Climate change effects on groundwater recharge in Yucatan Peninsula.

Application of water balance models to GCMs

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Abstract:

The effects of climate change are significant on groundwater recharge. In regions with socioeconomic structures highly dependent on this kind of water source, expected positive and negative variations in temperature and precipitation respectively, will have a negative effect on the recharge of groundwater and, consequently, on the future well-being of their inhabitants. In this paper we aim at estimating the effect that changes in climatic parameters will have on groundwater recharge in one of these areas: the Yucatan Peninsula (Mexico). We apply a monthly water balance model to five distinct Global Circulation Models in the near horizon (2015-2039), with RCP 4.5 and 8.5. In average terms, our results estimate a current recharge between 118 ± 33 mm per year, which represents around 10% of the total annual precipitation, and a reduction of 23% of groundwater recharge, a result which clearly threatens the future socioecological equilibrium of the region.

Keywords: Climate change; Groundwater recharge; Yucatan Peninsula; Monthly water balance model
1. Introduction

The effects on climate change are already perceptible in many places around the world, with changes in precipitation (temporal distribution and intensity) (Dore, 2005; Gao et al., 2018; Madsen et al., 2014; Trenberth, 2011), increasing and more threatening periods of drought (Dale et al., 2001, Magaña et al., 1999, Mulholland et al., 1997), and with a generalized increase in temperatures (Jauregui, 2005, Liverman & O’Brien, 1991, Schär et al., 2004). This rise in the global temperature causes at the same time an increase in potential evapotranspiration which, combined with rainfall variations, can modify the hydrological cycle of any region (Findlay, 2003, Green et al., 2011, R. G. Taylor et al., 2013). All these factors, combined with the effects caused by the growth and development of societies (i.e. modifications in water flows and water supply, transformation of the stream network, changes in runoff characteristics, land use, deforestation and urbanization) (Grobick, 2010, Savenije et al., 2014), are causing significant alterations in the water balance, and negative effects in water availability (Bates et al., 2008, Milly et al., 2005). In the particular case of coastal regions with socioeconomic activities mostly based on tourism and/or the tertiary sector, and highly dependent on groundwater sources and recharge (Pulido-Velazquez, Renau-Pruñonosa, et al., 2018), modifications in water flows and supply, together with changes in runoff characteristics and salinity in coastal aquifers, make alterations in the water balance much more critical (Aranda-Cirerol et al., 2010, Marin & Perry, 1994). For these reasons, assessing and quantifying the potential impact of climate change on water resources is an imperative task, especially for those regions with a generalized lack of bioclimatic data like the Yucatan Peninsula, in Mexico.

The IPCC Fourth Assessment Report (IPCC, 2007) identified a knowledge gap concerning the impact of climate change on groundwater resources, and how it affects hydrogeological processes in both direct and indirect ways. Since then, different studies have been carried out to analyze the relationship between, and variables involved in, climate change and groundwater recharge. For example, Green et al. (2011), Kløve et al. (2014), Meixner et al. (2016), Smerdon (2017), Taylor et al. (2013), (Holman et al., 2012) compiled key factors and described the effects of climate change on groundwater and dependent ecosystems. Ali et al. (2012) used climatic data from global circulation models (GCM) (D. M. Allen et al., 2010, Huebener et al., 2007, IPCC, 2013, Pulido-Velazquez, Collados-Lara, et al., 2018, von Storch et al., 1993) to project the effects of climate change on specific regions. Herrera-Pantoja and Hiscock (2008) applied a methodology based on a model of soil moisture balance, with a daily data generator to project the repercussions in recharge.
Here we aim at assessing the water balance of the hydrological region XII (CONAGUA & SEMARNAT, 2012) located in Yucatan Peninsula (YP) to determine the possible effects that climate change will have on the groundwater recharge. We consider different methods for the estimation of the potential evapotranspiration, and we include the effect of land uses and land cover (LULC) in the soil moisture storage capacity to analyze their influence in the variability of groundwater recharge. No similar analysis has been found for this same region and scale in the literature. The effects of climate change are analyzed using climatic data from GCM as input parameters in several groundwater recharge scenarios, and considering the variations in precipitation and temperature. Knowing these potential changes, will allow making a better planning of resources, generating more awareness in future allocations of water use and establishing new extraction limits that guarantee a sustainable water use in the YP.

Another contribution is to generate a tool for visualizing results (section 4.1), which allows the user (decision makers) to make personalized analyzes in different subregions, and choose different GCMs to visualize their effects on vertical recharge in the Yucatan Peninsula.

2. Materials and methods

In this section we present, firstly, the groundwater characteristics description of the region; secondly, the water balance model, including information about precipitation, temperature, soil moisture storage capacity and sub-models for evapotranspiration. Finally, we describe the processes of (1) combining water balance and climate change models and (2) adapting to a reduction of scale for the region.

2.1. Groundwater characteristics in Yucatan Peninsula

In 2010, 13 hydrological-administrative regions were defined by The National Water Commission of Mexico (CONAGUA), being the Yucatan Peninsula the Hydrological-Administrative Region XII (RHA-XII-PY) (CONAGUA, 2016). It includes the states of Yucatan, Quintana Roo, and Campeche. It is located in the southeastern part of Mexico and it has a territorial extension of 139,897 km² (CONAGUA, 2015a). The main source of water in the YP is groundwater, due to its topological and geological characteristics –karstic platform with dolomites, limestones, and evaporites—, surface-water runoff and drainage are practically non-existent, with the exception of some southern parts of the Peninsula (Campeche and Quintana Roo) (CONAGUA, 2015a) (Gondwe et al., 2010), whereby rainwater evaporates, it’s absorbed by plants, soil and infiltrates to the subsoil (Estrada Medina & Cobos Gasca, 2012).
Additionally, the high groundwater level and the lack of soil, make the solutes infiltrate to the groundwater, making it vulnerable to contamination (Aranda-Cirerol et al., 2010, Pérez Ceballos & Pacheco Ávila, 2004).

The high rainfall (CONAGUA, 2015a, INEGI, 2015), the great infiltration capacity of the karstic rock, and the reduced topographic slope favors the renewal of the YP groundwater, so practically the whole area behaves as a recharge zone (Bauer-Gottwein et al., 2011, Holliday et al., 2007). However, although the aquifer receives abundant recharge, deforestation and climate change effects in the region (i.e., less precipitation and temperature increase), suggest that the recharge will be diminished in the next years (Alan et al., 2015, Sánchez Aguilar & Rebollar Domínguez, 1999).

Scientific research studies have been carried out in the region in order to establish the groundwater recharge volume for the following purposes essentially (Table 1): (a) to describe the hydrological functioning of the area (Bauer-Gottwein et al., 2011, INEGI, 2002, Lesser, 1976, SEMARNAT, 2015, Villasuso & Méndez, 2000), (b) to establish the permissible limits for water extraction and supply (CONAGUA, 2015b), (c) to analyze the vulnerability of water resources (Beth I. Albornoz-Euán, 2007, Pérez Ceballos & Pacheco Ávila, 2004, Torres et al., 2014), and (d) to characterize the groundwater flows that exist in the region (González-Herrera et al., 2002).

Table 1. Summary of YP recharge studies. \((P\), precipitation, \(ET_a\), actual evapotranspiration, \(R\), recharge, \(NA\), not available/specified)
Complementary, studies on climate change impacts in the region have focused in relevant aspects, like changes on bioclimatic parameters description (Orellana et al., 2009), or the analysis of the vulnerability index of the aquifer to polluting agents (Bethsua Iztaccihuatl Albornoz-Euán et al., 2017). Nevertheless, a study about the effects of climate change on groundwater recharge in YP from a monthly water balance model, applied at a regional scale such as this study has not been found in the existing literature.

### 2.2. Water-balance model for Yucatan Peninsula

A water balance consists on the application of the mass conservation principle to a whole basin, or to a part of it, constrained by some boundary conditions, and during a period of time (Alley, 1984). The difference between the total of inputs and outputs must be equal to the storage variation (equation 1). When the unit of time is large, the variations in the stored volume are negligible and, in that case, inputs equal the outputs (Schulz & García, 2015).

\[
\text{Inputs} - \text{Outputs} = \Delta \text{Storage}
\]  

The recharge of groundwater \((R)\) can be explained following the precipitation path (Charles, 2003). An amount of the precipitation \((P)\) is returned to the atmosphere through evapotranspiration. Actual evapotranspiration \((ET_a)\) refers to water that returns to the atmosphere from vegetated areas by the evaporation of soil, plant surface, and soil, water absorbed by the plants roots and transpired through leaves. Water infiltrated into the soil that is not returned to the atmosphere by evapotranspiration moves vertically downwards, going into groundwater when it reaches the saturated zone (Figure 1). Surface runoff \((RO)\) processes have not been
considered since they do not practically occur in the study area due to the high infiltration capacity of karstic formations.

The groundwater recharge was established as potential aquifer recharge (PAR) because we consider that it is all water which filtrate below the root zone (Pulido-Velazquez, Collados-Lara, et al., 2018, Rushton, 1988) and includes excess precipitation that exceeds the maximum of soil-moisture storage capacity (STC) (de Vries & Simmers, 2002).

![Water-balance model diagram](image)

Figure 1. Water-balance model diagram. Adapted from (McCabe & Markstrom, 2007)

According to the physical conditions of the YP and the methodology for estimating the monthly water balance, the following assumptions were considered:

- The entire surface works as a recharge area (Bauer-Gottwein et al., 2011, Holliday et al., 2007).
- Runoff is considered negligible given the reduced topographic slope and geology characteristics (Beth I. Albornoz-Euán, 2007, Carballo Parra, 2016, Cervantes Martínez, 2007, Gondwe et al., 2010).
Groundwater recharge includes, but does not distinguish between, recharge to aquifers and non-aquifers.

Our model only includes natural groundwater recharge, and dismiss withdrawals of groundwater.

Changes in the parameters of land use change caused by human intervention, as well as the effects on soil cover, and vegetation patterns (Section 4.2) were omitted.

Recharge from surface water bodies and submarine groundwater discharge (SGD) (Null et al., 2014) are discarded.\(^1\) To calculate the recharge, we adapted the monthly water balance model developed by Thornthwaite (Thornthwaite, 1948, Thornthwaite & Mather, 1955, 1957) (equation 2). We consider model type \(T\) properties, described by Alley (1984). In this type of models, it is assumed that the soil has a specific soil-moisture storage capacity \(STC\), and moisture is added or subtracted monthly, depending on whether the precipitation is greater or less than evapotranspiration, as long as it remains within the maximum capacity of soil moisture \(SM\) (Alley, 1984).

\[
R = P - \Delta SM - ET_a \tag{2}
\]

2.2.1. Precipitation and temperature

Our objective in the use of these specific climatological data is to compare the results of historical data with the different climate change scenarios of the Digital Climatic Atlas of Mexico (DCAM) (Fernandez-Eguiarte A., J. Zavala-Hidalgo., 2010, A Fernández Eguiarte et al., 2015a) presented under the same format and spatial resolution. In addition, due to its very high spatial resolution, the deployment of the maps covers the national, state, municipal and regional scales.

Precipitation and temperature data were obtained by A Fernández Eguiarte et al. (2014, 2015a).

Agustín Fernández Eguiarte et al. (2014) calculated bioclimatic parameters from a daily climatological database from the Mexican National Meteorological Service (SMN) and from year 1961 to year 2000. In this work, daily data from more than 5200 meteorological stations

\(^1\) Surface water bodies and SGD occurs around the coast of the peninsula with estimated discharges between 23,500 m\(^3\) km\(^2\) d\(^{-1}\) (Hanshaw & Back, 1980) and 40,000 m\(^3\) km\(^2\) d\(^{-1}\) (Valle-Levinson et al., 2011).
were processed to obtain monthly values for bioclimatic parameters for each one of the meteorological stations, considering only those stations with more than thirty years of records. Subsequently, they obtained the difference between monthly averages of each station, and the corresponding value in the average monthly climatic surface of the WorldClim-Global Climate Data base (1950-2000)\(^2\) (Hijmans et al., 2005). From the set of differences, they eliminated the stations whose values were above or below 2 standard deviations in each corresponding month. Finally, they applied spatial interpolation of the remaining differences using inverse distance weighted method (IDW) (Lu & Wong, 2008) at very high resolution (926 m) according to the same methodology implemented by Hijmans et al. (2005), which was added to the reference surface of WorldClim-Global Climate Database. From these source data, in this paper we use monthly averages of maximum, minimum, and mean temperature, as well as accumulated monthly precipitation for the area RHA-XII-PY.

2.2.2. Soil-moisture storage capacity

Soil-moisture storage capacity \(STC\) (equation 3) or water holding capacity (Thornthwaite & Mather, 1955, 1957) is the total amount of water in the soil (reserve) that is susceptible to evapotranspiration (British Columbia & Ministry of Agriculture, 2015). It depends mainly on two factors: the root depth of the vegetation \(RDV\) and the available water capacity \(AWC\), which is related to soil characteristics, such as texture, and percentages of organic matter or sands and clays (Thornthwaite & Mather, 1957).

\[
STC = AWC \cdot RDV
\]

\(AWC\) can also be explained as the water available to plants from the time the soil stops draining water to the time the soil becomes too dry to prevent permanent wilting. It is calculated (equation 4) as the difference between field capacity \(FC\) and permanent wilting point \(PWP\) (British Columbia & Ministry of Agriculture, 2015, Kirkham, 2014, USDA Natural Resources Conservation Service, 1998).

\[
AWC = FC - PWP
\]

\(^2\) Interpolated climate surfaces for global land areas at a spatial resolution of 30 arc s.
\( FC \) and \( PWP \) can be obtained empirically (equations 5 and 6) considering the percentages of sand (\( \%s \)) and clay (\( \%c \)) in the soil, (Saxton & Rawls, 1986) (equations 7 and 8).

To obtain the values of AWC for YP, percentages of sand and clay from the soil profiles were taken from INEGI (2014, 2013a).

\[
FC = \left( \frac{0.3333}{A} \right)^{B^{-1}}
\] (5)

\[
PWP = \left( \frac{15}{A} \right)^{B^{-1}}
\] (6)

with

\[
A = \exp(-4.396 - 0.0715(\%c) - 0.000488(\%s)^2 - 0.00004285(\%s)^2(\%c))
\] (7)

and

\[
B = -3.14 - 0.00222(\%c)^2 - 0.00003484(\%s)^2(\%c)
\] (8)

Land-use / land cover (LULC) plays an important role in the retention of water in the soil. Tropical forests have deeper roots so that water retention is greater than in pastures. The depth of mature roots is given by Thornthwaite and Mather (1957), according to the type of vegetation cover (Table 2). Five categories of typical vegetation-root depths for five different soil types are provided (Charles, 2003). These parameters have been associated with the different land uses given by INEGI (2013b). The 75 different land uses have been grouped according to the maximum root depth ranges (see supplementary information, Table 1). Soil layers and LULC have been integrated with the parameters established for each component so \( STC \) values for the entire region can be obtained (Figure 2). The combination of soil and LULC data gives us a specific \( STC \) value for each YP area, that ranges from 50 to 300 mm, with an average\(^3\) of 118 mm, and a standard deviation of 38 mm.

\[^{3}\text{According Messina and Conner (1998) when } STC \text{ is unknown, 150 mm is considered as a globally accepted value. For YP } STC = 100 \text{ is a commonly accepted value (Orellana et al., 2009).}\]
Table 2. Maximum mature root depth (m). Source: (Charles, 2003, Thornthwaite & Mather, 1957)

<table>
<thead>
<tr>
<th>Soil Texture Classes</th>
<th>INEGI Classification</th>
<th>Shallow-rooted</th>
<th>Moderately-rooted</th>
<th>Deep-rooted</th>
<th>Orchard</th>
<th>Mature forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine sand</td>
<td>A</td>
<td>0.509</td>
<td>0.762</td>
<td>1.015</td>
<td>1.524</td>
<td>2.539</td>
</tr>
<tr>
<td>Fine sandy loams</td>
<td>L</td>
<td>0.509</td>
<td>1.015</td>
<td>1.015</td>
<td>1.692</td>
<td>2.030</td>
</tr>
<tr>
<td>Silt loams</td>
<td>Cl</td>
<td>0.634</td>
<td>1.015</td>
<td>1.271</td>
<td>1.524</td>
<td>2.030</td>
</tr>
<tr>
<td>Clay loams</td>
<td>Cr</td>
<td>0.405</td>
<td>0.814</td>
<td>1.015</td>
<td>1.015</td>
<td>1.625</td>
</tr>
<tr>
<td>Clay</td>
<td>R</td>
<td>0.253</td>
<td>0.509</td>
<td>0.677</td>
<td>0.677</td>
<td>1.189</td>
</tr>
</tbody>
</table>

Figure 2. Left: Soil group (AWC). Center: Vegetation root depth category. Right: Soil-moisture capacity (STC) in the Yucatan Peninsula

2.2.3. Evapotranspiration

The estimation of the potential evapotranspiration $ET_0$ was made with several temperature-based methods, since temperature is the fundamental and only parameter available in the definition of the different climate change scenarios (Table 3 and equations 9 to 12). Results are compared with a $ET_0$ reference value, estimated globally by FAO (2017).
Table 3. List of $ET_0$ calculation methods considered in this paper.

<table>
<thead>
<tr>
<th>Method (AKA)</th>
<th>Reference</th>
<th>Formula</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thornthwaite (THO)</td>
<td>Thornthwaite (1948)</td>
<td>$ET_0 = 16 \left( \frac{10 \times T_i}{I} \right)^\alpha \frac{N}{12} \frac{d}{30}$</td>
<td>$T_s, I, \alpha, N, d$</td>
</tr>
<tr>
<td>Hamon (HAM)</td>
<td>Hamon (1961)</td>
<td>$ET_0 = \frac{d \cdot 2.1 N^2 \cdot e_s}{T_i + 273.2}$</td>
<td>$T_s, e_s, N, d$</td>
</tr>
<tr>
<td>Hargreaves (HAR)</td>
<td>Hargreaves and Samani (1985)</td>
<td>$ET_0 = d \cdot 0.0023(T_{max} - T_{min})^{0.424}Ra$</td>
<td>$T_{max}, T_{min}, Ra$</td>
</tr>
<tr>
<td>Blaney-Criddle (BLA)</td>
<td>Blaney and Criddle (1950)</td>
<td>$ET_0 = a + bp(0.46T_i + 8.13)$</td>
<td>$T_s, a, b, p$</td>
</tr>
<tr>
<td>Average (AVG)</td>
<td>Combined</td>
<td>Average of all previous</td>
<td></td>
</tr>
</tbody>
</table>

The different parameters in Table 3 are defined as follows:

- $T_i$, mean temperature for each month $i$, in °C.
- $I$, annual heat index, (equation 13):

$$I = \sum_{i=1}^{12} \left( \frac{T_i}{5} \right)^{1.514}$$  \hspace{1cm} (13)

- $\alpha$, constant (equation 14):

$$\alpha = (I^3 \times 675 \times 10^{-9}) - (I^2 \times 771 \times 10^{-7}) + (I \times 1792 \times 10^{-5}) + 0.49239$$ \hspace{1cm} (14)

- $N$, theoretical sunshine hours for each month (equation 15) (R. G. Allen et al., 1998),

$$N = \frac{24}{\pi} \omega_s$$ \hspace{1cm} [15]

---

4 The exponent of the Hargreaves equation is adjusted from 0.5 to 0.424 according to studies in other regions with similar weather conditions (Tabari et al., 2013).
\( \omega_0 \), radiation angle at sunset time, as a function of the latitude (\( \phi \)) and day of the year (R. G. Allen et al., 1998). Here we use the average day of the month, as suggested by Klein (1977).

- \( d \), number of days for each month.
- \( e_s \), saturated water vapor density term (equation 16):

\[
e_s = 0.6108 \exp \left( \frac{17.27 T_i}{T_i + 237.3} \right)
\]

\( R \), extraterrestrial radiation for a specific latitude and day (R. G. Allen et al., 1998, Duffie & Beckman, 2013),

- \( a \) and \( b \), model parameters related to wind speed, relative humidity, and current insolation. For YP climate conditions: \( a = -1.75 \) and \( b = 1.06 \) (Ponce, 1989),

- \( p \), percentage of total daytime hours for the period over total daytime hours of the year.

\[ ET_a \] depends on the precipitation with respect to the potential evapotranspiration, and the available moisture in the soil for each month \( i \) \( (S_i) \). When \( P \) is greater than \( ET_o \), the soil remains humid, and \( ET_a \) is equal to \( ET_o \). In this case, \( S_i \) is equal to the difference between \( P_i \) and \( (ET_o)_i \) plus the soil moisture quantity of the previous month \( (S_{i-1}) \), as long as the value is less than \( STC \) (equations 17 to 19).

\[ \text{For } P_i \geq ET_o, ET_a = ET_o \text{ else } ET_a = P_i + \Delta S_i \] (17)

\[ \Delta S_i = S_i - S_{i-1} \] (18)

\[ S_i = \min\{(P_i - ET_o) + S_{i-1}, STC\} \] (19)

In contrast, in months when \( P_i \) is less than \( (ET_o)_i \), the soil dries and \( (ET_a)_i \) is lower than \( (ET_o)_i \). Under this circumstance, \( (ET_a)_i \) is equal to \( P_i \) plus the soil moisture that can be withdrawn from storage at the end of month \( i \) \( (\Delta Storage) \) (Alley, 1984, Thornthwaite & Mather, 1955). In this case, \( S_i \) is expressed as (equation 20):

\[ S_i = S_{i-1} \exp \left[ \frac{(P_i - ET_o)}{STC} \right] \] (20)

We can assume that groundwater recharge occurs when \( P_i \) exceeds \( (ET_o)_i \), and \( S_i \) equals \( STC \) (equation 21):
For \( P_t \geq ET_o \) and \( S_t = STC \), \( \Delta R = (P_t - ET_o) - (STC - S_{t-1}) \) else 0 \( (21) \)

To initialize the calculation procedure, an assumption is made: \( S_1 \) is the last month of the wet season (September for YP) and is equal to \( STC \) (Thornthwaite & Mather, 1957). However, in regions where annual \( ET_o \) is greater than precipitation, available moisture in the soil remains below \( STC \) so a second integration of the procedure is necessary to perform an adjustment to the initial value of \( STC \), assuming that \( S_{13} = S_1 \) until reaching \( S_{24} = S_{12} \).

According to the 4 methods (Table 3) and FAO’s reference \( ET_o \), the average \( ET_o \) value for the YP is 1420 mm ± 117 mm, with slight differences between the states:

- Campeche: 1432 mm ± 117 mm
- Quintana Roo: 1400 mm ± 118 mm
- Yucatan: 1430 mm ± 118 mm

As shown in figure 3, results\(^5\) for the different methods show \( ET_o \) average values from 1040 mm to 1161 mm. Compared with the rest of the methods, and the FAO reference values, the THO method overestimates \( ET_o \). This is in accordance with observations of Alkaeed et al. (2006), highlighting the inconvenience of using this method for humid climates. Thus, here we do not include this method for obtaining the average value for groundwater recharge.

\(^5\) Data visualization: https://public.tableau.com/profile/edgar.rodriguez.huerta#!/vizhome/EstimationActualEvapotranspirationYuca tan/ETa_final
2.3. Climate change scenarios

The effects of climate change in the RHA-XII-PY are based on 4 different General Circulation Models (GCM) and an ensemble average (REA) (Table 4). All GCM contemplate two Representative Concentration Pathways (RCP): 4.5 (low emissions) and 8.5 (high emissions) in the near future 2015-2039. Databases are available in the corresponding climatic atlas update for Mexico (A Fernández Eguiarte et al., 2015a).

GCM scenarios of Digital Climatic Atlas of Mexico by Fernandez-Eguiarte A., J. Zavala-Hidalgo. (2010) were developed based on 4 of the 15 models of the project ‘Coupled Model Intercomparison Project, Phase 5 (CMIP5)’ (Taylor, 2007, Taylor et al., 2012). CMIP5 provides projections of future climate change on two-time scales, near term (out to about 2035) and long term (out to 2100 and beyond). The proposal to establish a period of 25 years (near-future) is based on a new strategy for climate change experiment (Doblas-Reyes et al., 2011, Hibbard et al., 2007, Kirtman et al., 2013, Meehl et al., 2009), and is according on the needs of the end users defined in the IPCC workshops (Moss et al., 2007).

The adaptation of GCMs to Mexican territory is described in Cavazos et al. (2013), and Fernández Eguiarte et al. (2015). Downscaling method applied is Change Factor Method (CFM) (Hawkins et al., 2013, Matonse et al., 2011, Navarro-Racines et al., 2015, Tabor & Williams, 2010, Wilby et al., 2004). The GCMs were cut in space (0 to 40 N and -140 to -60 W), and the resolution was homogenized (0.5° x 0.5°) by a bilinear interpolation with the CDO platform by Max Planck Institute (Schelzweida, 2019) with the purpose to validate them with several climatological metrics of the East Anglia Climate Research Unit (CRU) (Cavazos et al., 2013).

Subsequently, variation layers were obtained by subtracting the GCM (near-future) values with their reference climatology (1961-2000). The new variation grids were subdivided into 30 x 30" to preserve the original values of each GCM. Finally, these grids in high resolution were added the corresponding historical monthly values (section 2.2.1) that passed through a process of quality control and that consider the topographic factors.
For RCP 4.5, all GCM models estimate an increase in the average annual temperature ($\bar{T}$), which ranges from 0.67 °C to 1.37 °C, while they reach up to 1.43 °C in RCP 8.5. However, precipitation show a different behavior. Two models estimate an increase in annual precipitation of 12 mm and 60 mm in the estimation of precipitation (CNRM-CM5 and GFDL_CM3), while the other three models estimate a reduction of 66 mm on average (5%).

The different results from this part are obtained in two consecutive steps:

1. Firstly, a monthly water balance of RHA-XII -PY is performed with the aid of historical climatic data. This is compared with other studies to observe coherence in our results and to validate the model.

2. Secondly, we apply the same monthly water balance model but this time with estimated climatological data (i.e., precipitation and temperature) for climate change scenarios and for the 2015 -2039 horizon, in order to establish the range of variation in groundwater recharge.
3. Results

3.1. Current recharge

According to the different methods, the recharge of RHA-XII-PY varies from 43 mm (THO) to 143 mm (HAM), with a recharge around 72 mm if we consider the reference values of FAO (Figure 4). The most important recharge areas are the southwestern and northeastern part of the Campeche and Yucatán states (between Cenotillo and Tizimín municipalities) respectively. In general, the northern coast of Yucatan does not receive a vertical recharge contribution. However, the area receives a contribution by groundwater flow. In addition, Figure 4 shows that the recharge occurs between July and November, being September the month with the highest contribution, with 46 mm average of groundwater recharge in the RHA-XII-PY. The months with the highest groundwater recharge contribution in the model corresponds to the weather-related seasons, being the rainy season for the Yucatan peninsula from June to November, with a peak between August and September (CONAGUA, 2015).
Figure 4. Recharge of groundwater (mm) simulation. Top: results for $ET_a$ and methods in Table 3. Bottom: monthly recharge for the whole area of the Yucatan Peninsula.

3.2. Sensitivity analysis

Compared to other studies (Table 1), our results tend to underestimate the groundwater recharge. This can be due to several factors. Firstly, the precipitation data periodicity, since calculations with monthly data tend to underestimate the groundwater recharge by around 3% compared to daily data (Rushton & Ward, 1979). Secondly, according to Rushton and Ward (1979), temperature-based methods underestimate groundwater recharge because they only consider groundwater recharge when the soil reaches its $STC$, which constrains the recharge during
summer months. This is precisely what happens in our model, which underestimates this value around 25%. In these particular cases, Lloyd et al. (1966) suggest modifying $ET_a$ calculation for the months when $P$ is less than $ET_o$. The reason lays in the evaporation rates of dry soils, which can be only 10% of the potential evaporation. Finally, it is necessary to analyze the effect of $STC$ within the model, since usually it is considered as a constant value. To identify these factors, a sensitivity analysis has been performed considering two scenarios:

- Variation in $ET_a$ calculation equal to $P$ plus 10% of $ET_o - P$ (equation 22) when $P$ is less than the $ET_o$;

$$ET_a = P + 0.1(ET_o - P)$$ (22)

- Null variation in $STC$, with a constant value of 100 mm for the whole peninsula (Orellana et al., 2009) to obtain a range closer to the current groundwater recharge (Table 4).

Table 5. Groundwater recharge according to model sensitivity analysis factors. A2: Alternative $ET_a$ (equation 22).

<table>
<thead>
<tr>
<th>Method</th>
<th>Conventional</th>
<th>A2</th>
<th>$STC = 100$</th>
<th>Percent change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A2</td>
</tr>
<tr>
<td>FAO</td>
<td>72.5</td>
<td>96.7</td>
<td>80.1</td>
<td>33%</td>
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<tr>
<td>THO</td>
<td>43.3</td>
<td>59.4</td>
<td>45.8</td>
<td>37%</td>
</tr>
<tr>
<td>HAM</td>
<td>143.4</td>
<td>176.1</td>
<td>153.1</td>
<td>23%</td>
</tr>
<tr>
<td>HAR</td>
<td>102.4</td>
<td>130.0</td>
<td>111.5</td>
<td>27%</td>
</tr>
<tr>
<td>BLA</td>
<td>68.2</td>
<td>91.3</td>
<td>74.7</td>
<td>34%</td>
</tr>
<tr>
<td>AVG</td>
<td>104.7</td>
<td>132.5</td>
<td>113.1</td>
<td>27%</td>
</tr>
</tbody>
</table>

The constant value definition of $STC = 100$, concerning the $STC$ calculated in this study, represents an increase in the groundwater recharge result of around 8%. This change in the evaluation of $ET_a$ has an important effect, since it modifies our previous estimation in approximately 26%, which is aligned with what was reported by Rushton and Ward (1979). Likewise, we observed that THO method underestimates the groundwater recharge due to the high values of $ET_a$, so this method was excluded in the calculation of climate change scenarios. Considering the results shown in table 4, we choose four methods to cover the range of results obtained by evapotranspiration methods:
(1) BLA method (Blaney & Criddle, 1950) as the lower limit of the recharge.

(2) HAM-A2 (Hamon, 1961) with the variation of $ET_a$ calculation described by equation 21 as the upper limit.

(3) Averaging results from HAM, BLA, and HAR methods, according to the methodology of Alley (1984), to obtain $ET_a$ (equation 17–20) (AVG).

(4) Considering the calculation of $ET_a$ according to Lloyd et al. (1966) (equation 22).

Numbers 3 and 4 as intermediate values (AVG-A2).

As expected, there is a direct correlation between precipitation and recharge (Figure 5). We integrate the recharge results with the RHA-XII-PY precipitation data, in order to generate a scatterplot and to identify the relationship that exists between them. In addition to the linear correlation between recharge and precipitation (which serves to make a simple estimate of the recharge from precipitation), a limiting value is observed, where no recharge is produced below 798 mm annual rainfall (Figure 5, red horizontal line). This is a remarkable outcome since it suggests that a region with annual rainfall below this threshold, will stop receiving natural recharge by infiltration.

Figure 5. Correlation between precipitation $P$ and recharge $R$ for every grid (926 x 926 m approximately).
3.3. Climate change effects

When we include $ET_o$ and $ET_o$ values from previous models into the different climate change projections, results show an average annual recharge of 91 mm ± 39 mm, and 94 mm ± 38 mm, for RCP 4.5 and RCP 8.5 respectively. This represents a 22% reduction in groundwater recharge, based on historical data. Table 6 shows recharge values for each method according to the precipitation and temperature estimations of the climate change projections. We observe that an increase in the representative concentration pathway from 4.5 to 8.5, implies a slight reduction in recharge: between 1% and 2%. Results on the percentage of change with respect to current recharge values depend on the chosen methodology: methods that only use mean temperatures for the calculation of $ET_o$ (i.e., HAM and BLA) give the highest recharge decrease (around 24%); the method that includes maximum and minimum temperatures (i.e., HAR) gives a decrease of approximately 13%.

Table 6. Effects of climate change on groundwater recharge in YP. Projections shown for RCP 4.5 and 8.5 include error and percentage change with respect to current values.

<table>
<thead>
<tr>
<th>$ET_o$ calculation</th>
<th>Method</th>
<th>Current</th>
<th>RCP 4.5</th>
<th>RCP 8.5</th>
<th>Percentage change (%)</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>RCP 4.5</td>
<td>RCP 8.5</td>
<td>RCP 4.5</td>
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<tr>
<td>Conventional</td>
<td>HAM</td>
<td>143.4</td>
<td>101.8 ± 39.4</td>
<td>103.5 ± 35.7</td>
<td>-29%</td>
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<tr>
<td></td>
<td>HAR</td>
<td>102.4</td>
<td>87.8 ± 34.7</td>
<td>90.3 ± 30.4</td>
<td>-14%</td>
</tr>
<tr>
<td></td>
<td>BLA</td>
<td>68.2</td>
<td>53.3 ± 24.2</td>
<td>53.7 ± 21.0</td>
<td>-22%</td>
</tr>
<tr>
<td></td>
<td>AVG</td>
<td>104.7</td>
<td>77.5 ± 32.6</td>
<td>79.0 ± 28.9</td>
<td>-26%</td>
</tr>
<tr>
<td>A2</td>
<td>HAM</td>
<td>176.1</td>
<td>130.4 ± 42.8</td>
<td>134.7 ± 40.6</td>
<td>-26%</td>
</tr>
<tr>
<td></td>
<td>HAR</td>
<td>130.0</td>
<td>111.5 ± 40.3</td>
<td>116.6 ± 37.1</td>
<td>-14%</td>
</tr>
<tr>
<td></td>
<td>BLA</td>
<td>91.3</td>
<td>70.1 ± 30.3</td>
<td>72.6 ± 27.9</td>
<td>-23%</td>
</tr>
<tr>
<td></td>
<td>AVG</td>
<td>132.5</td>
<td>100.9 ± 38.3</td>
<td>104.6 ± 35.5</td>
<td>-24%</td>
</tr>
</tbody>
</table>

Four out of five climate change projections (Figure 6) have negative effects on groundwater recharge, being HADGEM2_ES the most dramatic one, with average ranging from 51 mm to CNRM CM5 (A2) with 120 mm. Model GFDL_CM3 estimates an increase in recharge, from 129 mm to 161 mm with RCP 4.5 (approximately 22% of the recharge with historical data) and from 112 to 147 mm with RCP 8.5 (an increase of 10%). Only in the case of
RCP 8.5 with A2 methods for $ET_a$ estimation, GDFL_CM and CNRM-CM5 give higher values than the recharge ones with historical data.

The effect on groundwater recharge across the Yucatan peninsula is certainly heterogeneous. Our models give different patterns of recharge distribution as a result of the effects of climate change on each state of the peninsula. According to our results, the recharge will certainly decrease, with the most relevant effects in the center and northwest, presenting a high risk of not receiving vertical recharge in these areas.

4. Discussion and conclusions

426 Figure 6. Recharge distribution for GCM RCP 4.5 and RCP 8.5. Blue continuous line: Average recharge with historical data. Red dashed line: GCM average.

427 The effect on groundwater recharge across the Yucatan peninsula is certainly heterogeneous. Our models give different patterns of recharge distribution as a result of the effects of climate change on each state of the peninsula. According to our results, the recharge will certainly decrease, with the most relevant effects in the center and northwest, presenting a high risk of not receiving vertical recharge in these areas.

4. Discussion and conclusions

426 Given the irregular and thin thickness of soil layer of the YP, the infiltration from meteoric
recharge (precipitation) is fast, due to fractures, and it’s drained to the aquifer. This supports the idea that base flow comes from the interior of the Peninsula (Neuman & Rahbek, 2007).

Groundwater recharge levels around 118 ± 33 mm·year\(^{-1}\) obtained by our model are in agreement with the estimation obtained with a simple water-balance calculation by Lesser (1976) of 150 mm·year\(^{-1}\) (around 14% of mean annual precipitation), and by Back (1985), Hanshaw & Back (1980), with similar results of Lesser (1976). However, Beddows (2004) estimated a groundwater recharge between 30 and 70% of mean precipitation for Quintana Roo coast. Recently, Gondwe et al. (2010) computed a recharge value equivalent to 17% of average precipitation.

We consider different methods for \(ET_o\) estimation, that allow us to assess uncertainties in this variable in this particular case study. Our model presents a conservative estimate, since it is based on a monthly water balance, and, as mentioned in section 2.2, it dismisses the submarine groundwater discharge (SGD), as well as some parameters of hydraulic diffusivity and transmissivity that determine the groundwater flow and storage through the porosity and fractures of the karstic aquifer (Bakalowicz, 2005). At the same time, it also dismisses groundwater flows, caused mainly by karstic aquifer (González-Herrera et al., 2002, Perry et al., 2009). These flows are assumed to run radially across YP, following the belt of sinkholes (cenotes) (González-Herrera et al., 2002, Steinich & Marín, 1997), starting from Sierrita de Ticul (main physiographic feature with a maximum elevation of 275 meters above sea level) located in the southern of YP, about 70 km south of Mérida (Marín-Stillman et al., 2008) and ending at the northern coast of the peninsula.

According to Bauer-Gottwein et al. (2011), further research is needed in order to estimate precisely the groundwater recharge magnitudes for the YP karst aquifer and coastal outflow from the aquifer to the ocean.

### 4.1. Recharge and water use

When we disaggregate our results at the state-municipality level, we can compare allocated volume for different uses (CONAGUA, 2017) with groundwater recharge for each municipality. Although basic (because it does not consider underground flows to the coast), this process allows the generation of an 'elementary local water ecological footprint' to determine if it is possible to satisfy the regional needs by only covering its 'theoretical' recharge within the administrative boundaries, and only exploiting the aquifer flows that go from south to north, without affecting or intervening in the recharge of neighboring municipalities. We identify sub-
regions where recharge modifications will be most critical in Figure 7, considering method AVG-A2 with GCM CNRM-CM5 RPC 4.5. Location of water permits in YP for every economic sector are shown in Figure 7 (left), with the extension of agricultural activities, industrial hubs, and main urban and tourism (i.e., services) areas on the Caribbean coast.

Municipalities (in population size) and vertical recharge distribution of the groundwater (with GCM results considered as background) are shown in Figure 7 (right), where color indicates the ratio between allocated (i.e., use) and recharge water values.

Municipalities at the northwest region (i.e., North-Yucatan (32) hydrological basin) present the worst ratio (i.e., ~ 66%). With a population of ~ 2,000,000 (45% of the YP population), this region has an actual water consumption of 935 hm$^3$ (72% primary sector, 4% secondary, 2% tertiary, 22% public supply), which represents 20% of the water use in YP (CONAGUA, 2017). However, due to the demographic growth of 20% expected by 2030 (CONAPO, 2010), with an industrial growth in the area linked to the hub port in Progreso, associated with the tourism potential of the coastal zone, water consumption and demand will possibly increase at a higher rate in the upcoming years.

Figure 7. Left: Water uses in YP by sector, size allocated volume (hm$^3$). Right: Ratio between recharge and uses by municipality as color. Population as size.

Official data (CONAGUA, 2019) refer to recharge (and renewable water) as an average result across the YP. Studies on the estimation of recharge on a smaller scale raise awareness
about the differences that exist within the same territory. The application of downscaling methods in climatological data, and in climate change scenarios like the method developed by Fernández Eguiarte et al. (2015) provides more precise information at geographical level than the average recharge of groundwater, habitually used, and even questionable from a regional point of view. Water balance at a lower scale improves our ability to understand and estimates the effects of climate change on water availability.

Regionalization contributes to information support, planning of productive activities, defining the growth of specific areas where the resource may be compromised; and should be considered before allocating water uses, in such a way, avoided locating large extractions in sub-regions with potential risk or vulnerability. For example, the last major water allocation in Yucatan –with 7 hm³ per year, around 26% of water for industrial use (excluding electricity-generation)– (CONAGUA, 2017, Consultores en Prevención y Mitigación de Impactos Ambientales, 2015), was assigned after the environmental impact statement justified the application of projects in Yucatan, because the region (the whole peninsula) has a high annual availability of groundwater, and therefore, ‘will not cause the affectation, stress or significant decrease of the water of the subsoil’. However, the project is located in areas where vertical recharge, as well as availability, is much lower than the average of the entire hydrological region (Figure 7) and does not consider specifications about the actual availability and the effects of the urban contexts that are located to the north, and that will reduce their groundwater flow for their supply.

In this sense, vertical recharge of groundwater (from precipitation) is only one component within a more complex system such as the water cycle, and further research needs to be conducted to analyze the effects on water demand at different spatial level, as well as the groundwater flows in the region, which could buffer the effects of climate change in northern region of YP.

Our study serves as a new reference to describe the problems of groundwater in Yucatan Peninsula. It is a starting point to assess the region's renewable water (mostly from groundwater) considering future demand and socio-economic characteristics.

With the objective of exploring climate change effects on groundwater recharge in the Yucatan Peninsula at different spatial levels our results, open and freely available, have been

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6 Chapter III. Section: conservation criteria, point 12 (Consultores en Prevención y Mitigación de Impactos Ambientales, 2015)
transferred to a dashboard\textsuperscript{7} to compare specific regions (from map cell (926 m x 926 m), municipality, state or hydrological basin (Figure 8). This data visualization tool expects to be and auxiliary display for decision making support, with the objective to simplify the analysis and to deepen into the geographic and socioecological dimensions of water in the Yucatán Peninsula.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{groundwater_recharge.png}
\caption{Variation of groundwater recharge in the Yucatan peninsula caused by climate change.}
\end{figure}

\textbf{Figure 8.} Variation of groundwater recharge in the Yucatan peninsula caused by climate change. Dashboard in Tableau ® (Rodríguez-Huerta, 2018)

4.2. Interaction of groundwater and vegetation

Furthermore, water balance, vegetation and soil dynamics are complex with multiple feedback loops (Asbjornsen \textit{et al.}, 2011, Rodriguez-Iturbe, 2000). Several models (Breshears & Barnes, 1999, Huisman \textit{et al.}, 2009, Kefi \textit{et al.}, 2008, Li \textit{et al.}, 2009, Shnerb \textit{et al.}, 2003, Zhou \textit{et al.}, 2015) describe how alterations in the hydrological cycle change vegetation patterns. A decrease in precipitation will cause greater competition over this resource, which will initiate adjustments in the vegetation. In the first instance, reducing the density of the cover, generating vegetation patterns, and converting what was a uniform cover into another with areas of bare soil until reaching a new equilibrium of the ecosystem (Kefi \textit{et al.}, 2008, Klausmeier, 1999, Shnerb

\begin{footnotesize}
\textsuperscript{7} https://public.tableau.com/profile/edgar.rodriguez.huerta#!/vizhome/GroundwaterrechargeYucatanPeninsula/VIZ
\end{footnotesize}
et al., 2003, Solé, 2011). These interactions can be studied from the theory of complex systems and open a future line of research of the effects of climatic change in YP.

5. Acknowledgments

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### 7. Supplementary information

S.I. Table 1. Land uses are grouped according to the ranges of the maximum root depth

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<th>Description (in Spanish)</th>
<th>Vegetation root depth category</th>
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</tr>
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Vegetación secundaria arbórea de selva baja espinosa caducifolia
Vegetación secundaria arbustiva de selva baja espinosa caducifolia
Vegetación secundaria herbácea de selva baja espinosa subperennifolia
Vegetación secundaria arbórea de selva baja espinosa subperennifolia
Vegetación secundaria arbustiva de selva baja espinosa subperennifolia
Vegetación secundaria herbácea de selva baja espinosa subperennifolia
Pastizal halófilo
Sabana
Vegetación secundaria arbórea de selva de galería
Manglar
Vegetación secundaria arbórea de manglar
Vegetación secundaria arbustiva de manglar
Popal
Tular
Vegetación de petén
Vegetación secundaria arbórea de vegetación de petén
Vegetación halófila hidrófila
Vegetación de dunas costeras
Palmar natural
Sin vegetación aparente
Palmar inducido
Pastizal inducido
Desprovisto de vegetación
Cuerpo de agua
Asentamientos humanos
Zona urbana
7.1. Data Availability

In order to facilitate the model reproduction and apply under different climate change scenarios, the R code is attached in the following link –expecting it will serve as a support for the different hydrological studies that are being developed in the region–.

https://summlabbd.upc.edu/rodriguez-huerta-et-al/