diminished and the water demand for different uses increases. If continued, a 2.3% annual population growth rate will cause great pressure on water resources over the coming decades; this is borne out by the projections examined here. One potential solution that can be inferred from the projections is to reduce water consumption to a per-person average of less than 50 LPD.

Water is a particularly vital resource in this region. It is the engine of the economy in both urban and rural areas which are based on small business, tourism, agriculture, forestry, and ecotourism. In the last decade, insufficient water supplies have become notorious, but research on this problem has been very limited. It can be said that economic activities and population growth have increased environmental problems by the overexploitation of groundwater over the last 25 years. Some scholars have indicated that groundwater exploitation has yielded economic growth around the world over the last five decades, but it has also yielded significant social and environmental costs [69,70]. One future consequence that may arise in the area due to overexploitation of groundwater is subsidence of land surfaces; this is already happening in some regions of Mexico due to overexploitation of aquifers [71–73].

5. CONCLUSIONS

Over the 34-year period of analysis, water recharge in the study area has been driven primarily by climatological conditions in the sub-basin, especially the variations in rainfall and temperature, which are the main variables of the water balance calculation. There has been little change in the proportions of LULC categories; only urban area has increased significantly due to population growth over the last three decades. Runoff from urban areas increased, but the change was relatively small, from 1.45% in 1986 to 4.84% 2018. Thus, although urban areas increased in size and runoff amount, the largest contribution still comes from agricultural areas. Agricultural land use comprises 31% of the total sub-basin. Together, the impacts of agriculture and urban land use demonstrate the direct impact of human activities on groundwater resources in the Central Valleys of Oaxaca: population growth leads to increasing abstraction of continuously shrinking supplies of groundwater.

Groundwater is a high-risk resource due to fluctuating R_e rates and human activities. High levels of exploitation put all users into precarious positions, and this is demonstrated by the projections of future groundwater supplies and trends in groundwater extraction. The main threats in the Alto Atoyac sub-basin are CC, LULC change, and population growth.

Climate data indicate that despite increases in annual P, rising average annual T and increasing ET rates will produce diminishing R_e of groundwater resources for the future. According to the RCP4.5 climate-change scenario, mean annual T is projected to increase over the near, middle, and distant future by 1.46 °C, 2.49 °C, and 3.02 °C, respectively. This is likely to intensify ET rates by 1.86%, 3.49%, and 5.56%, respectively. The increases of 1.49 °C, 3.21 °C, and 4.95 °C projected by the RCP8.5 model will yield increases of 2.78%, 5.97%, and 8.18% in ET rates.

LULC change and shifting patterns of T are the main influencers of the water R_e changes. Increasing T and urbanization enhance both ET and R_u and allow for less potential R_e of aquifers. From 1986 to 2018, mean annual T increased 1.76 °C and the urban LULC increased 2.3 km^2/year. Projections under the RCP4.5 and RCP8.5 scenarios show that the R_e rate will diminish to the first horizon by 35.48% and 44.47 %, respectively. At the most distant horizons of both scenarios, potential R_e is projected to decrease 67.69% (RCP4.5) and 86.56% (RCP8.5), indicating that there will be groundwater availability problems in the future.

As urban areas increase, population will increase and so will the demand for fresh water. There will be a negative consequence on groundwater because of the concomitant increased R_u and magnified extraction of groundwater to meet basic needs. From 1986 to 2018, R_u increased at a rate of 0.24 mm/year in urban areas. The R_u in the urban portions of the study area, which are only 2.86% of the total area, increased by 236% (from 1986 to 2018). Water demand grew from 47.54×10^6 m^3 to 97.93×10^6 m^3 for the same period, which clearly demonstrates the implications of urbanization and population growth for water supplies.

Water balance is sensitive to climate variation, indicating the effects that CC can have in the study area. Physical changes consequential to LULC change have significant effects on the water balance, too. Increases of urban and agricultural areas can generate inverse changes of R_e, and they can generate negative consequences in the future. Agricultural areas are expected to shrink in the area due to farm abandonment and urban expansion into rural areas.

Groundwater volumes are being depleted at a rate of 284.34×10^6 m^3/year, a deficit of 115.34×10^6 m^3/year (a reduction in the groundwater levels of 0.1 m/year). This is consistent with the increased water demand of the last few years and with reduced R_e stemming from changing LULC and increasing T.

Some ways to confront these challenges could be to strategically protect R_e zones from urbanization, to undertake small-scale engineering projects that enhance R_e rates in areas prone to R_u, and to reduce water consumption rates throughout the basin to below 50 LPD to ease the pressure upon the region's groundwater resources.

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Chapter 4: A hierarchical model for assessing groundwater vulnerability in agricultural areas in the Central Valleys of Oaxaca, Mexico

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A hierarchical model for assessing groundwater vulnerability in agricultural areas of the Central Valleys of Oaxaca, Mexico

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ABSTRACT

Groundwater vulnerability was modeled for the Central Valleys of the state of Oaxaca, Mexico, a region known for its intensive agricultural activities and poor water policies. The analysis was conducted to create and evaluate scenarios reflecting anthropogenic and intrinsic stressors on groundwater using an analytical hierarchy process (AHP) and a geographic information system. Uncertainty in the vulnerability model was measured with a Monte Carlo analysis. The indices for the study were selected according to the effects of population growth, climatology, hydrogeological features, and social marginalization in access to groundwater resources. Five indicators were determined: abstraction (Abs), pollution (Po), runoff (Ru), groundwater recharge (Re) and marginalization (Ma). Abstraction, pollution, and recharge rates are the main drivers of groundwater vulnerability, accounting for 86% of the vulnerability. The analysis revealed that the model was low in uncertainty and that more than 50% of the region has a high vulnerability, indicating the high pressure on groundwater resource in the Central Valleys due mainly to abstraction and pollution. The approach and the indicators establish a baseline for the management and preservation of water resources in the region.

Keywords: groundwater management, water scarcity, water indicators, analytical hierarchy process.

Highlights

•A simple approach considers abstraction, water recharge, runoff, pollution, and marginalization as indicators of groundwater vulnerability.
•A groundwater vulnerability index is developed to evaluate water resource in areas with limited and scarce information
•The Central Valleys of Oaxaca is facing serious quantity and pollution problems.
•Water policies should implement regulation that permits reductions in groundwater abstraction and conservation of water recharge zones.
•Population growth and poverty have been the main factor of vulnerability increase in the Central Valleys of Oaxaca.

1 INTRODUCTION

Water scarcity is spreading throughout the world, beyond the regions that have perennially experienced water shortages. Climate change (CC) has intensified the problem, and the number of studies that evaluate the complications of CC on top of other stressors for water vulnerability in specific regions have significantly increased (Hoque et al., 2016; Mo et al., 2017; Yang et al., 2012; Zou et al., 2017).

The main contemporary stressors for water resources are deforestation, overgrazing, agriculture, urbanization, agrochemical pollution, air pollution, aquifer overexploitation, and industrialization. Irrigated agriculture and industry are the activities that demand the greatest water; representing about 70% and 23%, respectively, of global water use. Households, by comparison, consume only about 8% (Falkenmark and Widstrand, 1992). Urbanization, industrialization, low levels of awareness, and failures to recognize the vital importance of water have led to 80% of Earth's population to experience some degree of water crisis (Jayaswal et al., 2018). Furthermore, urban development is closely tied to increasing contamination of water bodies and the discharging of untreated and poorly treated sewage effluent into waterways (Noorhosseini et al., 2017; Sartor et al., 1974).

Vulnerability is the degree to which a system becomes susceptible to, or unable to cope with, effects of change (McCarthy et al., 2001). Water resource vulnerability is the ease with which a groundwater system can be damaged by natural processes and human activities (Wang et al., 2012). The task of estimating vulnerability has yielded numerous methodologies that account for a number of variables like climate change, economics, the characteristics of infrastructure, educational levels, agricultural intensity, land use change, and population growth (Jun et al., 2011; Wang et al., 2012; Yoo et al., 2011).

Such methodologies must be allow the incorporation of quantitative and qualitative indicators. The analytical hierarchy process (AHP) has been used to evaluate water resources in the USA, Bolivia, India, China (Calizaya et al., 2010; Li and Sun, 2017; Willett and Sharda, 1991; Zyoud et al., 2016). The AHP is a general theory of measurement used to derive ratio scales from both discrete and continuous paired comparisons (Saaty, 1987). To employ this method, a problem must be well defined and structured. A pairwise matrix is constructed to determine the priority of each parameter and consistency must be calculated (Calizaya et al., 2010; Saaty, 1980, 2008).

More than 100 aquifers in Mexico are over-extracted and threatened by pollution from urban and agricultural expansion (CNA, 2017). Very little information is available upon which an assessment model can be developed to evaluate the water vulnerability for the areas in which such analysis is needed. The aim of this study is to develop a method and a model to assess groundwater vulnerability in a region of intensive agricultural activities: the Central Valleys of Oaxaca, Mexico.

1.1 Study area

The study area is delineated by a polygon bounded by 16°30' and 17°25'N and 96°15' and 97°00'W. This area is the Alto Atoyac sub-basin in Oaxaca. It comprises the Valleys of Etla, Tlacolula, and Zaachila, the so-called Central Valleys (Figure 4.1). Its borders are with the Mixteca region to the west, the Cañada region to the northeast, the Sierra de Juarez to the north, and the Tehuantepec Isthmus region to the east, and the Sierra Madre del Sur to the south. The sub-basin has a surface of 3,744.64 km2 and an approximate extraction surface of 1,130 km2 (Ojeda-Olivares et al., 2018). In the Central Valleys region, 87.6% of groundwater is used for agriculture. Public-urban services use only 9.5% (Ojeda-Olivares et al., 2018). There are 115 municipalities in the sub-basin. The 396 km long Atoyac River is the main river course in the region. Municipal sewage is discharged into the Atoyac River, affecting water quality (Belmonte-Jiménez et al., 2001).

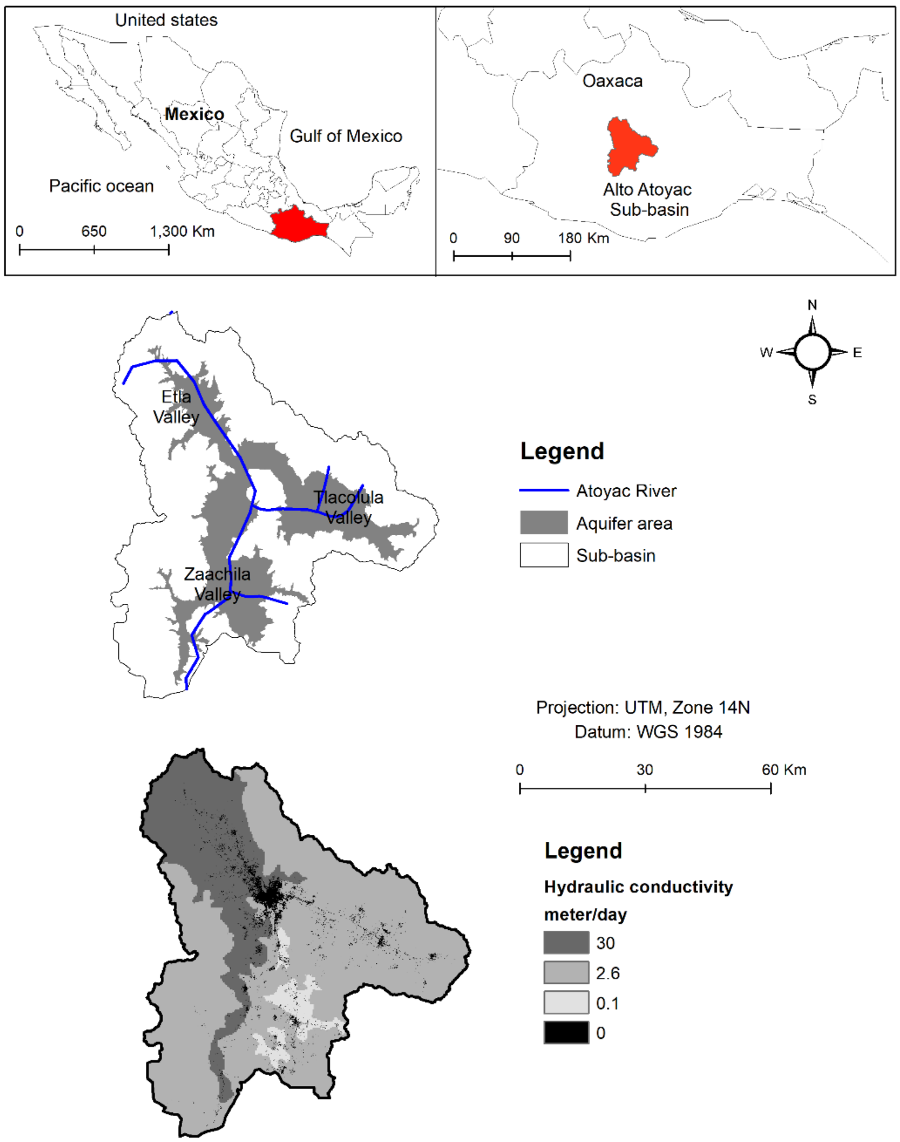

Figure 4. 1 Location of the Atoyac sub-basin

The study area contains an unconfined aquifer constituted by alluvium that includes a heterogeneous mixture of unconsolidated sediments, with a thickness between 15 and 100 m (the saturated thickness), thinning toward its edges. The basement comprises metamorphic and igneous rocks. Metamorphic rocks and, extrusive and intrusive volcanic rocks constitute the impermeable limits of the sub-basin

(Ojeda-Olivares et al., 2018), (see figure 4.2). A more detailed description of the study area geology can be found elsewhere (i.e., Campos-Enríquez et al., 2010, 2013).

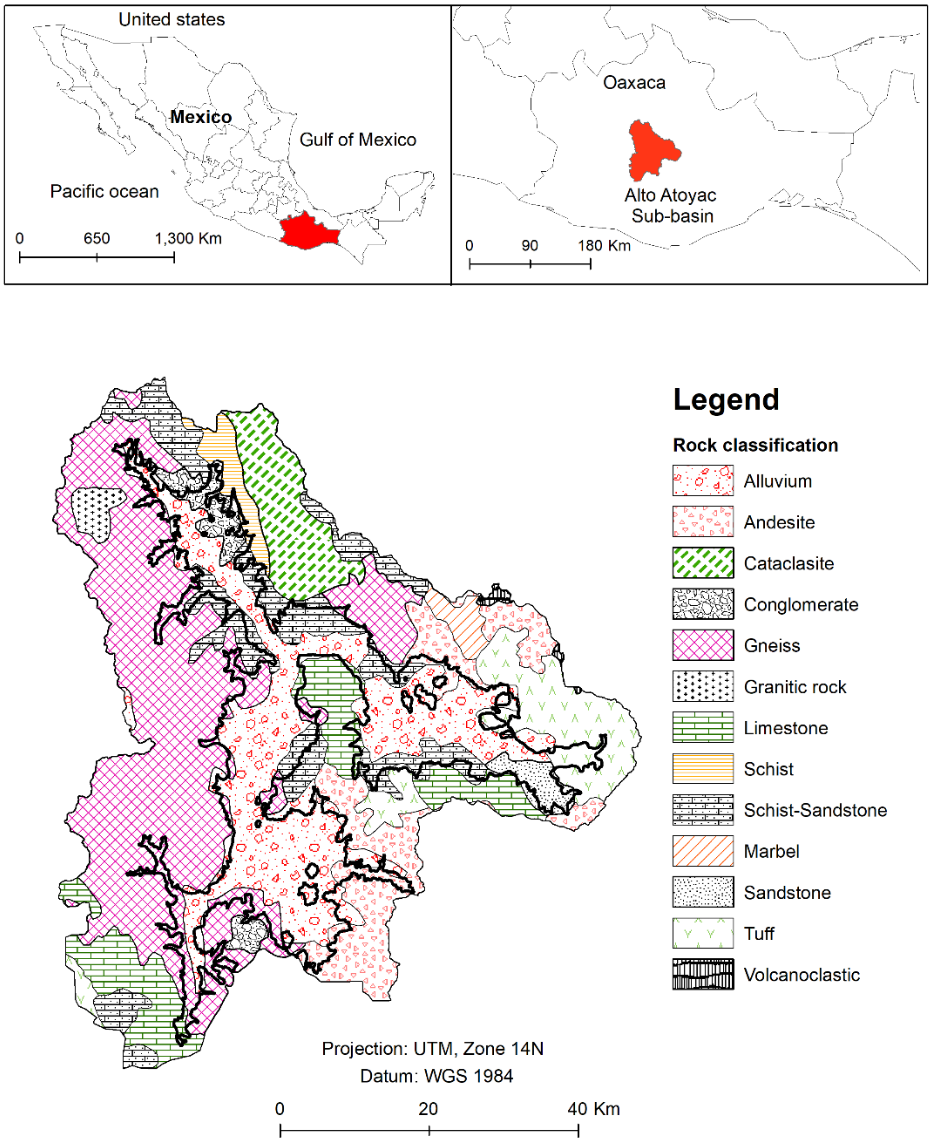

Figure 4. 2 Geology of the Atoyac sub-basin

2 MATERIALS AND METHODS

2.1 Establishing groundwater vulnerability approach

To assess the groundwater vulnerability, the main water stressors must be considered. The indices were selected according to three large water stressors and the water balance variables, growing population, land change use, and CC (Jayaswal et al., 2018; Vörösmarty et al., 2000, 2010; Watson et al., 2013). Considering the impacts that population growth, climatological conditions, and marginalization have on groundwater according to its hydrogeological features (Figure 4.3), five indices were selected: abstraction (Abs), pollution (Po), recharge (Re), runoff (Ru), and marginalization (Ma).

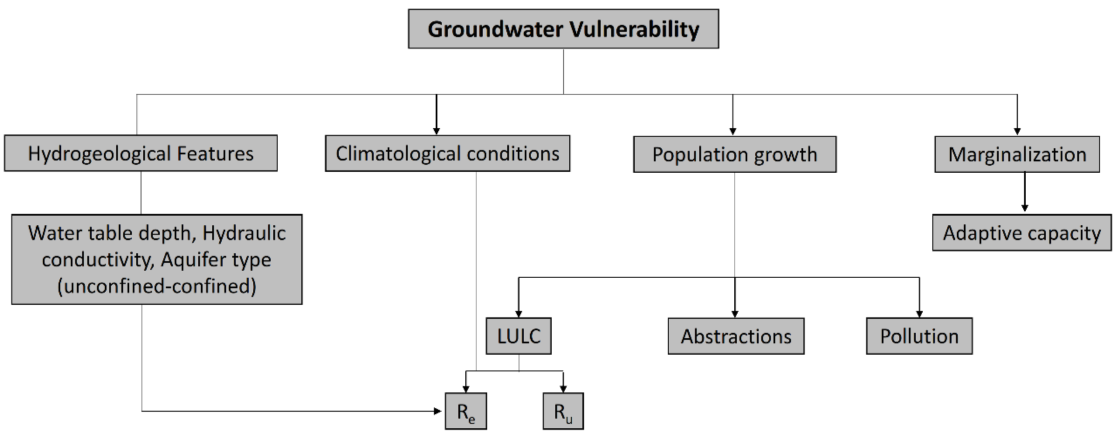

Figure 4. 3 Linkages between the groundwater vulnerability indices.

To determine the effects of the variables in the groundwater vulnerability a simple linear relationship is established:

$$GwV = w_1 * A_{abs} + w_2 * P_o + w_3 * R_e + w_4 * R_u + w_5 * M_a \quad (1)$$

where w_1, w_2,.., w_n, represent the weight or importance level of every variable. The weights can change according to the specific conditions of a study area. Five logical limititing conditions (upper and lower) were analyzed to evaluate vulnerability (Table 4.1).

Table 4. 1 Conditions to evaluate the groundwater vulnerability

Conditions supposed	Vulnerability scale
High groundwater extraction	More vulnerable
Low water recharge	More vulnerable
High levels of contamination	More vulnerable
High runoff	More vulnerable
High levels of marginalization	More vulnerable
Low groundwater extraction	Less vulnerable
High water recharge	Less vulnerable

Low levels of contamination	Less vulnerable
Less runoff	Less vulnerable
Low levels of marginalization	Less vulnerable

To compare variables, their units must be similar. In the cases of groundwater abstraction, recharge, and runoff, they can be compared, but pollution and marginalization cannot. To make the variables comparable, they must be normalized, and a scale must be determined. In this case, we assigned 0 for systems that are not vulnerable (i.e., there have been no changes caused by people or anthropogenic factors) and 1 for systems that are very vulnerability. These indicate when exploitation and pollution are unsustainable, surpassing the level of recharge.

2.2 Normalization and assumptions of indices

2.2.1 Abstraction index (Abs)

Overexploitation of groundwater is a big concern around the world due to LULC change (urbanization, urban growth, conversion of land to agriculture, etc.), increased water consumption, and large-scale food production, for instance. These changes can deplete water stores, reduce discharge rates, cause land to subside, and even impair groundwater quality (Postigo et al., 2018).

This index evaluates the degree of groundwater extraction, taking how reference the annual Re. For a system to be in equilibrium, the inputs have to be equal to the outputs. If there is human intervention, the environment always will be at risk or will be vulnerable. If we consider a system without human intervention (no groundwater abstraction) to be equal to 0 or invulnerable, and a system in which groundwater abstraction rates exceed recharge rates has a value of 1, highly vulnerable, then systems with moderate conditions would fall somewhere in between (Table 4.2).

Table 4. 2 Normalization assumption for the abstraction index

No abstraction	*Abs* < *or* = R_e	Abs > R_e
0	0 > R_e > 1	1

2.2.2 Pollution index (Po)

Population growth has fomented groundwater pollution over the last half-century by causing intensive and extensive exploitation for human consumption and economic activities and by changing LULC. It has been said that groundwater contamination has increased due to anthropogenic activities, and is directly related to land use (Postigo et al., 2018).

Pollutants are measured according to the concentration levels at which they are found in groundwater, and if they surpass permissible levels, they are very likely to produce negative health effects and environmental impacts. In this study, nitrate concentration is used as the indicator of groundwater contamination in agricultural areas. This indicator can be changed according to the context of the area to be evaluated. The Water Regulatory Norm for Human Consumption (SSA, 1994) is the maximum permissible concentration of nitrate in water. It is 10 mg per liter. Therefore, concentrations above this level are likely to cause significant health and environmental consequences and can indicate high vulnerability. The proposed scale for Po sets a value of 0 for no anthropogenic pollution and 1 for concentrations above the permissible limit (Table 4.3).

Table 4. 3 Normalization assumption for the pollution concentration index

Po = 0	0 < *Po* = Permissible limit	*Po* > Permissible limit
0	0 > *Po* > 1	1

2.2.3 Water recharge index (Re)

Water recharge depends on the conditions of the study area, soil type, hydraulic conductivity in recharge areas, infrastructure and LULC, and weather patterns. CC plays an important role in the trajectory of *Re* rates because links with other stressors can reduce the volumes of water in the system. With historical climate data, LULC, and soil conditions the values of annual *Re* can be calculated. Using the historical values of *Re* and including the effects of CC on groundwater, a *Re* index can be determined:

$$Rei = 1 - \frac{Re_{CCh}}{Re_H} \quad (2)$$

where Re_i represents the normalized index, Re_{CCh} water recharge as projected by a General Circulation Model (GCM) under a climate change scenario, Re_H, represents the historical water recharge data.

2.2.4 Runoff index (Ru)

As with recharge, runoff depends on LULC conditions, soil type, and precipitation rates, the latter can vary unpredictably due to CC. The historical values of *Ru* are calculated with the historical normal of precipitation and these values can be compared to various CC scenarios in order to predict the long-term effects of global warming. Present and future values can be determined with:

$$Rui = 1 - \frac{Ru_{CCh}}{Ru_H} \quad (3)$$

where Re_i represents the normalized index, R_{eCCh} water recharge as projected by a general circulation model (GCM) under a CC scenario, R_{eH}, represents the historical water recharge data.

2.2.5 The social marginalization index

Marginalization and water-access vulnerability are driven by three factors: (1) water management and water infrastructure, (2) environmental and human impacts, and (3) the consequences of CC (Ruettinger, 2012). Marginalized zones have limited access to financial and technical capacities to develop CC resilience. So highly marginalized areas have low capacities to adapt to natural hazards like floods and droughts and the effects of CC.

In many areas, the marginalization index can be constructed by accounting for the socioeconomics and living conditions of the population. In Mexico, the social marginalization index (CONAPO, 2012) factors in nine municipal socio-economic measures: literacy rates, rates of completion of primary education, sanitary drainage services, residential access to electricity, access to a water system, population concentration or overcrowding, percentage of homes with dirt-floors, size of municipality, and income levels. The index is an economic indicator showing the degree of marginalization of a community. It is normalized to values between 0 and 1.
The *Ma* index is normalized as follows:

$$Ma = \frac{X_i - X_{i_{min}}}{X_{i_{max}} - X_{i_{min}}} \quad (4)$$

where *Ma* is the normalized index, Xi_{min} the lowest value of the series, Xi_{max} the maximum value of the series, and *Xi* the value to be normalized.

2.3 Analytical hierarchy process (AHP)

The analytic hierarchy process (AHP), developed by Saaty (Saaty, 1980, 1994, 2008), is a mathematical calculation based on pairwise comparisons. The comparisons are made using a scale of absolute judgments that represent the degree of dominance of one element over another in a specific attribute. This methodology has been used in water resource studies (Calizaya et al., 2010; Li and Sun, 2017; Willett and Sharda, 1991; Zyoud et al., 2016). To conduct an AHP analysis, it is necessary first to establish and understand the relationship between the selected indexes and then to develop a comparison matrix to determine the hierarchy levels. The weight of each index is obtained by normalizing the comparison matrix.

Consistency among the elements within the matrix is required. Saaty (1980) proposes to calculate a consistency ratio (CR) to measure the consistency of the entire matrix. For the calculation of CR, the consistency index (CI), random index (RI) and the eigenvalues (λ) must be estimated. The CI is a statistical measure to determine the degree of consistency among the weights of the analyzed indexes. Then we can write:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

where n represents the number of parameters and λmax is the maximum value of the eigenvalues.

Once the CI determined, the CR can be calculated using the eigenvalue (Alonso and Lamata, 2006; Saaty, 1980):

$$CR = \frac{CI}{RI} \qquad (6)$$

where RI is a function of the number of parameters analyzed.

2.4 Vulnerability scale

A water-vulnerability scale was established to evaluate the effects of the indices on the groundwater resource and was divided into four categories (Table 4.4). The vulnerability scale ranges from 0 to 1; 1 represents extreme vulnerability.

Table 4. 4 Vulnerability scale proposed

Classification	Range	Observations
No Vulnerability	0	There are no impacts caused by the human or anthropogenic factors.
Low Vulnerability	$0<WV<0.33$	Problems of water availability and pollution are of not a big concern.
Medium Vulnerability	$0.33<WV<0.67$	There are problems of water availability and pollution in some areas.
High Vulnerability	$0.67<WV\leq1$	The levels of exploitation and pollution are high, surpassing the water's capacity to recover.

WV - groundwater vulnerability.

2.5 Water Resource Vulnerability in the Central Valleys of Oaxaca

2.5.1 Abstractions, Ru, and Re levels

In the Central Valleys of Oaxaca, contamination and groundwater extraction are the primary stressors due to population growth, LULC, and the effects of CC. Due to population growth over the last 30 years, water consumption has increased. Changes in LULC have reduced groundwater recharge and increased runoff (Table 4.5), producing a constant water deficit in the region (Ojeda Olivares, 2018, 2019) (Table 4.6). The values for abstraction, recharge, and runoff were normalized and integrated into a GIS to generate maps. Visualization enables evaluation of groundwater vulnerability in the area.

Table 4. 5 Water recharge and runoff in the Central Valleys for different years (Ojeda Olivares et al., 2019)

Indices	1986	1994	2002	2010
Ru (mm/year)	221.23	222.38	221.91	220.65
R_e (mm/year)	2.21	9.91	-29.83	308.99

Table 4. 6 Groundwater abstraction for different uses and annual average recharge (Ojeda Olivares., 2019).

Years	Extracted volume as volume change (m^3)	Annual average human consumption (m^3)	Agriculture and other uses (m^3)	Annual average recharge (m^3)
1984-2001	$-115.53x10^6$	$47.54\text{-}69.22x10^6$	$57.15x10^6$	$138.910\text{-}158.77x10^6$
2001-2003	$-347.5x10^6$	$69.22\text{-}71.78x10^6$	$277x10^6$	$158.77\text{-}160.491x10^6$
2003-2007	$-342.5x10^6$	$71.78\text{-}77.19x10^6$	$325.95x10^6$	$160.491\text{-}170.89x10^6$
2007-2009	$-331.8x10^6$	$77.19\text{-}80.04x10^6$	$253.185x10^6$	$170.89\text{-}171.75x10^6$

2.5.2 Pollution level (Nitrate concentrations as indicators of agricultural pollution)

Groundwater pollution is related to the physical and chemical parameters of the area's water. In this case, we use nitrate concentrations in 71 wells (Figure 4.4). Consumption of nitrate-contaminated water can directly induce adverse human health effects. Studies suggest that prolonged ingestion of nitrates and nitrites may cause lymphoma and cancer, respiratory tract infections, and malformations in newborns (Bryan et al., 2012; Bryan and Loscalzo, 2017; Mirvish, 1991). Nitrogen also causes eutrophication which may favor the development of infectious diseases. The nitrate concentration was used as a potential indicator of contamination from the use of agricultural chemicals and fertilizers. These data were obtained from the National Institute of Statistics and Geography (INEGI, 2012).

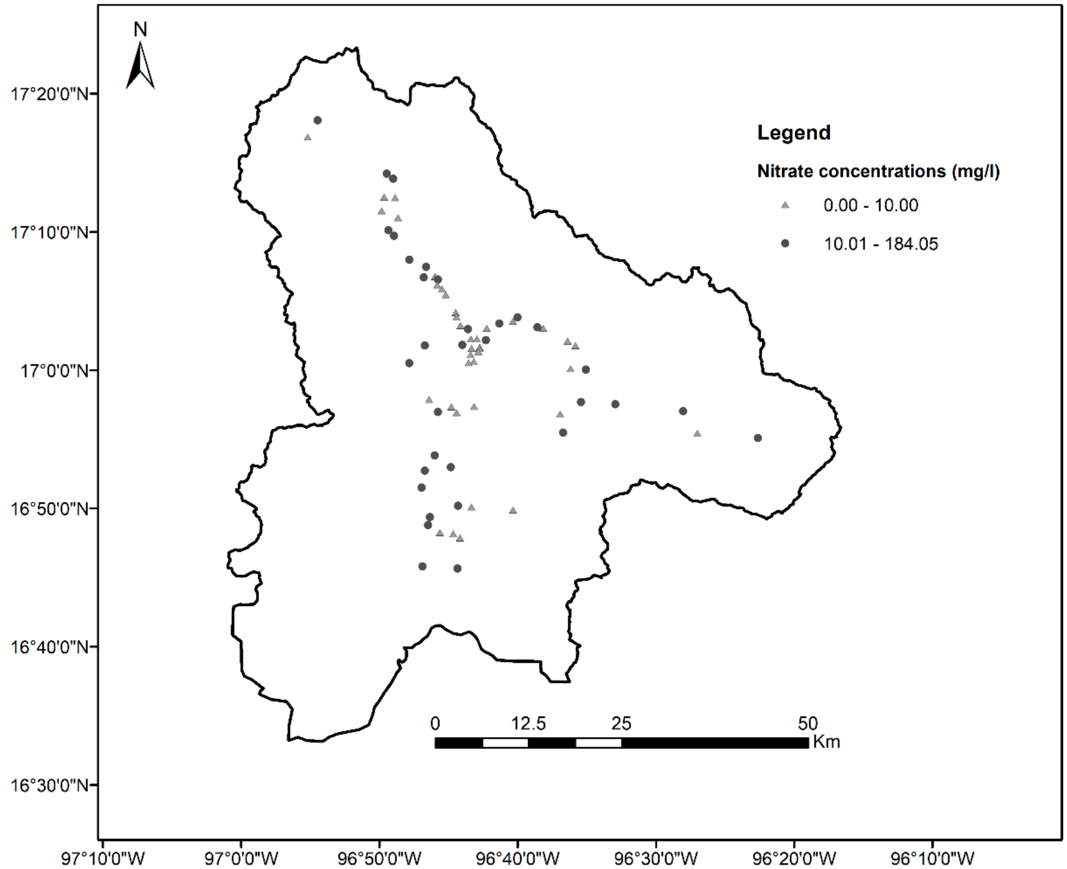

Figure 4. 4 Nitrate concentrations in 71 wells in the Alto Atoyac sub-basin, 2012.

Ojeda Olivares et al, (2019) indicates that since 1986, there has been little change in the distribution of agriculture in the sub-basin. With the expectation of future reductions of soil fertility due to the intensive cultivation, increased deforestation and clearance of vegetation, as well as wind and water erosion, the use of fertilizers will increase. It is estimated that globally by the year 2020, 70% of plant nutrients will have to come from fertilizers (Ayoub, 1999). Though there have been no significant variations in the nitrate levels in the study area during the period from 1986 to 2018, future concentrations are expected to be 50% higher due to lost soil fertility.

2.5.3 Social Marginalization – Adaptive Capacity in the Central Valleys of Oaxaca

As vulnerability is related to the socioeconomics of a population, developing countries are likely to be more vulnerable than in developed countries. The main cause of water stress in any country is overpopulation (Vörösmarty et al., 2010). A measure of social marginalization has been reported by the National Council of Population (CONAPO, 2012). The state of Oaxaca is a marginalized region with high rates of poverty and a lack of basic services (Figure 4.5).

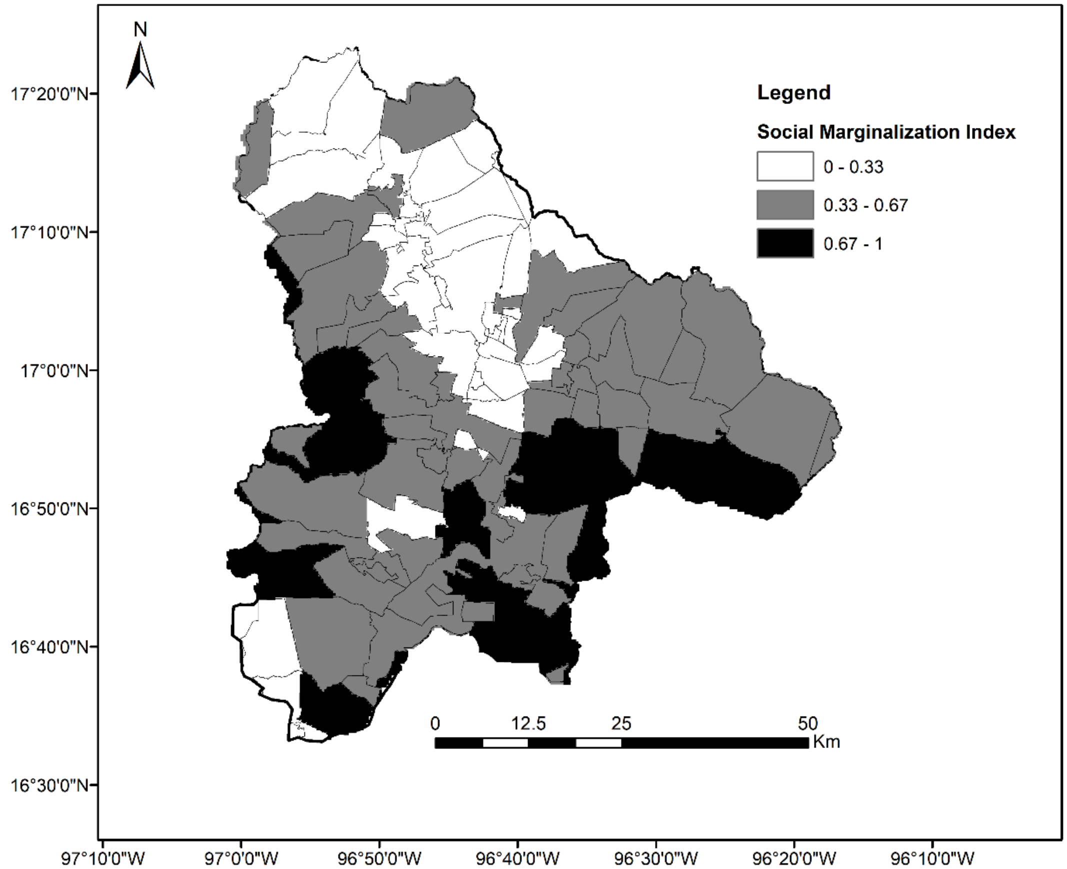

Figure 4. 5 Social Marginalization Index. The highest values depict municipalities with a high level of poverty and lack of basic services (National Council of Population).

2.6 Importance and relation of the selected variables

Ru, Re, and Abs values were obtained for the study area to Ojeda Olivares et al., (2018) and (2019). The values were measured as the percentage of the water that is recharging the aquifer (6.06%), running off the study area surface (29.65%), and being abstracted (10.17%). Annual rainfall in the study is 746 mm/year. Abstractions exceed recharge so that the system would be vulnerable to water extraction, and we can see that abstraction is of greater importance than recharge because it is the leading cause of vulnerability (Table 4.7).

Table 4. 7 Importance values calculated with the study area information.

Variables relation	Importance	Observation
R_e-R_u	5	*Re* is 5 times more importance than *Ru*
R_e-*Abs*	3/5	*Re* is 0.6 times more importance than *Abs*
R_u-R_e	1/5	*Ru* is 0.2 times more importance than *Re*
R_u-*Abs*	1/3	*Ru* is 0.33 times more importance than *Abs*
Abs-R_e	2	*Abs* is 2 times more importance than *Re*

Abs-R_u	3	Abs is 3 times more importance than Ru

We consider pollution to have an impact that is similar to abstraction in the study area's vulnerability as they have the same level of importance – "1". To assign an importance value for social marginalization relative to the other variables is a difficult task because the measurement of the direct impact of social marginalization on water resources is difficult and is not documented in the literature. The values, therefore, were calculated with a calibration matrix, assigning values until the consistency rate reached values below 0.1.

2.7 Uncertainty analysis of the groundwater vulnerability

A Monte Carlo method was used to determine the uncertainty of the groundwater vulnerability indices. This is a stochastic technique based on the use of random numbers and statistics to evaluate the consequences of altered inputs. Multiple evaluations of the model were performed with probabilistically selected model inputs to evaluate and quantify the uncertainty in the model predictions and to identify the input factors that contributed to the uncertainty (Saltelli et al., 2004, Kovoor and Nandagiri, 2018).

Monte Carlo simulations were executed using SimLab V2.2 (Simulation Environment for Sensitivity and Uncertainty Analysis) software which was downloaded at https://ec.europa.eu/jrc/en/samo/simlab. It consists of three modules: the statistical preprocessor module, the model specification and execution module, and the statistical post-processor module. To use SimLab, the user performs the following operations (Saltelli et al., 2004):

1. Select a range and distribution for each input factor.
2. Generate a sample of elements from the distribution of the inputs previously specified.
3. Feed the model with the sample elements and produce a set of outputs.
4. Use the results of the model outputs for uncertainty analysis.

A 10,000 item randomly sampled data set was generated for the five indices Abs, Pc, Re, Ru and Ma. A 0.95 confidence level was selected for the Kolmogorov bound of the cumulative and inverse cumulative distribution of Yvar, the T Chebycheff, and the T-test bound of the mean.

3. RESULTS
3.1 Analytical Hierarchy Process

The pairwise comparison matrix was constructed (Table 4.8). The matrix represents the pairwise comparisons of the five selected indexes, under the umbrellas of the water availability and pollution levels to determine the importance of each index in the calculation of groundwater vulnerability. The levels of importance of *Abs* and *Pc* are the same, as they contribute equally to the calculation of groundwater vulnerability.

Table 4. 8 Comparison matrix for the used Indexes.

	Abs	*Pc*	*Re*	*Ru*	*Ma*

Abs	1	1	2	3	9
Pc	1	1	2	2	9
Re	1/2	1/2	1	5	4
Ru	1/3	1/2	1/5	1	3
Ma	1/9	1/9	1/4	1/3	1

Abs Abstraction Index, *Pc* Pollutant Concentration Index, *Re* Water Recharge Index, *Ru* Runoff Index, *Ma* Social Marginalization Index.

Once the importance values were established and compared, a normalized matrix was obtained (Table 4.9). With this matrix, the criterion priority vector is obtained by averaging the values of the rows, then the eigenvalues can be computed (Table 4.10).

Table 4. 9 Normalized matrix.

	Abs	*Pc*	*Re*	*Ru*	*Ma*
Abs	0.340	0.321	0.367	0.265	0.346
Pc	0.340	0.321	0.367	0.176	0.346
Re	0.170	0.161	0.183	0.441	0.154
Ru	0.113	0.161	0.037	0.088	0.115
Ma	0.038	0.036	0.046	0.029	0.038

Abs Abstraction Index, *Pc* Pollutant Concentration Index, *Re* Water Recharge Index, *Ru* Runoff Index, *Ma* Social Marginalization Index.

Table 4. 10 Eigenvalues of the indices.

Index	Eigenvalue
Abs	5.272
Pc	5.288
Re	5.354
Ru	5.063
Ma	5.360

The weights of the indices were obtained by averaging the rows of the normalized matrix (Table 4.11). The weights indicate *Abs*, *Pc*, and *Re* are the most important indices. If the matrix analysis indicates that there is consistency among the indices, then the assigned values are adequate. The consistency ratio (CR) was 6.02% which is lower than 10%; therefore, with the weights, it is possible to calculate the groundwater vulnerability.

Table 4. 11 Index weights to calculate groundwater vulnerability.

Index	Weight
Abs	0.33
Pc	0.31
Re	0.23
Ru	0.10

Ma	0.04
CR: 0.06	Σ=1

CR: Consistency Ratio

A linear equation to assess the groundwater vulnerability (WV) can be formulated. It comprises the sum of the impact of all five indices. Each component has a specific effect on the water resource, and it can be integrated into the GIS to generate vulnerability maps that highlight the areas where groundwater is or will be vulnerable. Therefore, groundwater vulnerability (*WV*) is approximated by:

$$WV = 0.33 \cdot Abs + 0.31 \cdot Pc + 0.23 \cdot Re + 0.10 \cdot Ru + 0.04 \cdot Ma \qquad (7)$$

The maximum possible value of WV is 1 (extreme vulnerability) and the minimum is 0 (no vulnerability). The vulnerabilities represented in equation (9) are generated by anthropogenic factors. Human activities are the main stressors of water resources, so in areas with no human impacts, the vulnerability will most likely approach zero.

3.2 Uncertainty and Sensibility analysis of the groundwater vulnerability

Variability or uncertainty in the mathematical modelling is a significant (inverse) indicator of confidence and quality. The uncertainty analysis of the groundwater vulnerability index, aimed at the quantification of output uncertainties, evaluates the five inputs to the vulnerability model (Table 4.12). The distribution of the model results using 10,000 random values is a normal distribution (Figure 4.6). If the variance is considered the range of uncertainty, the global model has an uncertainty of 2.3%.

Table 4. 12 Statistic indicators of the uncertainty analysis.

Summary Statistics	
Mean	0.507
Variance	0.023
Standard deviation	0.152
Skewness	0.0058
Kurtosis	-0.4134
T Chebycheff test	0.00678
T Test	0.00249

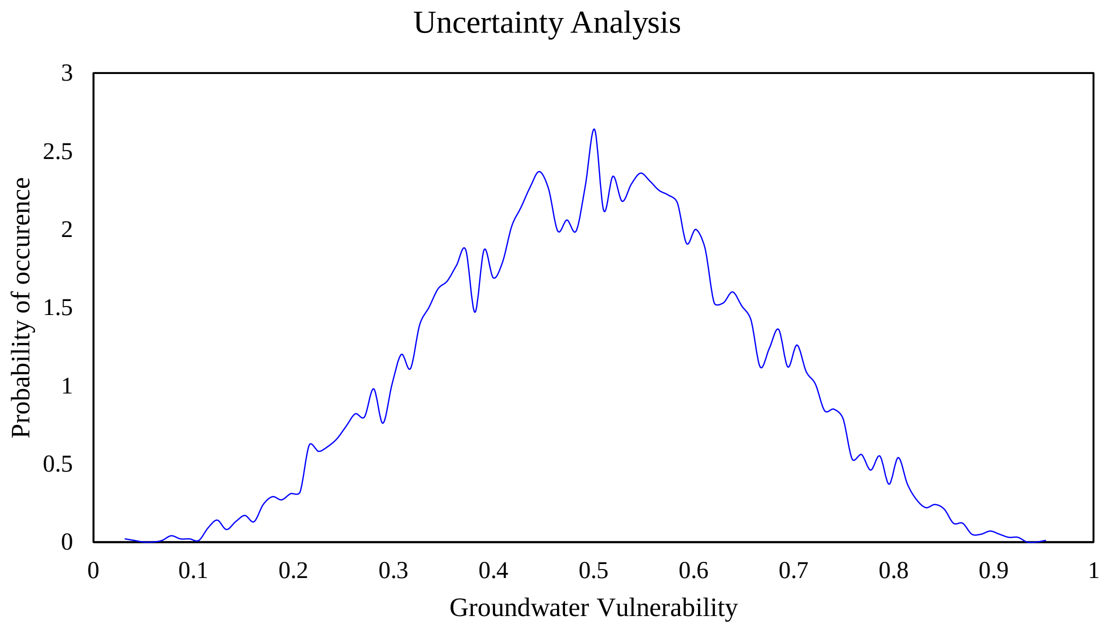

Figure 4. 6 Probability distribution of the model output values.

The sensitivity analysis reveals the sensitivity of the measurements of groundwater vulnerability (Table 4.14), when *Abs*, *Pc*, *Re*, *Ru*, and *Ma* are changing within the range from 0 to 1, and with a uniform probability distribution. The correlation among the input parameter have to be calculated (Table 4.13).

Table 4. 13 Correlation Matrix for the Input parameters

	Abstraction	**Pollution**	**Recharge**	**Runoff**	**Marginalization**
Abstraction	1.00	0.83	0.86	0.08	0.16
Pollution		1.00	1.00	-0.46	0.63
Recharge			1.00	-0.41	0.60
Runoff				1.00	-0.75
Marginalization					1.00

Table 4. 14 Partial rank correlation coefficient and ranks for the model inputs

	Sensitivity indices	
Input factors	PRCC	Rank
Abstraction	0.966769	1
Pollution	0.962028	2
Recharge	0.933914	3
Runoff	0.74304	4
Marginalization	0.40112	5

Groundwater vulnerability is very sensitive to variations of the Abs, *Pc*, and *Re* indices, reaching the highest values of 0.966 and 0.962, indicating a direct, positive relationship: if abstraction and pollution levels increase, groundwater vulnerability will also increase.

3.3 Groundwater Vulnerability Assessment in the Central Valleys of Oaxaca.

Groundwater vulnerability in the study area has been increasing since 1986 (Figure 4.7), changing from low to medium vulnerability. The main drivers of increased vulnerability are increasing abstraction, increasing contamination, and reduced recharge rates.

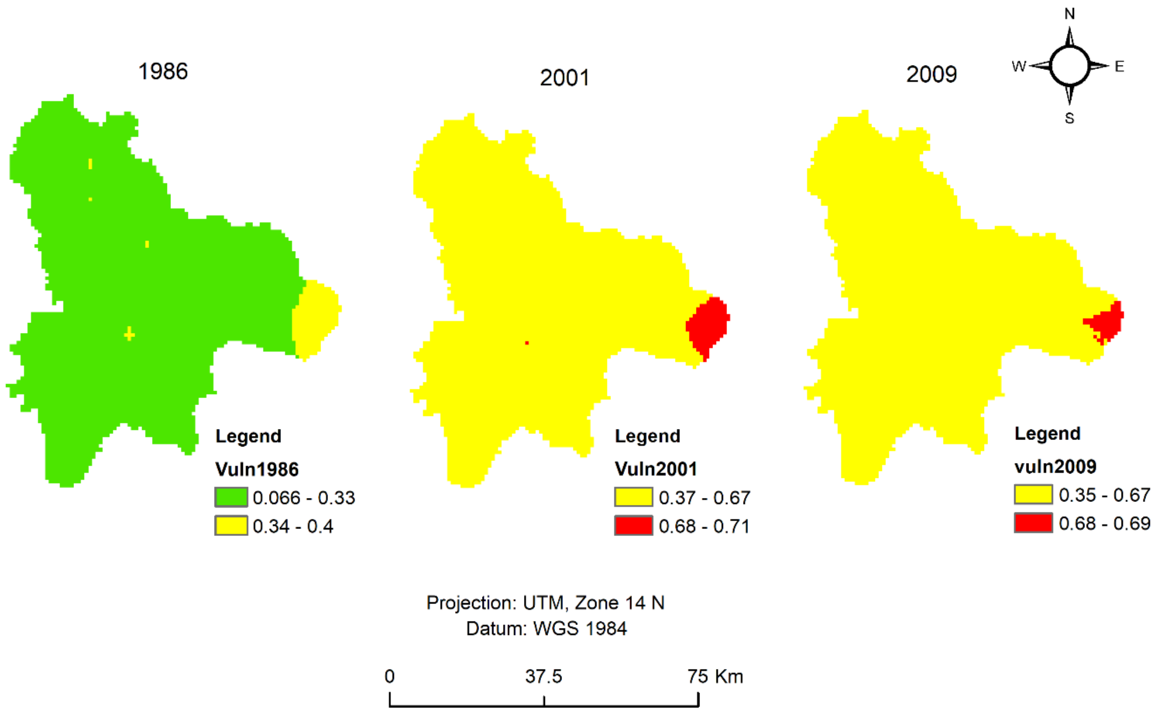

Figure 4. 7 Changes in groundwater vulnerability in the Central Valleys of Oaxaca from 1986 to 2009.

Considering CC scenarios for the study area, as presented in Ojeda Olivares et al (2019), groundwater vulnerability will increase from medium to high vulnerability, due to the variations of recharge and runoff produced by changing annual rainfall amounts and increased groundwater pollution (Figure 4.8).

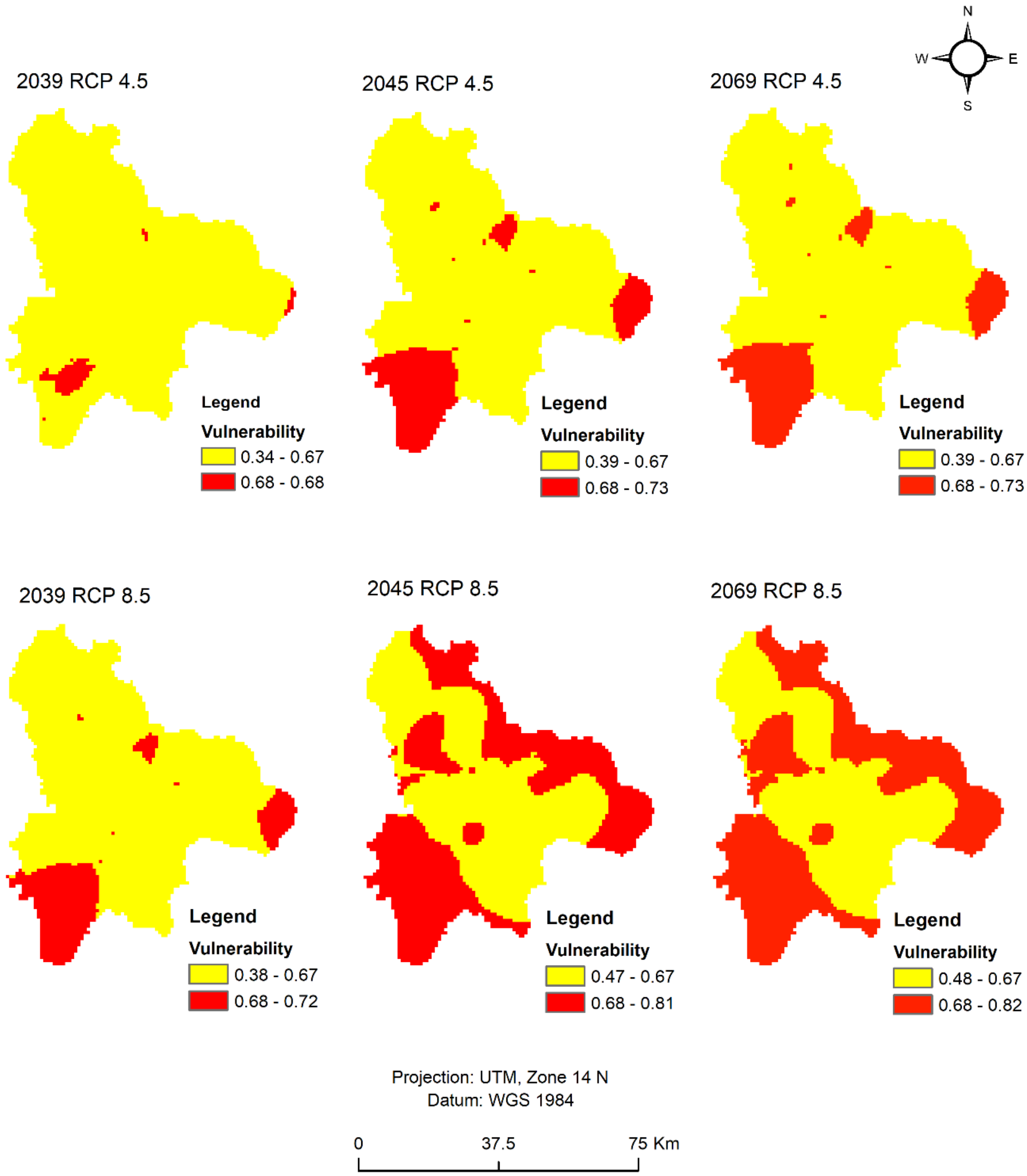

Figure 4. 8 The changes of groundwater vulnerability in the Central Valleys of Oaxaca using RCP4.5 and RCP8.5 for the near-term horizon from 2015 to 2039 and the medium-term horizon from 2045 to 2069.

4. DISCUSSION
4.1 AHP and the Uncertainty/Sensitivity Analysis

The AHP methodology is a useful tool to calculate the weights of variables in linear models, once the ranks of importance among the variables are defined with the available data. This approach has been widely used in risk and vulnerability studies. The more data and variables included in a model, the better will be its resolution and the lower will be its uncertainty. But this is difficult to achieve for deterministic models used in rural areas of developing countries where there is usually a lack of information. This is an important constraint. So models that allow us to evaluate empirical circumstances and future scenarios of groundwater resources requires the use of the available data for the area of interest.

The AHP analysis revealed that groundwater abstraction, pollution concentration, and water recharge are the most relevant indexes. All of these are related to population growth, increases impervious cover, and losses of forest cover; the three together account for 87% of groundwater vulnerability. In areas with large populations, shrinking vegetative coverage, and increasing impervious surfaces, the pressure upon water resources will be large. This indicates that water scarcity and pollution are linked to growing population and land use change (Chi and Ho, 2018; Lerner and Harris, 2009; Namugize et al., 2018; Neset et al., 2018; Stevenazzi et al., 2017). The results are very consistent (CR: 0.6) which indicates that the variables are adequately related to each other.

CC affects both Re and Ru because these two indices are tied to precipitation and temperature changes. They are also influenced by land use change, giving rise to increased Ru and decreased Re, depending on the specific LULC. Ru and Re together account for 33 % of groundwater vulnerability and both include intrinsic aspects of the area (e.g., soil type, hydraulic conductivity, depth of the water table, aquifer type, and LULC). All of these are included in the calculations of Re and Ru indices (Ojeda-Olivares et al., 2018).

Marginalization can be defined as a social exclusion, where the marginalized group can be deprived of basic services like water, education, job opportunities, etc. The link between social marginalization and the effects on groundwater resources (water availability and pollution) have been little explored or studied. Ruettinger (2012), however, characterized the relationship between marginalization and water availability by three factors: (1) water management and infrastructure, (2) environment and human impacts, and (3) the effects of CC. Marginalized zones have no access to financial and technical resources for development of resilience to CC, therefore areas with high levels of social marginalization will experience greater water resource vulnerability. But the correlation of water extraction over the last 3 decades and increased social marginalization in the Central Valleys of Oaxaca is positive but weak, indicating that marginalized communities are not necessary the locations that extract more water resource even if the infrastructure is less efficient. Nonetheless the impact that marginalized areas have upon pollution of water is relevant: there is a correlation of 0.63 reflecting the close relationship of contamination to marginalization. The same is the case between water recharge and marginalization – if recharge is great, it can be explained by “conservation” of recharge areas because of the lacunae of infrastructure which might limit or stop natural recharge. Marginalization, however, has an inverse effect on runoff because construction of the infrastructure that improves the quality of life can increase impervious surfaces and can reduce forest cover. Addressing social marginalization can be an adaptive technique to reduce groundwater vulnerability, but implementing conservation strategies that promote the consumption of less water, increase regional water treatment capacity, and improve water recharge may be the most efficient approaches. It is worth noting that, recently, social marginalization, water contamination, water exploitation and land-use change have increased in the study area (Belmonte-Jiménez et al., 2003, 2005; Ramos-Leal et al., 2012; Ojeda-Olivares et al., 2018).

The quality of the models is judged by their levels of uncertainty. Models with high uncertainty are no reliable and are considered to be of low quality. Results that are sub-optimal can lead to bad or ineffective management. The product of a model is intrinsically affected to some degree by the uncertainty that stems from and resides in the theories, assumptions, and levels of knowledge or understanding of relevant relationships and processes. So, it is imperative to define the variables that generate high levels of uncertainty. In this model, the uncertainty stemming from the interactions between the effects of social marginalization, a qualitative variable, and the other quantitative variables is high, mainly because the effects of social marginalization on groundwater resources have not been widely studied. Additionally, the relationship between water extraction and water pollution is not easily measured. Fortunately, social marginalization explains only about 4% of an area's vulnerability. The assumption that groundwater extraction and groundwater pollution can be considered to have the same levels of importance also introduces some amount of uncertainty in the results as well. Nevertheless, the variability of the results is low, and this is shown by the 2.3% uncertainty in the global model. The sensitivity analysis is consistent with the AHP, indicating that Abs, Pc, and Re are the most relevant variables. They, therefore, could introduce significant uncertainty into the model if wrong assumptions are made or if modelers develop an insufficient understanding of the relationships between these variables in their region of study.

4.2 Groundwater Vulnerability in the Central Valleys of Oaxaca and results validation

Groundwater vulnerability in the Central Valleys of Oaxaca has changed since 1986. By 2006 vulnerability increased from low to medium in most sections of the Valley. In isolated areas, the vulnerability has climbed to high levels. In the Tlacolula Valley, this evolution is driven by groundwater abstraction, pollution, and recharge rates, leading to increased pressure on water resources over the last three decades. The stressors that have increased abstraction and pollution are population growth and land-use conversion. These factors have been described by Velázquez et al. (2003) as well. The growing population and land-use changes are related to economic development and, in particular, to the growth of urban land uses. Urbanization breeds overexploitation of groundwater to meet local water demands. Some intrinsic conditions of the study area as its hydrogeological features (i.e., shallow water table, permeable soils, etc.) make the area highly vulnerable to overexploitation and vertical pollution (Belmonte-Jiménez et al., 2003, 2005).

Considering the CC scenarios for the study area as presented by Ojeda Olivares et al (2019), (RCP4.5 and RCP8.5), groundwater vulnerability should be expected to worsen from medium to high vulnerability, especially due to variation in rainfall, increasing temperatures, and the anticipated population growth and requisite LULC. In the future, water consumption and pollution are expected to increase under population growth. Considering the different CC scenarios for the near- and medium-term time horizons, we can clearly see how groundwater vulnerability will change from medium to high in the Zaachila and Etla valleys over the period of analysis. This indicates how sensitive the model is to the changes in these variables.

Validation of the model can be conducted by evaluating the different groundwater vulnerabilities in the study area in comparison to similar studies. Studies conducted in the area indicate that zones are more vulnerable due particularly to soil properties, aquifer types, and depth to the water table. Permeable soils, unconfined aquifers, and shallow water tables make areas very sensitive to pollution and prone to overexploitation (Ramos-Leal et al., 2012, Belmonte-Jiménez et al. 2003, 2005). The water stress risk for the Central Valleys of Oaxaca is low-medium to medium-high (WRI, 2019) according to the results from the model. Therefore, this model can be useful for the development of groundwater conservation strategies for rural areas where much less empirical information is available.

5. CONCLUSIONS

A hierarchical model and methodology were developed for a management tool that assesses groundwater vulnerability in the Central Valleys of Oaxaca, Mexico. The model uses climatological (precipitation and temperature), socioeconomic, population, and LULC change data to evaluate current and future conditions of the region's groundwater to discern the spatial distribution of vulnerability. From the results, one can develop strategies to conserve groundwater resource in the study area.

Abs, Pc, and Re are the most vital factors that make an aquifer vulnerable. They are primarily driven by population growth and LULC change (loss of cover forest, loss of recharge areas, and an increase impervious surface), combined the three account for 87% of the total groundwater vulnerability.

The marginalized areas of the Central Valleys of Oaxaca don't directly increase groundwater exploitation even though their water use practices are less efficient than in other areas. There is, however, a positive, direct correlation between pollution levels and social marginalization, indicating that marginalized areas tend to increase water contamination due to the lack of wastewater treatment and management infrastructure. The relationship between runoff and marginalization, however, is inverse: marginalized areas generate less runoff and actions to decrease marginalization will enhance runoff rates because land development, road construction and other infrastructure that segues into urban land uses increase runoff and decrease recharge. Development risks significant reductions of water availability.

Groundwater resources in the Central Valleys of Oaxaca have become more vulnerable over the last few decades as the vulnerability has increased from minimal to high, in some places. This indicates that water supply and contamination are and will become significant problems in the study region. If precipitation and temperature patterns shift according to the modeled CC scenarios, and if LULC changes and population growth follow the trends experienced in the region, the area will face a severe water crisis in the next few decades. The main problems will be diminishing availability of clean, freshwater.

The model developed and presented here can be used in assessments of agricultural or rural areas where data are limited because the uncertainty of the model's output is low. The conditions from one location to the next could change dramatically, but if the relationships of and the relative importance between the variables are carefully determined, this method can be adapted to any region.

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Chapter 5: Methodology approach to include potential water pollution in water availability studies

Paper Draft waiting under revision and waiting to be submitted

Methodology approach to include potential water pollution in water availability studies

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ABSTRACT

Water availability problems have spread around the world, and in Mexico, it is an issue of national security. The majority of the actual methods to study water availability are based in the water quantification, using water balances and computational modeling to evaluate the variation of the water levels due to the pumping in different areas, and rarely considered the water quality as an indicator of water scarcity. The study was developed in Oaxaca, Mexico, a region with issues related to water availability (scarcity and pollution problems). An AHP-Fuzzy methodology was used to linkage the water pollution and water quantity in the study through the use of MATLAB and geographic information systems. Four indicators were selected, total groundwater abstractions (water for all the uses), water for human consumption, annual water recharge, and treatment capacity of the sewage of the area. The sensibility and uncertainty of the parameter were analyzed with Monte Carlos simulation. The area has a treatment capacity of 14%, indicating a high pollution potential of water resource and the abstraction overpass water recharge by 111.52%. The 67% of the water scarcity is due to the exploitation level and the recharge level which are overpassed during the year, and the 33% of the water scarcity is the product of the weak treatment capacity of the sewer water. Groundwater index values from 0-0.33 indicate a good balance in the water availability, but values close to zero indicate a high risk of pollution since the treatment capacity is close to zero. The approach and the indicators establish a baseline to analyze and evaluate the water availability taking into account the exploitation and water pollution. The approach of alternative methodologies for the water study is needed in areas with limited and null information, due water resource is a key for the economic and social development, and its conservation should be a priority.

Keywords: Groundwater exploitation, Water Management, Water Recharge, Treatment Capacity.

Highlights

- A simple approach considers the wastewater treatment capacity to evaluate water availability.
- A groundwater availability index is developed to evaluate water resource in areas with limited and scarce information
- The treatment capacity of the study area represents 14%, indicating a high risk of water pollution, while abstraction level overpass the water recharge by 111.52%.
- The Central Valleys of Oaxaca is facing serious quantity and pollution problems.
- Water policies should implement regulation that permits reductions in groundwater abstraction and increase the treatment capacity to reduce the water pollution risk.
- Reuse of wastewater can improve the water availability of the study area.
- AHP-Fuzzy and GIS are suitable tools to evaluate water availability

1 INTRODUCTION

Water availability is essential for the management of groundwater resource. The water reduction is related to the climatologic variations, overexploitation, water recharge rates, hydrogeological medium features (Bloomfield and Marchant, 2013, Bloomfield et al., 2015, Chao et al., 2018), and water quality. Climate change affects directly the groundwater recharge rates, and the extreme climatological conditions as the drought that cause increases in the water demand, groundwater depletion and adverse effects on the economic activities and in the environment (Chao et al., 2018, Nilsalab et al., 2018, Sanginabadi et al., 2019). If water demand exceeds the availability of a scarcity problem is faced, which can be written as a direct relationship between Overexploitation and recharge (Van Loon and Van Lanen, 2013). If human activities increase the demand of water and the water availability is below the permit threshold of exploitation, water stress can be defined, and this water stress will be severe if human demands for water exceed 40% of the available water in a watershed (Nilsalab et al., 2018). In the future, it is expected that the rates of groundwater depletion will depend on the economic and environmental viability to extract water from stressed aquifers (Turner et al., 2019).

Water pollution represents a growing problem in global water availability, mainly in developing countries, and it is an essential parameter in the water availability assessment (Vörösmarty et al., 2010). Water quantity and quality are not easy to task to evaluate, and many researchers have defined methodologies to index both, and to do an integral evaluation of water resource. The most known indices are The Water Resource Vulnerability Index, Water Stress Index (Falkeman index), The Critically Ratio, International Water Management Institute (IWMI indicator) and the Water poverty index (WPI) (Raskin et al., 1997, Falkenmark et al., 1989, Seckler et al., 1998, Alcamo et al., 2000, Sullivan, 2002). The WPI considered both concepts (quantity and quality) to evaluate the water scarcity, but its complexity makes it hard to use in areas with no information or lack of it. A scarcity index that includes water pollution was developed by Zeng et al. (2013), which includes the concepts of blue, green and grey water and water footprint, where the grey water footprint is the amount of freshwater required to dilute pollutants to reach the water quality standards. The development of continuous methodologies that help us to evaluate the water resource in areas with limited data and information is needed, the implementation of tools as the Geographic Information Systems, Analytical Hierarchy Process and Fuzzy Logic in the water management has been widely used (Gemitzi et al., 2006, Sadiq et al., 2007, Ouma and Tateishi, 2014, Nadiri et al., 2017a, Nadiri et al., 2017b).

The concept of treatment capacity as an indicator of water pollution has not been used for the evaluation of water availability. Research focusses mainly in the direct evaluation of pollutant concentration. The idea of the sewage capacity treatment as indicator of water pollution and water availability, can be an excellent parameter to have into account since, areas with null treatment capacity present high level of contamination in its water sources, mainly in developing countries, and some countries that face the water scarcity and pollution have created alternatives as reduction of effluents discharges and wastewater reuses, practice that has been recognized as an essential part of water and wastewater management scheme (Ouma and Tateishi, 2014). The aim of this study is to develop a methodology to evaluate water availability in the Central Valley of Oaxaca, by considering water quantity and quality, the sewage treatment capacity as indicator of water pollution; making it easily to use with easily obtainable data, to be applied in regions where lack and deficiency of the monitoring systems are problems.

1.1 Study area

The Central Valleys of Oaxaca located between 16°30' and 17°25' north latitude, and 96°15' and 97°00' west longitude, It comprises by the Etla, Tlacolula, and Zaachila valleys as shown in Figure 5.1. It is limited to the north by the Sierra de Juarez, to the northeast by the Cañada Region, to the south by the Sierra Madre del Sur, to the east by the Tehuantepec Isthmus Region and to the west by the Mixteca Region. The delimited sub-basin is called the Alto Atoyac with a surface of 3,744.64 km^2, inside the sub-basin is the aquifer area with a surface of 1,130 km^2, where comes the 100% of drinking and irrigation water. It is estimated that agriculture uses 87.6% of the groundwater in the entire region.

The aquifer is shallow and unconfined formed by alluvium, constituted for a heterogeneous mixture of unconsolidated sediments, with a thickness between 15 and 100 m (saturated zone). The basement is formed by metamorphic and igneous rocks (gneiss, schist, limestone, rhyolites, sandstone, conglomerate, cataclasite, volcanoclastic, extrusive and intrusive volcanic rocks). The gneiss, schist, and extrusive volcanic rocks formations constitute the impermeable limits of the sub-basin (Ojeda Olivares et al., 2017). The mainstream of the area is the Atoyac River with a length of 396 kilometers. The high discharge volume of sewage in the river has deteriorated its quality affecting many communities close to the river.

The mains stressor of water resource in the study area is identified as Climate Change, land use/land change, population growth. The population has grown to a rate of 2.32% in the last 30 years, increasing the pressure in the abstraction levels for irrigation and human consumption (Ojeda Olivares et al., 2019). This population growth has caused the loss of recharge areas, the increase of impervious surfaces, the loss of vegetation cover (Ojeda Olivares et al., 2017, Ojeda Olivares et al., 2019), and the increase of pollution charge in the Atoyac River.

For the evaluation of water resource in the area, the sources of information are limited, and some general information can be found in The National Water Commission, The National Institute of Statistics and Geography and in the National Meteorological System. The Climate stations are limited and for the area can be identified five stations appropriate for the elaboration of hydrological studies (Table 5.1).

Table 5. 1 Climate stations located in the Alto Atoyac sub-basin.

Name	Code	Annual rainfall (mm/year)	Annual temperature (°C)
San Francisco Telixtlahuaca	20151	774.4	19
Etla	20034	753.5	19.7
Oaxaca	20079	746	21.3
Jalapa del Valle	20044	761.6	18.9
San Miguel Ejutla	20118	671.9	20.9

With an average rainfall of 741.48 millimeters per year and an average temperature of 20.2 °C, which are expected to change negatively due to climate change effects in the study area. All of that represents an adverse scenario for groundwater resource so that the proposal of alternating methodologies with allowing use the minimum amount of data to asses groundwater resource that let us implement adaption strategies are needed.

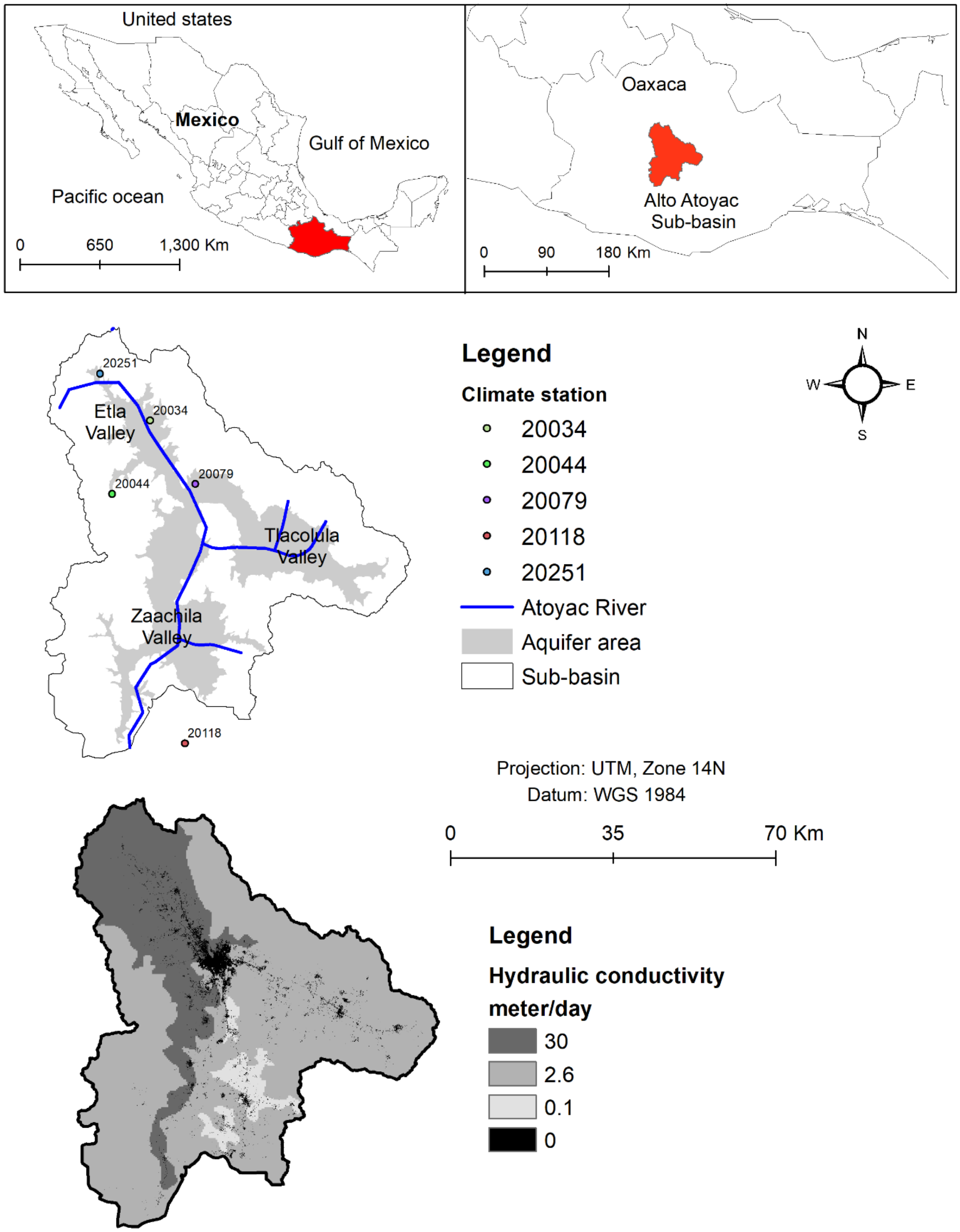

Figure 5. 1 Location of the study area

2 METHOD AND DATA

2.1 Water indicators

According to the concept of water scarcity and water stress (Van Loon and Van Lanen, 2013, Nilsalab et al., 2018), four indicators to evaluate water availability were selected. Water abstraction (Wa), Water human consumption (Wc), Water recharge (Wr) and Sewage treatment capacity (Tc), the last one was selected as an indicator of water pollution since the lack of water quality monitoring is a limitation in the study area.

Water abstraction levels: The water abstraction level was obtained from the analysis of the hydraulic head variations in 25 years (1984, 2001, 2003, 2007 and 2009). Changes in the water table depth allowed calculating the change in volume due to groundwater pumping. A triangular irregular network was modeled in ARC GIS to quantify the volumes in every analyzed period (Figure 5.2).

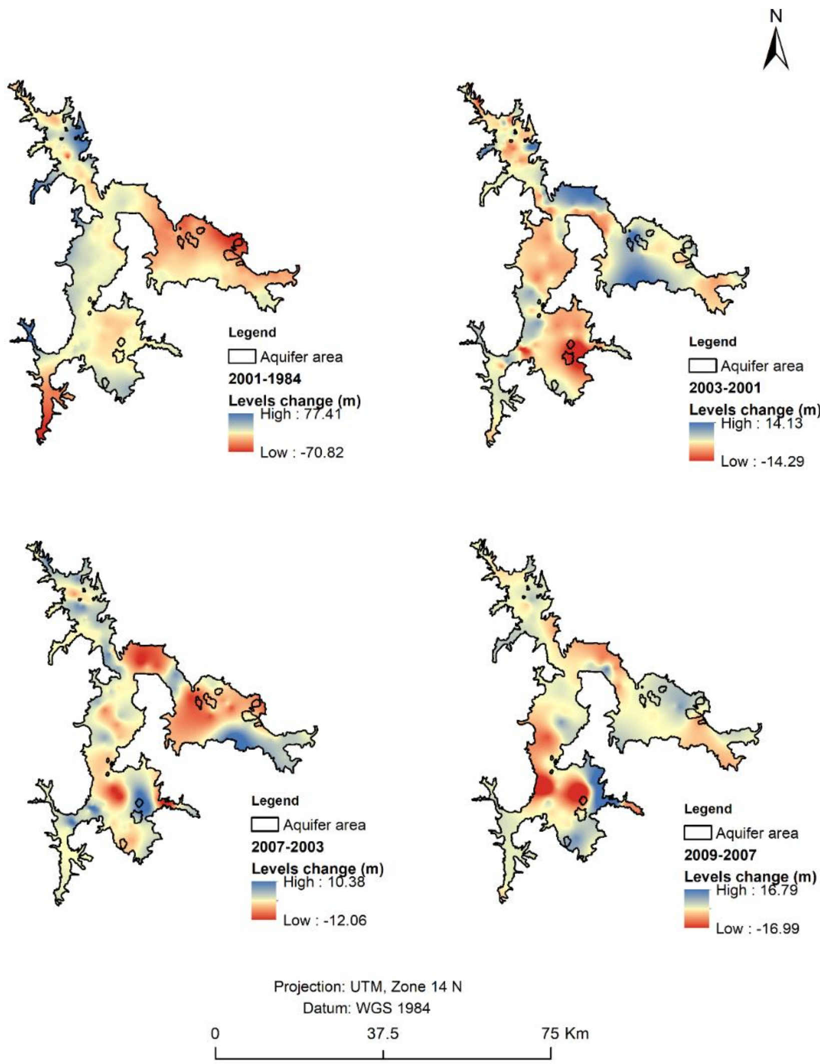

Figure 5. 2 Volume storage change evolution

Water for human consumption: Human consumption of the area can be ranged from 48 to 384 liter per person per day (Table 5.2), according to Ojeda Olivares et al. (2019) an average consumption of 216 liters per person per day can be considered for the study area, for an approximate population of 1,242,099 for 2018.

Table 5. 2 The volume of water consumption in the central valleys of Oaxaca for an average per capita consumption of 216 liters.

Year	Population	Water for human consumption (Mm^3)
1984	603,009	47.54
1994	773,122	60.95
2003	910,426	71.78
2010	1,033,884	81.51
2018	1,242,099	97.93

Mm^3: Millions of cubic meter

Water recharge: Water balance is calculated from annual Precipitation values, taking into account the water losses by runoff and evapotranspiration into the sub-basin, one these losses are calculated the hydrogeological conditions of the media as hydraulic conductivity, water table depth, and soil type will define the rate of water recharge. Water recharge values were obtained from two different studies conducted in the study area by Ojeda Olivares et al. (2017), Ojeda Olivares et al. (2019), where are presented values of water recharge for different periods including climate change affectations, for this study an average value of 160 million of meter per year was selected.

Sewage treatment capacity: The information of the treatment plant in operation and the installed capacity and the actual volumes of water treated were obtained from the catalog of sewer treatment plants in operation published for the National Water Commission of water (CONAGUA, for its acronym in Spanish) Mexico. A resume of the plants into the study area are presented in Table 5.3.

Table 5. 3 Volumes of water treated for different years in the Central valleys of Oaxaca.

Year	Volume (Mm^3/year)	Year	Volume (Mm^3/year)
1986	0.29	1999	2.31
1988	0.85	2000	3.26
1990	1.04	2001	3.45
1992	0.54	2002	3.74

1996	0.25	2003	3.96
1997	0.65	2004	4.12
1998	2.18	2006	4.79
1999	2.31	2008	23.71

Mm^3: Millions of cubic meter

2.2 Fuzzy logic

When there is a tolerance for imprecision which can be exploited to achieve tractability, robustness, low solution cost and better relationship with reality, fuzzy logic is an appropriate tool to use due to the exploitation of the tolerance for imprecision is its strength (Zadeh, 1999). The fuzzy logic analysis allows incorporating human reasoning in the control algorithm. The inference process was described in a Mamdani system because it is intuitive, well suited to human expert knowledge, more interpretable rule base, and have widespread acceptance (Mamdani and Assilian, 1975).

The analysis was conducted in the Matlab Fuzzy Logic Designer, and six rules were analyzed, and four scenarios of water availability were tested (no water availability, low water availability, medium water availability and high water availability), see Table 5.4.

Table 5. 4 Rules and potential scenarios of groundwater availability.

Criteria for the rules	Potential Scenario
Groundwater extracted < Water recharge	High groundwater availability
Groundwater extracted = Water recharge	High-Medium groundwater availability
Groundwater extracted > Water recharge	Low-No groundwater availability
Water for human use < Wastewater treated	High-Medium groundwater availability
Water for human use = Wastewater treated	Medium-Low groundwater availability
Water for human use > Wastewater treated	Low-No groundwater availability

2.3 Analytical hierarchy process (AHP)

The AHP is a mathematical measurement tool based on pairwise comparisons, and it was developed by Saaty (1980), Saaty (1987), Saaty (2000). It has been applied in different studies of water resource management (Calizaya et al., 2010, Zyoud et al., 2016, Li and Sun, 2017).

Two indexes were built to describe the water availability taking into account the quantity and quality, Water extraction and recharge index and the Water treatment capacity index.

$$\mathrm{I_{abs-re}} = \frac{\text{Water recharge} - \text{Groundwater abstraction}}{\text{Water recharge}} \qquad (1)$$

Considering the amount of treated water as the potential among of water to be reused to face the water scarcity without to affect the quality of the water system we have:

If Wastewater treated ≤ Water for human consumption:

$$\mathrm{I_{Tc}} = \frac{\text{Wastewater treated}}{\text{Water for human consumption}} \qquad (2)$$

If Wastewater treated ≥ Water for human consumption:

$$\mathrm{I_{Tc}} = 1 \qquad (2)$$

If the effect of both indexes is considered as the sum of effects to describe the water availability we have:

$$\mathrm{Iwa} = \mathrm{A} * \mathrm{I_{Abs-re}} + \mathrm{B} * \mathrm{I_{Tc}} \qquad (3)$$

Where: Iwa, Water availability index, A and B, are coefficients to be determined with the AHP, $I_{Abs\text{-}re}$ Water abstraction and recharge index, I_{Tc} Water treatment capacity index

A comparison matrix is built to determine the hierarchy level among the parameter selected for the analysis. A paired comparison of the parameter is conducted assigning values from 1 to 9 according to the relationship of the parameter, taking into account the contribution to the output result of the model. The weights of the indices are obtained by averaging the rows of the normalized matrix. The results are tested with a consistency test, Saaty (1980), proposed the calculation of Consistency Ratio (CR), however the consistency index (CI), random index (RI) and the eigenvalues (λ) of the matrix were calculated as follow:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

Where n represents the number of parameters, and λmax is the maximum value of the eigenvalues.

Once the CI determined, the CR can be calculated using the eigenvalue (Saaty, 1980, Alonso and Lamata, 2006):

$$CR = \frac{CI}{RI} \qquad (5)$$

Where: RI is a function of the number of parameters analyzed.

2.4 Sensitivity analysis

The analysis allowed to evaluate the sensitivity of the model to the parameters (groundwater abstraction, water recharge, water for human uses and wastewater treatment) used to calculate water availability. Normalized sensitivity coefficients were calculated through the software SIMLAB which uses the Monte Carlos Simulation (Saltelli et al., 2004), and the Partial rank correlation coefficients were selected to evaluate the sensitivity of the model to the evaluated parameters, the range of value of the parameters corresponded to the study are presented in Table 5.5.

Table 5. 5 Distribution of parameters correspond to the study area

Parameter	Range of values in Mm^3
Groundwater abstraction	[115.53, 347.5]
Water recharge	[160]
Water consumption	[47.54, 97.93]
Wastewater treated	[0.29-23.71]

Mm^3, millions of cubic meter

A total of 10,000 random values were analyzed to test the groundwater availability model. For the sensitivity analysis, this range of values was extended (Table 5.6), to make the model more sensitive to the extreme changes.

Table 5. 6 Distribution of selected parameters for the sensitivity analysis

Parameter	Distribution and range of values in Mm^3
Groundwater abstraction	Uniform [115.53, 700]
Water recharge	Uniform [1, 160]
Water consumption	Uniform [47.54, 400]
Wastewater treated	Uniform [0.29-400]

Mm^3, millions of cubic meter

3 RESULTS AND DISCUSSIONS

Fuzzy model allows to see the groundwater availability evolution, while groundwater abstraction, water recharge, water consumption and wastewater treatment change (See Figure 5.3, 5.4), it can be seen that if abstraction level increase in a value that overpass the water recharge and the treatment capacity the water scarcity increases, the same can be said if the water consumption is higher than the wastewater treated and the abstraction level are higher than water recharge values, indicating a decrease in the water availability of the study area.

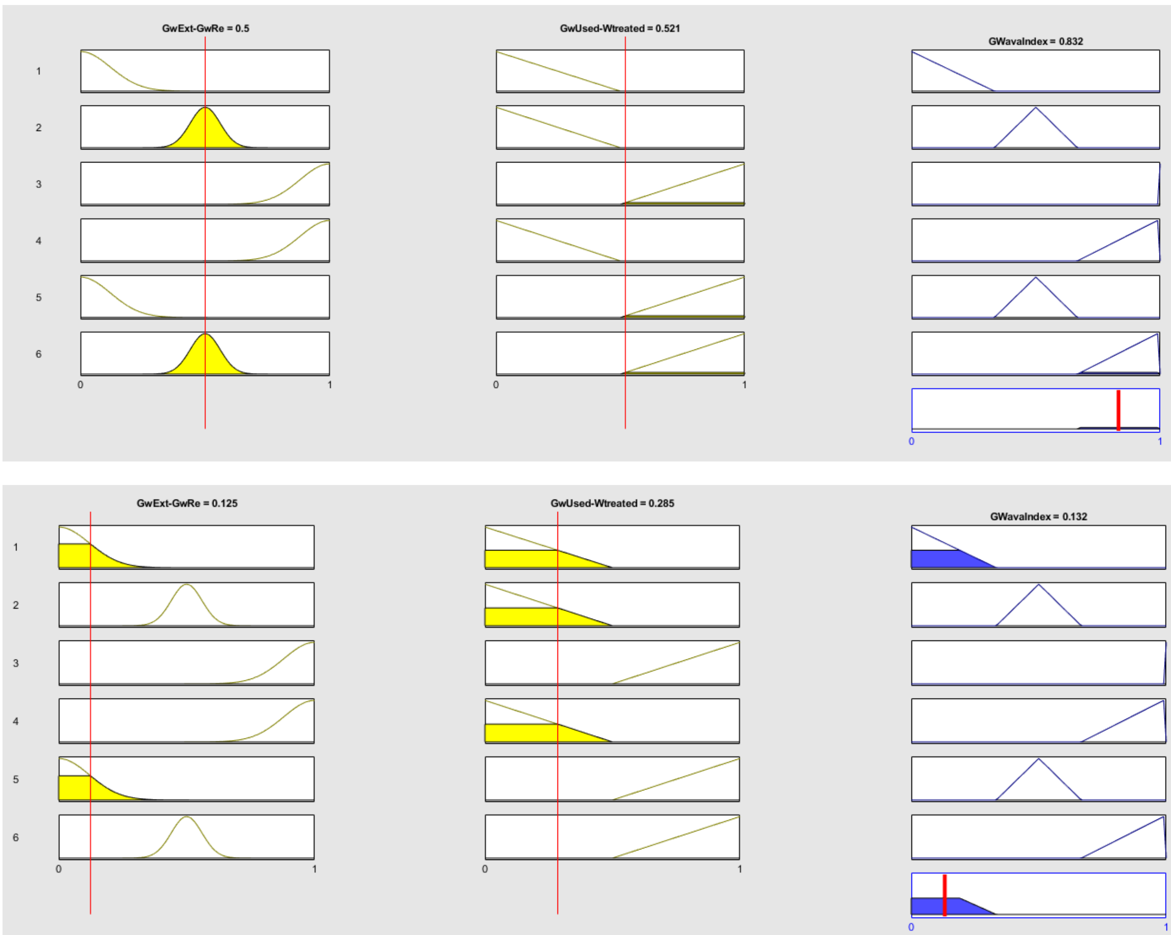

Figure 5. 3 Rules for the fuzzy logic analysis. GwUsed-Wtreaed: Water for human consumption and wastewater treated, GwExt-GwRe: Groundwater abstraction and water recharge.

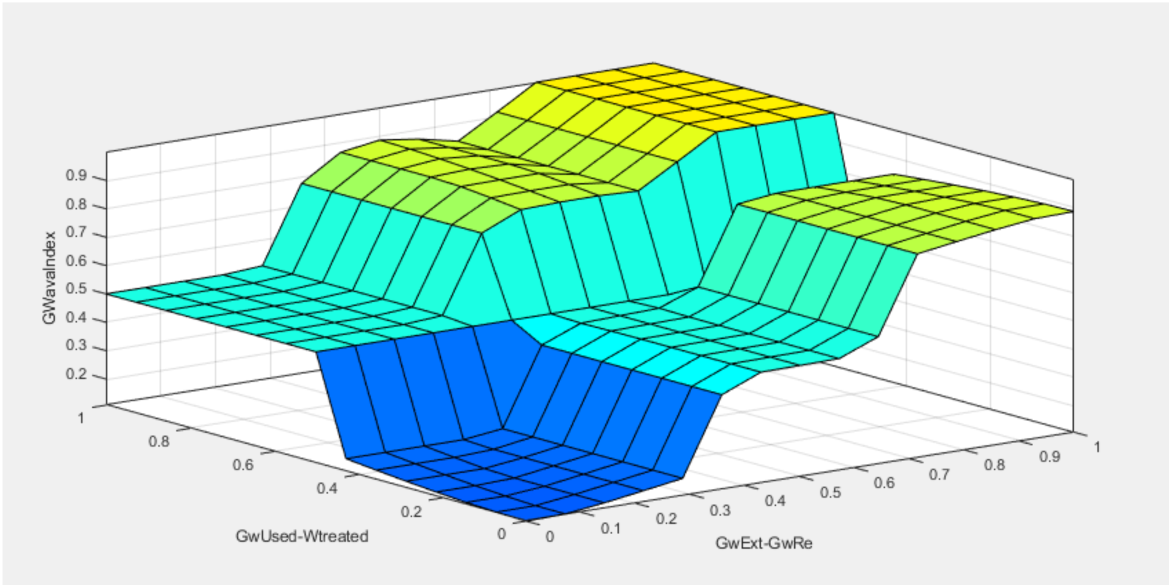

Figure 5. 4 Control output surface for the fuzzy logic analysis of output. GwUsed-Wtreaed: Water for human consumption and wastewater treated, GwExt-GwRe: Groundwater abstraction and water recharge.

The fuzzy hierarchical model allows assigning the weights and rates for each attribute associated with the groundwater availability. If groundwater availability can measure the parameter with a higher importance will be those that include water quantity, in this case groundwater abstraction and groundwater recharge since both are the main element to take into account when water scarcity and water stress can be evaluated (Van Loon and Van Lanen, 2013, Nilsalab et al., 2018). However, the $I_{abs\text{-}re}$ will be more important than I_{TC} (See Table 5.7)

Table 5. 7 Water availability coefficients with AHP

	Treatment capacity	Abstraction-Recharge	Normalized matrix		Weight	Row Vector total	λ
Treatment capacity	1	1/2	0.33	0.33	0.33	0.67	2
Abstraction-Recharge	2	1	0.67	0.67	0.67	1.33	2
CR			5%				

The consistency ratio (CR) was 5% which is lower than 10%; therefore, consistency among the parameter can be found, and the groundwater availability can be evaluated with equation 6.

$$I_{wa} = 0.67 * \mathrm{I}_{\mathrm{Abs-re}} + 0.33 * \mathrm{I}_{\mathrm{TC}} \quad (6)$$

Which indicates that 67% of the groundwater availability depends on the groundwater abstraction level and water recharge, while the 33% are represented for the water for human consumption and wastewater treated.

3.1 Groundwater availability index in the Central Valleys of Oaxaca

The groundwater is a highly stressed resource in the Central Valley of Oaxaca; it can be seen in the abstraction, recharge, and treated volumes of water. The human consumption is increasing in the area at the same time abstraction level increases as well and the recharge values decreased, while the treatment capacity of the wastewater is precarious, indicating future risks for the groundwater in the next years, which could drive the aquifer to a total water scarcity, if no action is taking to conserve the groundwater. Groundwater abstraction overpass the water recharge by 111.52% and the treatment capacity of the area is of 14%. In the future this values are expected to change negatively due the population growth, the increase of impervious surfaces and the climate change (Ojeda Olivares et al., 2017, Ojeda Olivares et al., 2019), which will produce an extreme pressure in the water resource the same is expected in other regions worldwide (Wada et al., 2010, Wada, 2016, Cotterman et al., 2018, Healy, 2019). Table 5.8 present the index for the study; negative values indicate a high level of pressure upon the resource in the area, which can lead to a scenario of water scarcity shortly.

Table 5. 8 Groundwater availability index for the study area

Year	Groundwater abstraction (Mm3/year)	Average Water recharge (Mm3/year)	Water human consumption (Mm3/year)	Wastewater treated (Mm3/year)	I_{abs-re}	I_{TC}	I_{wa}
1984	115.53	160	47.54	0.29	0.278	0.006	0.188
2001	347.5	160	69.22	3.45	-1.172	0.050	-0.769
2003	342.5	160	71.78	3.74	-1.141	0.052	-0.747
2007	331.8	160	77.19	4.79	-1.074	0.062	-0.699
2009	331.8	160	80.09	23.71	-1.074	0.296	-0.622

If there is an equilibrium/balance in the system the annual abstraction have to be the same or lower than the annual recharge, and if the treatment capacity represents the 100%, the maximum value of the groundwater availability index reached will be 0.33, while if the treatment capacity is 0% the value of the index will be zero (see Table 9). This because it is expected that 33% of the treated water reaches the aquifer system without any pollution risk. Between 0 and 0.33, we can expect the right balance of the system, nevertheless with values close to cero of the Treatment capacity index; the pollution risk is high. Values minor than zero will be reached when abstraction overpasses the water recharge. When abstraction is two or three times higher than water recharge and the treatment capacity is zero the expected values will be -0.67, -1.34 (This values can increase until minus infinite), which indicate severe water availability and pollution problems, turning into a potential scarcity in the future if actions are not taking to face it. For the contrary, the maximum values to be obtained with the method is 0.67 if the treatment capacity is zero and the recharge overpass the abstraction by 134 times and close to one when recharge overpass 13.4 times the abstraction and the treatment capacity is 100%, the maximum value to obtain is 1 (See Table5. 9).

Table 5. 9 Groundwater availability index testing for different values.

Groundwater abstraction (Mm3/year)	Water recharge (Mm3/year)	Water human consumption (Mm3/year)	Wastewater treated (Mm3/year)	I_{abs-re}	I_{TC}	I_{wa}
1	1	2	0	0.000	0.000	0.000
1	1	2	2	0.000	1.000	0.330
2	1	2	0	-1.000	0.000	-0.670
2	1	2	2	-1.000	1.000	-0.340
3	1	2	0	-2.000	0.000	-1.340
3	1	2	2	-2.000	1.000	-1.010
1	2	2	2	0.500	1.000	0.665
1	2	2	0	0.500	0.000	0.335
1	3	2	2	0.667	1.000	0.777
1	3	2	0	0.667	0.000	0.447
1	4	2	2	0.750	1.000	0.833
1	4	2	0	0.750	0.000	0.503
1	5	2	2	0.800	1.000	0.866
1	5	2	0	0.800	0.000	0.536
1	134	2	0	0.993	0.000	0.665
1	13.4	2	2	0.925	1.000	0.950

Some studies indicate the susceptibility of the study area to the pollution and groundwater extraction, mainly because of the hydrogeological properties of the aquifer (shallow water levels and permeability) (Belmonte-Jiménez et al., 2001, Belmonte-Jiménez et al., 2005, Ramos Leal et al., 2012).

Groundwater availability is an essential issue in agriculture areas, since the economy depends on the water resource, mainly because agriculture process takes more or less the 80% of the resource (USDA, 2019), in the last years an increasing problem of water scarcity and pollution have been experienced in the central valleys of Oaxaca, and it can be noticed in the abstraction level and the low treatment capacity of the area. However, this is a general problem around the world, during the 20th century a rapid intensification of the groundwater exploitation as well as a different perspective of groundwater that allow emerging integrated groundwater management and governance, marking a radical historical change in the relation between human society and groundwater (Van der Gun, 2019).

3. 2 Uncertainty and sensitivity

The development of the conceptual and perceptual model is per se qualitative and the statement of boundary conditions, aquifer heterogeneities could bring uncertainties in the modeling process, so the process demands the acquisition of field parameters that allow the quantitation of errors (Nobre and Sykes, 1992). There are many sources of uncertainties in the modeling process, such as data acquisition, assumption, spatial data interpolation, assigning of weighs in the AHP (Nobre et al., 2007). Validation of the modeling process can be conducted by the result comparison with another Groundwater availability or vulnerability studies carried out in the area. Belmonte 2006, 2008 , mention the pollution and groundwater extraction present in the area, while Ojeda 2017, 2018, present the water recharge reduction and groundwater depletion levels due the population growth, increase of impervious surfaces, climate change among other, which is traduced in a constant pressure upon the groundwater resource, which leads the groundwater resource to a future scarcity situation.

A sensitivity analysis was conducted to evaluate the relative impacts of groundwater abstraction, water recharge, water for human consumption, and wastewater treated in the groundwater availability. Table 5.10 presents the correlation between the parameters, and Table 5.11 shows the correlation coefficient with the Monte Carlos analysis.

Table 5. 10 Pearson Correlation Coefficients among the parameters in the central valleys of Oaxaca

	Groundwater abstraction	Water recharge	Water for human consumption	Wastewater treated
Groundwater abstraction	1	0.59	0.92	0.37
Water recharge		1	0.68	0.5
Water for human consumption			1	0.63
Wastewater treated				1

Table 5. 11 Partial rank correlation coefficient and ranks for the input factors

Input parameters	PRCC	Rank
Groundwater abstraction	-0.865	2
Water recharge	0.941	1
Water for human consumption	-0.291	4
Wastewater treated	0.298	3

The most sensitive parameters in the calculation of groundwater availability are groundwater abstraction and water recharge with indices significantly broader than ±0.5, reaching the values of -0.865 for groundwater abstraction and 0.94 for water recharge (Figure 5.5).

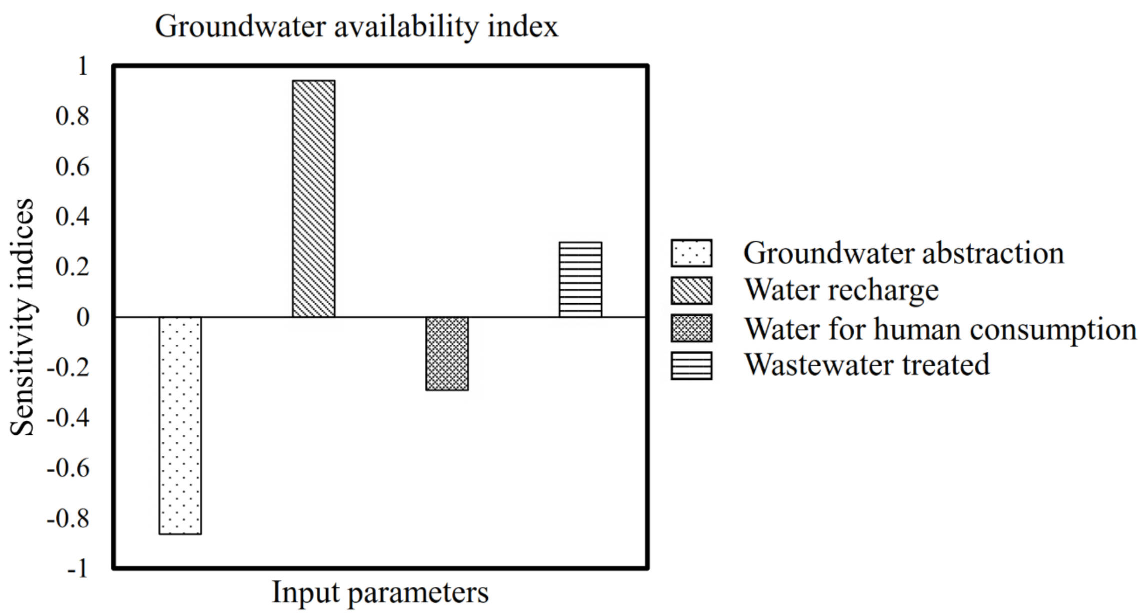

Figure 5. 5 Sensitivity indices for groundwater availability index in the study area

Groundwater abstraction present an inverse relationship indicating that increases in the abstraction level will reduce the groundwater availability, producing problems of availability, the same inverse relationship can be found in the water for human consumption, if the consumption increase water availability will be reduced, for the contrary the increase in the treatment capacity could help to improve water availability in a 33%. Water availability will depend on the recharge ratios of the study area, and those depend on hydrogeological features, external and anthropogenic factors as climate change, soil type, hydraulic conductivities and land use/land change, increase of impervious surfaces, loss of recharge areas among others.

4 CONCLUSIONS

Groundwater is a susceptible resource, which availability will depend on abstraction level and water recharge rates since both represent the 67% of the water availability if abstraction and human consumption (related with the population growth) increase water availability will decrease. While abstraction level can be regulated, water recharge not because it depend on the climatological condition and hydrogeological features but we can prevent the reduction of the infiltration rates by managing the land use/land change, the increase of impervious surfaces, the urban areas spread and the loss of recharge areas. The increase of treatment capacity and reuse of sewage would help to face the groundwater availability problem, increasing the availability of water, and reducing the pressure in the aquifer system.

The study indicates some trends: As human population increase groundwater abstraction increase and water recharge remain the same with a reduction trending according to some studies conducted in the study area, water treatment capacity have increased in the last 30 year but still is not enough to cover the 100% of the treatment need, which mean water pollution is severe problem in the central Valleys of Oaxaca, indicating negative values in the groundwater availability index. Future water policies should further decrease water withdrawal from the aquifer within the Central Valleys of Oaxaca, and increase the treatment capacity to reuse the wastewater and increase the water availability in the area.

The research described here aimed at assessing groundwater availability by employing an integrated approach that includes potential water pollution. Groundwater availability index could be an excellent decision-making tool to be considered in water resource management programs in areas with scarce information, and it could help in the land use/land change planning. The use of Fuzzy-AHP methodologies with the integration of geographic information systems will provide the mechanism to evaluate and identify areas of water scarcity, which have to be emphasized for groundwater monitoring and abstraction regulations. The methodology proposed could lead to a low-cost, effective approach to evaluate groundwater resource in developing countries to manage groundwater resource for future generations by understanding the extend and type of water availability problems between different regions and periods in a quickly and easy way that allow take quick actions to face the problem.

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Chapter 6. General conclusions

Water resources, especially groundwater, play a crucial role in economic and social development, and the population is so dependent on water to produce goods and services. This dependence can evolve into a susceptible situation and two possible scenarios, the reduction of the water supplies (water scarcity) and pollution of the water sources. The availability of groundwater resources (quantity), will depend on two essential parameters, abstraction volumes, and water recharge ratios. The last one depends on climatological conditions and changes and hydrogeological features; nevertheless, water recharge ratios can decrease with the increase of impervious surfaces, the urban areas spread, and the loss of recharge areas. It makes groundwater a high-risk resource due to fluctuating recharge rates and human activities. So, three global stressors always put the resource at risk, climate change, land use/land cover change and population growth. When the population grows the amount of water need for water consumption, food production will increase; at the same time, its quality will diminish. At the same time, land use/land cover will change, increasing the urbanization and the agriculture areas so supply the human demand for accommodation and food, promoting the increase of impervious surfaces and the loss of recharge areas.

Water management should include an integral plan to preserve this recourse, and water policies should implement regulation that permits reductions of groundwater abstraction, identification of water recharge areas, promoting of induced water recharge, protection of the forest cover and an increase of the water treatment capacity, avoiding water bodies pollution and providing an alternative water sources, making the water 100% recyclable, improving water availability, especially when scenarios predict reduction in the recharge due to climate change affectations, in the near and medium future.

The implementation of simple models to evaluate and study the groundwater resource are needed especially in areas of developing countries where the access to information is limited, and the lack of monitoring or historical data is scarce; a common situation found in the study area — allowing the application of efficient management tools with less quantity of data, granting a quick response that lets the application of adaption strategies.

This study, evaluate the main stressors for water depletion and pollution and how they are related and developed two simple models to evaluate groundwater resource, the first consider abstraction, water recharge, runoff, pollution, and marginalization as indicators of groundwater vulnerability, while the second considers the wastewater treatment capacity to evaluate water availability in terms of quantity and quality; which can be an essential management tool to help in the study and conservation of groundwater resource.