A water balance model to estimate climate change impact on groundwater recharge in Yucatan Peninsula, Mexico

Edgar Rodríguez-Huerta[a], *, Martí Rosas-Casals[a,b] and Laura Margarita Hernández-Terrones[c]

[a] Sustainability Measurement and Modeling Lab (SUMMLab), Universitat Politècnica de Catalunya (UPC – BarcelonaTech), ESEIAAT, Campus Terrassa, 08222 Barcelona, Spain; [b] Institute for Sustainability Science and Technology (IS.UPC), Universitat Politècnica de Catalunya (UPC – Barcelona Tech), Campus Diagonal Nord, 08034 Barcelona, Spain; [c] Universidad del Caribe, L-1. Mz 1, Esq. Fracc. Tabachines SM 78, 77528, Cancún Quintana Roo, México

* Corresponding author: edgar.rodriguez@upc.edu

Abstract:

The aim of this paper is to estimate the effect that climate change will have on groundwater recharge at the Yucatan Peninsula, Mexico. The groundwater recharge is calculated from a monthly water balance model considering eight methods of potential and actual evapotranspiration. Historical data from 1961-2000 and climate model outputs from five downscaled General Circulation Models in the near horizon (2015-2039), with Representative Concentration Pathway (RCP) 4.5 and 8.5 are used. The results estimate a recharge of 118 ± 33 mm·year^{-1} (around 10 % of precipitation) in the historical period. Considering the uncertainty from GCMs under different RCP and evapotranspiration scenarios, our monthly water balance model estimates a groundwater recharge of 92 ± 40 mm·year^{-1} (RCP4.5) and 94 ± 38 mm·year^{-1} (RCP8.5) which represent a reduction of 23% and 20%, respectively, a result that threatens the socio-ecological balance of the region.

Keywords: Climate change; Groundwater recharge; Yucatan Peninsula Mexico; Monthly water balance model

1 Introduction

The effects of climate change are already perceptible in many places around the world, with changes in precipitation (temporal distribution and intensity), (Dore 2005, Trenberth 2011, Madsen *et al.* 2014, Gao *et al.* 2018) increasing and more threatening periods of drought (Mulholland *et al.* 1997, Magaña *et al.* 1999, Dale and Beyeler 2001), and with a generalized increase in temperatures (Liverman and O'Brien 1991, Schär *et al.* 2004, Jauregui 2005). 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, 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 on water availability (Milly *et al.* 2005, Bates *et al.* 2008, Martinez *et al.* 2015). In the particular case of coastal regions with socioeconomic activities mostly based on tourism and/or the tertiary sector, and highly dependent on groundwater (Custodio 2010, 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 (Marin and Perry 1994, Aranda-Cirerol *et al.* 2010).

The Working Group II of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (Jiménez Cisneros *et al.* 2014) 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), Holman *et al.* (2012), Taylor et al. (2013), Kløve et al. (2014), Meixner et al. (2016), Smerdon (2017), compiled key factors and described the effects of climate change on groundwater and dependent ecosystems. In addition, several case studies Bardossy and Van Mierlo (2000), Nyenje *et al.* (2009), Ali *et al.*, (2012), Refsgaard *et al.* (2016) apply bioclimatic output data (precipitation and temperature) of different climate change scenarios to compare the projected groundwater recharge with the groundwater recharge under the baseline climate in specific regions. For these reasons, assessing and quantifying the potential impact of climate change on groundwater resources is a crucial task, especially for those regions with a generalized lack of bioclimatic data like the Yucatan Peninsula (YP), in Mexico.

We focus on the Yucatan Peninsula due to the importance of groundwater for the region. YP is high dependence on groundwater since it is practically the only source of supply (around 90%) (CONAGUA 2019). Also, the demographic and economic growth of YP (under the premise that the region receives a large volume of annual recharge) has caused an accelerated increase in the exploitation of groundwater in the last 15 years (CONAGUA 2017). Besides, changes of water balance are expected for the coming years due to precipitation reduction and temperatures increase on the area (Sánchez Aguilar and Rebollar Domínguez 1999, Ellis *et al.* 2015), jeopardizing the sustainable use of water. Considering the effects of climate change on groundwater recharge is the first step for elaborate management alternatives for climate change adaptation, and generate new boundaries for sustainable yield (Healy 2010) without exceeding recharge, and without putting at risk the natural discharge that covers multiple ecosystem services.

Scientific research studies have been carried out in the region in order to establish the groundwater recharge volume for the following purposes essentially: (a) to describe the hydrological functioning of the area (Lesser 1976, Villasuso and Méndez 2000, INEGI 2002, Gondwe *et al.* 2010, Bauer-Gottwein *et al.* 2011, SEMARNAT 2015), (b) to establish the permissible limits for water extraction and supply (CONAGUA 2015a), (c) to analyze the vulnerability of water resources (Albornoz-Euán, 2007, Pérez Ceballos *et al.*, 2004, Torres *et al.*, 2014), and (d) to characterize the groundwater flows that exist in the region (González-Herrera *et al.* 2002).

In addition, other studies on climate change impacts in the region have focused on 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 (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.

We aim to assess the water balance of the hydrological region XII (CONAGUA 2012) located in YP to determine the possible effects that climate change will have on the groundwater recharge. We consider different temperature-based methods for the estimation of the potential evapotranspiration, and we include the effect of land use and land cover (LULC) in the soil moisture storage capacity to analyze their influence on the variability of groundwater recharge. Throughout this paper, we consider groundwater recharge (R) as the potential aquifer recharge. This is defined as precipitation which filtrates below the root zone and exceeds the maximum of soil-moisture storage capacity (STC) (Rushton 1988, de Vries and Simmers 2002, Pulido-Velazquez, Collados-Lara, *et al.* 2018).

The method was selected considering the available data. Given the region's high dependency on this kind of water input, we can find groundwater recharge studies for YP in the literature. But none of them includes estimation of climate change effects on groundwater recharge, as we have done in this work. In addition, our aim is to identify the differences in groundwater recharge applying bioclimatic output parameters of the different climate change projections. Therefore, we include a model able to estimate groundwater recharge as a function of the available bioclimatic parameters of the different GCMs (i.e., precipitation and temperature).

Another contribution is to generate a tool for visualizing results (section 6), 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 YP.

2 Study area: Yucatan Peninsula

In 2010, 13 hydrological-administrative regions were defined by The National Water Commission of Mexico (CONAGUA), being the YP the Hydrological-Administrative Region XII (RHA-XII-PY) (CONAGUA 2015b). 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 km^2 (CONAGUA 2019) (Figure 1). 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) (Gondwe *et al.* 2010, CONAGUA 2019), whereby rainwater evaporates, it's absorbed by plants, soil and infiltrates to the subsoil (Estrada Medina *et al.*, 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 *et al.*, 2004).

[Figure 1 near here]

The high rainfall (INEGI 2015, CONAGUA 2019), 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 (Holliday et al. 2007, Bauer-Gottwein et al. 2011). Previous studies (Table 1) estimated the groundwater recharge between 155 and 255 mm, and a recharge between 12% to 18% of the total annual rainfall, this range being the consequence of the different methodologies, geographic scale and input data used. However, although the aquifer receives abundant recharge, deforestation and climate change effects in the region (i.e., less precipitation and temperature increase) suggest that this recharge will be diminished in the next years (Sánchez Aguilar and Rebollar Domínguez 1999, Ellis et al. 2015).

[Table 1 near here]

3 Materials and methods

In this section, a description of the water balance model, including information about precipitation, temperature, soil moisture storage capacity, and sub-models for evapotranspiration is presented, followed by a description of climate change scenarios and downscaling method.

The estimation of the effect of the climatic change within the hydrological processes carries several uncertainties (Pechlivanidis *et al.* 2017, Hattermann *et al.* 2018). Uncertainty explores the impact of factors such as data source choice, parameter definition, downscaling methods, as well as GCM selection and emission scenarios. Through the results of our manuscript, we present the standard uncertainty (u), which is considered as the standard deviation from the mean, calculated by the square root of the sum of the squares of the differences between the result of each GCM or evapotranspiration estimation methods x_i (depending on the case) and the general average $\bar{x}$, divided by one less than the number of measurements N (Giorgi and Mearns 2002):

$$u = \left[\frac{\sum_i^n (x_i - \bar{x})^2}{N-1}\right]^{1/2} \quad (1)$$

3.1 Water-balance model for Yucatan Peninsula

A water balance model 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 2). When the unit of time is large, the variations in the stored volume are negligible and, in that case, inputs equal the outputs (Schulz *et al.*, 2015).

$$Inputs - Outputs = \Delta\, Storage \tag{2}$$

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 2). 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.

[Figure 2 near here]

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 (Holliday *et al.* 2007, Bauer-Gottwein *et al.* 2011).
- Runoff is considered negligible, given the reduced topographic slope and geology characteristics (Albornoz-Euán 2007, Cervantes Martínez 2007, Gondwe *et al.* 2010, Carballo Parra 2016).
- 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 were omitted (Section 5).
- Recharge from surface water bodies and submarine groundwater discharge (SGD) (Null *et al.* 2014) are discarded.[1]

To calculate the groundwater recharge, we adapted the monthly water balance model developed by Thornthwaite (Thornthwaite 1948, Thornthwaite and Mather 1955, 1957) (equation 3). 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).

$$R = P - \Delta SM - ET_a \quad (3)$$

3.1.1 Precipitation and temperature

We use the monthly reference climatological database for the period 1961-2000 from meteorological stations of the National Service (abbreviated to SMN in Spanish) with quality control, incorporated topographic effect and with a high spatial resolution (926 x 926 m) (Fernández Eguiarte *et al.* 2015a). The reference climatology is the result of the Digital Climatic Atlas of Mexico (DCAM). DCAM is developed in the Informatics Unit for Atmospheric and

---

[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 and Back 1980) and 40,000 m^3 km^2 d^{-1} (Valle-Levinson *et al.* 2011).

Environmental Sciences (abbreviated to UNIATMOS in Spanish) of the Centro de Ciencias de la Amtósfera of the Universidad Nacional Autónoma de México (abbreviated to UNAM in Spanish) (Fernandez-Eguiarte *et al.* 2010, Fernández Eguiarte *et al.* 2015b).

The monthly averages of bioclimatic parameters are calculated from a daily climatological database from the SMN from 1961 to 2000 from more than 5200 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 Database (1950-2000)[2] (Hijmans *et al.* 2005). From the set of differences, they eliminated the stations whose values were above or below two standard deviations in each corresponding month. Finally, they applied spatial interpolation of the remaining differences using inverse distance weighted method (IDW) (Lu and 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, getting a process of quality control and that consider the topographic factors. 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.

3.1.2 Soil-moisture storage capacity

Soil-moisture storage capacity STC (equation 4) or water holding capacity (Thornthwaite and 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

[2] Interpolated climate surfaces for global land areas at a spatial resolution of 30 arc s.

clays (Thornthwaite and Mather 1957):

$$STC = AWC \cdot RDV \quad (4)$$

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 5) as the difference between field capacity FC and permanent wilting point PWP (USDA (US Department of Agriculture Natural) Resources Conservation Service 1998, Kirkham 2014, British Columbia. Ministry of Agriculture 2015):

$$AWC = FC - PWP \quad (5)$$

FC and PWP can be obtained empirically equations (6) and (7) considering the percentages of sand ($\%s$) and clay ($\%c$) in the soil, (Saxton and Rawls 1986) equations (8) and (9). To obtain the values of AWC for YP, percentages of sand and clay from the soil profiles were taken from INEGI (2014, 2013a):

$$FC = \left(\frac{0.3333}{A}\right)^{B^{-1}} \quad (6)$$

$$PWP = \left(\frac{15}{A}\right)^{B^{-1}} \quad (7)$$

with

$$\mathrm{A} = \exp(-4.396 - 0.0715(\%\mathrm{c}) - 0.000488(\%\mathrm{s})^2 - 0.00004285(\%\mathrm{s})^2(\%\mathrm{c}) \quad (8)$$

and

$$\mathrm{B} = -3.14 - 0.00222(\%\mathrm{c})^2 - 0.00003484(\%\mathrm{s})^2(\%\mathrm{c}) \quad (9)$$

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 material, Table S1). Soil layers and LULC have been integrated with the parameters established for each component, therefore STC values for the entire region can be obtained (Figure 3). 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.

[Table 2 near here]

[Figure 3 near here]

3.1.3 Evapotranspiration

The estimation of the potential evapotranspiration ET_0 was made with several temperature-based methods[4], since the temperature is the fundamental and only parameter available in the definition of the different climate change scenarios (Table 3). Results are compared with a ET_0 reference value, estimated globally by FAO (2017).

[Table 3 near here]

The different parameters in Table 3 are defined as follows:

---

[3] According Messina and Conner (1998) when STC is unknown, 150 mm is considered as a globally accepted value. For YP $STC = 100$ is a commonly accepted value (Orellana *et al.* 2009).

[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).

- $\mathrm{T_i}$, mean temperature for each month i, in °C.
- I, annual heat index:

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5}\right)^{1.514} \tag{10}$$

- α, constant:

$$\alpha = (I^3 \times 675 \times 10^{-9}) - (I^2 \times 771 \times 10^{-7}) + (I \times 1792 \times 10^{-5}) + 0.49239 \tag{11}$$

- N, theoretical sunshine hours for each month (Allen *et al.* 1998):

$$N = \frac{24}{\pi}\ \omega_s \tag{12}$$

- ω_s, radiation angle at sunset time, as a function of the latitude (φ) and day of the year (Allen *et al.* 1998). Here we use the average day of the month, as suggested by Klein (1977).
- d, number of days in each month.
- e_s, saturated water vapor density term:

$$e_s = 0.6108\exp\left(\frac{17.27T_i}{T_i + 237.3}\right) \tag{13}$$

- R_a, extraterrestrial radiation for a specific latitude and day (Allen *et al.* 1998, Duffie and 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.

$\mathrm{ET_a}$ 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 $\mathrm{ET_o}$, the soil remains humid, and $\mathrm{ET_a}$ is equal to $\mathrm{ET_o}$. In this case, S_i is equal to the difference between P_i and

$(\mathrm{ET_o})_\mathrm{i}$ plus the soil moisture quantity of the previous month (S_{i-1}), as long as the value is less than STC:

$$ETa_i = ETo_i \text{ for } P_i \geq ETo_i \quad (14)$$

$$\Delta S_i = S_i - S_{i-1} \quad (15)$$

$$S_i = \min\{(P_i - ETo_i) + S_{i-1}, STC\} \quad (16)$$

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

$$ETa_i = P_i + S_{i-1} exp\left[\frac{(P_i - ETo_i)}{STC}\right] - S_{i-1} \text{ for } P_i < ETo_i \quad (17)$$

We can assume that groundwater recharge occurs when P_i exceeds $\mathrm{ET_{o_i}}$, and $\mathrm{S_i}$ equals STC:

$$\Delta R = (P_i - ETo_i) - (STC - S_{i-1})\ else\ 0 \text{ for } P_i \geq ETo_i\ and\ S_i = STC, \quad (18)$$

To initialize the calculation procedure, we made an assumption: $\mathrm{S_1}$ is the last month of the wet season (September for YP) and is equal to STC (Thornthwaite and Mather 1957). However, in regions where annual $\mathrm{ET_o}$ 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 four methods (Table 3) and FAO's reference $\mathrm{ET_o}$, the average $\mathrm{ET_o}$ value for the YP is 1420 ± 117 mm·year^{-1}, with slight differences between the states:

- Campeche: 1432 ± 117 mm·year^{-1}
- Quintana Roo: 1400 ± 118 mm·year^{-1}
- Yucatan: 1430 ± 118 mm·year^{-1}

As shown in Figure 4, results for the different methods show ET_a average values from 1040 to 1161 mm·year^{-1}. Compared with the rest of the methods, and the FAO reference values, the THO method overestimates ET_a. 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.

[Figure 4 near here]

3.2 Climate change scenarios

In most cases, the selection of GCMs contributes to most of the uncertainty of the impact of climate change (Giorgi and Mearns 2002, Ali *et al.* 2012, Hattermann *et al.* 2018). To represent the range of uncertainty in near-future climate projections, our study in the RHA-XII-PY is based on four different General Circulation Models (GCM) and a reliability ensemble averaging (REA) (Cavazos *et al.* 2013, Colorado-Ruiz *et al.* 2018) (Table 4). Selected GCMs are based on two Representative Concentration Pathways (RCP): 4.5 (low emissions) and 8.5 (high emissions) in the near future 2015-2039, and datasets were downloaded in the corresponding climatic atlas update for Mexico (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)*' which provides projections of future climate change on two-time scales, near term (out to about 2035) and long term (out to 2100 and beyond) (Taylor *et al.* 2012).

The GCMs and REA applied are described in Table 4, indicating the historical period and ensemble. The adaptation of GCMs to Mexican territory (including downscaling) is described by Cavazos *et al.* (2013), and Fernández Eguiarte *et al.* (2015b). Monthly variables used were selected according to the periods defined by the "Digital Climatic Atlas of Mexico" project. For GCM, the historical climate time span used is 1961-2000, and for near-future projections it is

2015-2039. The proposal to establish a period of 25 years (near-future) is based on a new strategy for climate change experiment (Hibbard *et al.* 2007, Meehl *et al.* 2009, Doblas-Reyes *et al.* 2011, Kirtman *et al.* 2013), and it is according to the needs of the end-users defined in the IPCC workshops (Moss *et al.* 2008).

The downscaling method applied is Change Factor Method (CFM) (Wilby *et al.* 2004, Tabor and Williams 2010, Matonse *et al.* 2011, Hawkins *et al.* 2013, Navarro-Racines *et al.* 2015). The GCMs were cut in space (0 to 40 N and – 140 to – 60 W), and the resolution was homogenized (0.5° × 0.5°) by a bilinear interpolation with the Climate Data Operators (CDO) platform by Max Planck Institute (Schelzweida, 2019). Subsequently, monthly variation layers were obtained by subtracting the near future projections values with their respective reference climatology. The new variation grids were subdivided into 30 × 30" to preserve the original values of each GCM for their respective RCPs and horizons. Finally, the corresponding historical monthly values (section 3.1.1) were added to these high-resolution grids. In the case of REA, monthly variations were averaged over a 30 year period (1971-2000) and the validation was made using climatological metrics of the East Anglia Climate Research Unit (CRU) (Cavazos *et al.* 2013, Colorado-Ruiz *et al.* 2018). The apparent inconsistency of comparing time periods with different lengths (1961-2000 vs 2015-2039), is essentially explained in terms of data availability.

[Table 4 near here]

For RCP4.5, all GCM models estimate an increase in the average annual temperature ($\overline{T}$), which ranges from 0.67 to 1.37°C, while they reach up to 1.43°C in RCP8.5. However, precipitation shows a different behavior. Two models estimate an increase in annual precipitation of 12 and 60 mm·year^{-1} in the estimation of precipitation (CNRM-CM5 and GFDL_CM3), while the other three models estimate a reduction of 66 mm·year^{-1} on average (–5%).

The results are divided as follows:

1. Firstly, a monthly water balance model of RHA-XII -PY is performed with the historical climatic data 1961-2000; 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 output data of climate change scenarios and for the 2015 -2039 horizon, in order to establish the range of variation in groundwater recharge.

4 Results

4.1 Current recharge

According to the different methods, the recharge of RHA-XII-PY varies from 43 mm·year^{-1} (THO) to 143 mm·year^{-1} (HAM) If we consider the reference values of FAO (2017), the recharge is around 72 mm·year^{-1} (Figure 5). The most important recharge areas are the southwestern and northeastern part of the Campeche and Yucatan 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 (González-Herrera *et al.* 2002, Bauer-Gottwein *et al.* 2011, Pérez-Ceballos *et al.* 2012). In addition, Figure 5 shows that the recharge occurs between July and November, being September the month with the highest contribution, with 46 mm·year^{-1} 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 YP from June to November, with a peak between August and September (CONAGUA 2019).

[Figure 5 near here]

4.2 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 with monthly periodicity tend to underestimate the groundwater recharge by around 3% compared to daily data (Rushton and 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 19) when P is less than the ET_o:

$$ET_a = P + 0.1(ET_o - P) \quad (19)$$

- Null variation in STC, with a constant value of 100mm for the whole peninsula (Orellana *et al.* 2009) to obtain a range closer to the current groundwater recharge (Table 5).

[Table 5 near here]

The constant value definition of $\mathrm{STC} = 100$, 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 5, we choose four methods using the conventional one proposed by Alley (1984) equation (15) to (18) and four with the modified A2 according to Lloyd et al. (1966) (equation 19):

(1) BLA method (Blaney and Criddle 1950) as the lower limit of the recharge,

(2) HAR (Hargreaves and Samani 1985),

(3) HAM (Hamon 1961) as the upper limit,

(4) Averaging results from HAM, BLA, and HAR methods,

4.3 Relationship between precipitation and recharge

As expected, there is a direct correlation between precipitation and recharge (Figure 6). 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·year^{-1} annual rainfall (Figure 6, red horizontal line); this is a remarkable outcome since it suggests that a region with an annual rainfall below this threshold, will stop receiving natural recharge by infiltration.

[Figure 6 near here]

4.4 Climate change effects

When we apply the different outputs of climate change projections to water balance model, the results show an average annual recharge of 91 ± 39 mm·year^{-1}, and 94 ± 38 mm·year^{-1}, for RCP4.5 and RCP8.5 respectively, which represents a reduction between 23% and 20% 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 concerning 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) have a highest decrease. For example, HAM methods (conventional and A2) decrease between 29% and 24% for RCP4.5 and 8.5, BLA methods reduce between 23% and 21%. While the method that includes the maximum and minimum temperatures (i.e., HAR) gives a much lower decrease, of 14% and 11% for RCP4.5 and RCP8.5, respectively.

[Table 6 near here]

For the case of RCP4.5, the average decrease of the groundwater recharge is 27 and 32mm·year^{-1} for the conventional methods and the A2 respectively. While for the projections RCP8.5, the reduction is 26 and 28 mm·year^{-1} (Figure 7). If we analyze each climate projection output individually, five of the 20 combinations of climate change projections and ET_a have a positive effect groundwater recharge, being GFDL_CM3 the only one with positive effect in RCP and both methods (conventional and A2), with an increase between 7 and 28 mm·year^{-1} compared with historical data. The most dramatic reduction is estimated for HADGEM2_ES (conventional methods) with an average reduction of 54 mm·year^{-1} compared with historical data.

[Figure 7 near here]

Although most GCMs indicate a reduction (including REA), the GCM contributes to most of the uncertainty of the impact of climate change, coinciding with other studies on uncertainty (Giorgi and Mearns 2002, Pechlivanidis *et al.* 2017, Vetter *et al.* 2017, Hattermann *et al.* 2018). The uncertainty related to GCM indicates that our results should be considered with caution since two GCMs (CNRM_CM5 and GFDL_CM3) have different recharge patterns.

The effect on groundwater recharge across the YP 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, west, and northwest, presenting a high risk of not receiving vertical recharge in these areas (Figure 8). Additionally, we present in the supplementary material (Figure S1 and S2), the spatial distribution of the difference in groundwater recharge between projections and historical data for each GCM.

[Figure 8 near here]

5 Discussion

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 is drained to the aquifer; this supports the idea that base flow comes from the interior of the Peninsula (Neuman and Rahbek 2007). The results obtained by our model are in agreement with the estimation obtained with a simple water-balance calculation by Lesser (1976) of 150 $mm \cdot year^{-1}$ (around 14% of mean annual precipitation), and by Hanshaw and Back (1980), Back (1985), 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.

When we disaggregate our results at the state-municipality level, we can compare the 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), allows the generation of an 'elementary local water ecological footprint' to determine if it is possible to satisfy the local needs by only covering its 'theoretical' recharge within the administrative boundaries, and only exploiting the aquifer flows that goes from south to north, without affecting or intervening in the recharge of neighboring municipalities. We identify subregions where recharge modifications will be most critical in Figure 9, considering method AVG-A2 with GCM CNRM-CM5 RCP4.5. Location of water permits in YP for every economic sector are shown in Figure 9 (a), 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 9 (b), 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., approx. – 66%). With a population of approx. 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 2014), 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 9 near here]

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. 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. The results of the present study can provide more reliable future predictions about the potential impact of climate change of groundwater recharge in YP.

For example, the last major water allocation in Yucatan –with 7 hm^3 per year, around 26% of water for industrial use (excluding electricity-generation) (Consultores en Prevención y Mitigación de Impactos Ambientales 2015, CONAGUA 2017), was assigned after the environmental impact statement justified the application of projects in Yucatan, because the region (the whole YP) has a high annual availability of groundwater, and therefore, '*will not cause the affectation, stress or significant decrease of the water of the subsoil*'.[5] 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 9) 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.

Our model presents a conservative estimate, based on a monthly water balance, and, as mentioned in section 3.1, 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, due to karstic characteristics of the 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) (Steinich and Marín 1997, González-Herrera *et al.* 2002), 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. 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

[5] Chapter III. Section: conservation criteria, point 12 (Consultores en Prevención y Mitigación de Impactos Ambientales 2015)

on water demand at a different spatial level, as well as estimate precisely the groundwater recharge magnitudes for the YP karst aquifer and coastal outflow from the aquifer to the ocean, which could buffer the effects of climate change in the northern region of YP.

Although it is usual to use historical periods of the same length, due to the availability of data, the length of the period of historical data differs with the climate change projections (40 vs. 25 years). We assume that using a baseline climate period of 40 years (1961 – 2000) with horizons projections of 25 years (2015 – 2039) does not generate significant differences when estimating monthly variations between future projections and the historical period. However, for future studies and to improve methodological consistency, it would be more convenient to use periods with similar length.

Furthermore, water balance, vegetation, and soil dynamics are complex with multiple feedback loops (Rodríguez-Iturbe 2000, Asbjornsen *et al.* 2011). Several models (Breshears and Barnes 1999, Shnerb *et al.* 2003, Kefi *et al.* 2008, Huisman *et al.* 2009, Li *et al.* 2009, Zhou *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 (Klausmeier 1999, Shnerb *et al.* 2003, Kefi *et al.* 2008, Solé 2011). These interactions can be studied from the theory of complex systems and open a future line of research on the effects of climatic change on YP.

6 Conclusions

We applied a monthly water balance model for the estimation of groundwater recharge in the Yucatan peninsula (YP). We evaluated the effect of the uncertainty generated during the calculation of groundwater recharge based on eight methods of potential and actual evapotranspiration as well as the effect of the soil-moisture storage capacity. In the historical period ((1961 – 2000), groundwater recharge is around 118 ± 33 mm·year^{-1}, which represent about 10% of the precipitation.

Subsequently, we used climate model outputs from four downscaled General Circulation Models (GCM) and a reliability ensemble averaging (REA) in the near horizon (2015 – 2039), with representative concentration pathway (RCP) 4.5 and 8.5 to determine the impact that climate change projections will have on groundwater recharge. Considering the uncertainty from the GCMs projections, our monthly water balance model estimated a groundwater recharge of 92 ± 40 mm·year^{-1} (RCP4.5) and 94 ± 37.9 mm·year^{-1} (RCP8.5), which represent a reduction of 23% and 20% respectively. The selection of GCM generates the greatest uncertainty of the factors in the study. The use of multiple GCMs offers a range of possibilities that should be considered in the definition of policies for determining the sustainable performance of groundwater in the region.

The impact on groundwater recharge will be different across the peninsula. On the one hand, any region where the precipitation falls below 800 mm will compromise its vertical recharge. In this sense, the northern region - where precipitation is lower - will depend even more on groundwater flows coming from the central region, where recharge is expected to decrease. On the other hand, the combination of temperature increase and precipitation reduction will be more evident on the west coast of the region.

These changes in the water cycle of the region should not be ignored and will be an important condition for establishing new limits for the extraction of water in the region. Our study serves as a new reference to describe the problemshed[6] of groundwater in YP. It is a

---

6 Problemshed: It refers where a problem or solution is generated or impacted. It involves a geographical and social context, and it relates actions, influences, and needs. It means a change

starting point to assess the region's renewable water (mostly from groundwater) considering future demand and socio-economic characteristics.

The application of downscaling methods in climatological data and climate change scenarios provides more precise information at the 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. Our results, open and freely available, have been transferred to a dashboard[7] to compare specific regions (from map cell (926 m x 926 m), in order to explore climate change effects on groundwater recharge in the YP at different spatial levels (municipality, state or hydrological basin). This data visualization tool expects to be an auxiliary display for decision making support, to simplify the analysis, and to deepen into the geographic and socio-ecological dimensions of water in the Yucatán Peninsula.

7 Acknowledgements

We thank Luisa Andrade for sharing her work on the map of the Yucatan Peninsula (Figure 1). We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 4 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

---

of perspective of not only considering the watershed, but going more there to include all the stakeholders involved. (Mollinga *et al.* 2007, Daré *et al.* 2018).

7 https://public.tableau.com/profile/edgar.rodriguez.huerta#!/vizhome/GroundwaterrechargeYucatanPeninsula/VIZ

8 Funding

This work was supported by CONACYT-Mexico under Ph.D. grant number 220474.

9 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/

References

Albornoz-Euán, B.I., 2007. *Análisis de riesgo de contaminación de aguas subterráneas utilizando sistemas de información geografica*. Thesis (MSc). Universidad Autónoma de Yucatán (UADY).

Albornoz-Euán, B.I. and González-Herrera, R.A., 2017. Aquifer pollution vulnerability in Yucatan under climate change scenarios. *Ecosistemas y Recursos Agropecuarios*, 4 (11), 275–286.

Ali, R., McFarlane, D., Varma, S., Dawes, W., Emelyanova, I., Hodgson, G., and Charles, S., 2012. Potential climate change impacts on groundwater resources of south-western Australia. *Journal of Hydrology*, 475, 456–472.

Alkaeed, O., Flores, C., Jinno, K., and Tsutsumi, A., 2006. Comparison of several reference evapotranspiration methods for Itoshima Peninsula Area, Fukuoka, Japan. *Memoirs of the Faculty of Engineering, Kyushu University*, 66 (1), 1–14.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop requirements. *Irrigation and Drainage Paper No. 56, FAO*, (56), 300.

Alley, W.M., 1984. On the Treatment of Evapotranspiration, Soil Moisture Accounting, and Aquifer Recharge in Monthly Water Balance Models. *Water Resources Research*, 20 (8), 1137–1149.

Aranda-Cirerol, N., Comín, F., and Herrera-Silveira, J., 2010. Nitrogen and phosphorus budgets for the Yucatán littoral: An approach for groundwater management. *Environmental*

Monitoring and Assessment, 172 (1–4), 493–505.

Asbjornsen, H., Goldsmith, G.R., Alvarado-Barrientos, M.S., Rebel, K., Van Osch, F.P., Rietkerk, M., Chen, J., Gotsch, S., Tobón, C., Geissert, D.R., Gómez-Tagle, A., Vache, K., and Dawson, T.E., 2011. Ecohydrological advances and applications in plant-water relations research: A review. *Journal of Plant Ecology*, 4 (1–2), 3–22.

Back, W., 1985. Hydrogeology of the Yucatan. *In*: *Geology and hydrogeology of the Yucatan and quaternary geology of northeastern Yucatan Peninsula*. New Orleans : LA: Published by New Orleans Geological Society, 99–124.

Bakalowicz, M., 2005. Karst groundwater: A challenge for new resources. *Hydrogeology Journal*, 13 (1), 148–160.

Bardossy, A. and Van Mierlo, J.M.C., 2000. Regional precipitation and temperature scenarios for climate change. *Hydrological Sciences Journal*, 45 (4), 559–575.

Bates, B.C., Kundzewicz, Z.W., Wu, S., and Palutikof, J.P., 2008. *Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*. 2008th ed. Geneva.

Bauer-Gottwein, P., Gondwe, B.R.N., Charvet, G., Marín, L.E., Rebolledo-Vieyra, M., and Merediz-Alonso, G., 2011. Review: The Yucatán Peninsula karst aquifer, Mexico. *Hydrogeology Journal*, 19 (3), 507–524.

Beddows, P.A., 2004. Groundwater hydrology of a coastal conduit carbonate aquifer: Caribbean coast of the Yucatán Peninsula, México, PhD Thesis. University of Bristol, UK.

Blaney, H.F. and Criddle, W., 1950. Determining water requirements in irrigated areas from climatological and irrigation data. *Technical Paper. U.S. Soil Conservation Service*, No. 96 (Washington, D.C.), 48 pp.

Breshears, D.D. and Barnes, F.J., 1999. Interrelationships between plant functional types and soil moisture heterogeneity for semiarid landscapes within the grassland/forest continuum: a unified concept. *Landscape Ecology*, 14 (5), 465–478.

British Columbia. Ministry of Agriculture, 2015. Soil water storage capacity and available soil moisture. *Water conservation Factsheet*, 619.000–1.

Carballo Parra, R.M., 2016. *Identificación del flujo subterráneo como consecuencia de la incidencia de plaguicidas y de cargas hidráulicas en una zona de campo de golf de la Riviera Maya*. Thesis (MSc). Centro de Investigaciones Cientifica de Yucatán, A.C.

(CICY).

Cavazos, T., Salinas, J.A., Martínez, B., Colorado, G., De Grau, P., Prieto González, R., Conde Álvarez, A., Romero Centeno, R., Maya-Magaña, M.E., Rosario de la Cruz, J.G., Ayala Enríquez, M. del R., Carrillo Tlazazanatza, H., Santiesteban, O., and Bravo, M.E., 2013. *Actualización de escenarios de cambio climático para México como parte de los productos de la Quinta Comunicación Nacional (Informe Final)*. Centro de Investigación Científica y de Educación Superior de Ensenada, B. C.; Instituto Mexicano de Tecnología del Agua; Centro de Ciencias de la Atmosfera, UNAM.

Cervantes Martínez, A., 2007. El balance hídrico en cuerpos de agua cársticos de la Península de Yucatan. *Teoría y Praxis*, 3, 143–152.

Charles, E., 2003. *A Method for Evaluating Ground-Water-Recharge Areas in New Jersey*. New Jersey Geological.

Colorado-Ruiz, G., Cavazos, T., Salinas, J.A., De Grau, P., and Ayala, R., 2018. Climate change projections from Coupled Model Intercomparison Project phase 5 multi-model weighted ensembles for Mexico, the North American monsoon, and the mid-summer drought region. *International Journal of Climatology*, 38 (15), 5699–5716.

CONAGUA, 2012. *Programa Hídrico Regional Visión 2030*. Ciudad de México, México.

CONAGUA, 2015a. *Actualización de la disponibilidad media anual de agua en el acuífero Península de Yucatán (3105), Estado de Yucatán*. Ciudad de México, México: Diario Oficial de la Federación.

CONAGUA, 2015b. *Atlas del agua en México 2015*. Ciudad de México, México: Comisión Nacional del Agua.

CONAGUA, 2017. Consulta a la base de datos del REPDA [online]. Available from: http://app.conagua.gob.mx/Repda.aspx [Accessed 3 Jul 2017].

CONAGUA, 2019. *Estadisticas de Agua en México. 2018*. Ciudad de México, México: Comisión Nacional del Agua.

CONAPO, 2014. *Dinámica demográfica 1990-2010 y proyecciones de población 2010-2030 Yucatán*. 1st ed.

Consultores en Prevención y Mitigación de Impactos Ambientales, 2015. *Manifiesto de impacto ambiental para la construcción y operación de infraestructura de Servicios en Cervecería*

Yucateca. Mérida, Yucatán.

Custodio, E., 2010. Coastal aquifers of Europe: an overview. *Hydrogeology Journal*, 18 (1), 269–280.

Dale, V.H. and Beyeler, S.C., 2001. Challenges in the development and use of ecological indicators. *Ecological Indicators*, 1 (1), 3–10.

Daré, W., Venot, J.P., Page, C. Le, and Aduna, A., 2018. Problemshed or watershed? Participatory modeling towards IWRM in North Ghana. *Water (Switzerland)*, 10 (6).

Doblas-Reyes, F.J., van Oldenborgh, G.J., García-Serrano, J., Pohlmann, H., Scaife, A.A., and Smith, D., 2011. CMIP5 near-term climate prediction. *CLIVAR Exchanges*, 16 (2), 8–11.

Dore, M.H.I., 2005. Climate change and changes in global precipitation patterns: What do we know? *Environment International*, 31 (8), 1167–1181.

Duffie, J.A. and Beckman, W.A., 2013. *Solar engineering of the thermal processes*. 4th ed. Wiley.

Ellis, E.A., Romero Montero, A., and Hernández Gómez, I.U., 2015. *Evaluación y mapeo de los determinantes de la deforestación en la Península Yucatán*. México, Distrito Federal: Agencia de los Estados Unidos para el Desarrollo Internacional (USAID), The Nature Conservancy (TNC), Alianza México REDD+.

Estrada Medina, H. and Cobos Gasca, V., 2012. *Programa Nacional contra la sequía PRONACOSE (Informe Final)*. Mérida, Yucatán.

FAO (Food and Agriculture Organization of the United Nations), 2017. Global map of monthly reference evapotranspiration - 5 arc minutes [online]. Available from: http://ref.data.fao.org/map?entryId=db326f70-88fd-11da-a88f-000d939bc5d8 [Accessed 6 Mar 2018].

Fernandez-Eguiarte, A., Zavala-Hidalgo, J., and Romero-Centeno, R., 2010. Digital climatic Atlas of Mexico [online]. *Centro de Ciencias de la Atmósfera, UNAM*. Available from: http://atlasclimatico.unam.mx/atlas/uniatmos_eng.html.

Fernández Eguiarte, A., Zavala Hidalgo, J., Romero Centeno, R., Conde Álvarez, A., and Trejo Vázquez, R., 2015a. Actualizacion de los escenarios de cambio climatico para estudios de impactos, vulnerailidad y adaptacion [online]. *Climatología de referencia: SMN 1961 - 2000*. Available from: http://atlasclimatico.unam.mx/AECC_descargas/ [Accessed 7 Nov

2018].

Fernández Eguiarte, A., Zavala Hidalgo, J., Romero Centeno, R., Conde Álvarez, A., and Trejo Vázquez, R., 2015b. *Actualización de los escenarios de cambio climático para estudios de impactos, vulnerabilidad y adaptación*. Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México. Instituto Nacional de Ecología y Cambio Climático, Secretaría de Medio Ambiente y Recursos Naturales.

Findlay, R., 2003. Global climate change: implications for water quality and quantity. *American Water Works Association*, 95 (9), 36.

Gao, L., Huang, J., Chen, X., Chen, Y., and Liu, M., 2018. Contributions of natural climate changes and human activities to the trend of extreme precipitation. *Atmospheric Research*, 205, 60–69.

Giorgi, F. and Mearns, L.O., 2002. Calculation of average, uncertainty range, and reliability of regional climate changes from AOGCM simulations via the 'Reliability Ensemble Averaging' (REA) method. *Journal of Climate*, 15 (10), 1141–1158.

Gondwe, B.R.N., Lerer, S., Stisen, S., Marín, L., and Rebolledo-Vieyra, M., 2010. Hydrogeology of the south-eastern Yucatan Peninsula: New insights from water level measurements, geochemistry, geophysics and remote sensing. *Journal of Hydrology*, 389 (1–2), 1–17.

González-Herrera, R., Sánchez-y-Pinto, I., and Gamboa-Vargas, J., 2002. Groundwater-flow modeling in the Yucatan karstic aquifer, Mexico. *Hydrogeology Journal*, 10 (5), 539–552.

Green, T.R., Taniguchi, M., Kooi, H., Gurdak, J.J., Allen, D.M., Hiscock, K.M., Treidel, H., and Aureli, A., 2011. Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology*, 405 (3–4), 532–560.

Grobick, A., 2010. Managing water for green growth: Supporting climate adaptation and building climate resilience. *Sustainable Water*, 118–121.

Hamon, W.R., 1961. Estimating potential evapotranspiration. *Journal of Hydraulics Division*, 87 (3), 107–120.

Hanshaw, B.B. and Back, W., 1980. Chemical mass-wasting of the northern Yucatan Peninsula by groundwater dissolution. *Geology*, 8 (5), 222.

Hargreaves, G.H. and Samani, Z.A., 1985. Reference Crop Evapotranspiration from

Temperature. *Applied Engineering in Agriculture*, 1 (2), 96–99.

Hattermann, F.F., Vetter, T., Breuer, L., Su, B., Daggupati, P., Donnely, C., Fekete, B., Flörke, F., Gosling, S.N., Hoffmann, P., Liersch, S., Masaki, Y., Motovilov, Y., C, M., Samaniego, L., Stacke, T., Wada, Y., Yang, T., and Krysnaova, V., 2018. Sources of uncertainty in hydrological climate impact assessment: A cross-scale study. *Environmental Research Letters*, 13 (1).

Hawkins, E., Osborne, T.M., Ho, C.K., and Challinor, A.J., 2013. Calibration and bias correction of climate projections for crop modelling: An idealised case study over Europe. *Agricultural and Forest Meteorology*, 170, 19–31.

Healy, R.W., 2010. *Estimating Groundwater recharge*. New York: Cambridge University Press.

Hibbard, K.A., Meehl, G.A., Cox, P.M., and Friedlingstein, P., 2007. A strategy for climate change stabilization experiments. *Eos Transactions American Geophysical Union*, 88 (20), 217–221.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., and Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25 (15), 1965–1978.

Holliday, L., Marin, L., and Vaux, H., 2007. *Sustainable management of groundwater in Mexico.* Strengthening Science-Based Decision-Making for Sustainable Management of Ground Water in Mexico. Workshop proceedings held. Washington, DC: National Academy of Sciences.

Holman, I.P., Allen, D.M., Cuthbert, M.O., and Goderniaux, P., 2012. Towards best practice for assessing the impacts of climate change on groundwater. *Hydrogeology Journal*, 20 (1), 1–4.

Huisman, J.A., Breuer, L., Bormann, H., Bronstert, A., Croke, B.F.W., Frede, H.G., Gräff, T., Hubrechts, L., Jakeman, A.J., Kite, G., Lanini, J., Leavesley, G., Lettenmaier, D.P., Lindström, G., Seibert, J., Sivapalan, M., Viney, N.R., and Willems, P., 2009. Assessing the impact of land use change on hydrology by ensemble modeling (LUCHEM) III: Scenario analysis. *Advances in Water Resources*, 32 (2), 159–170.

INEGI, 2002. *Estudio hidrológico del estado de Yucatán*. 1st ed. Aguascalientes, Ags. México: Instituto Nacional de Estadística, Geografía e Informática.

INEGI, 2013a. Conjunto de datos de Perfiles de suelos. Escala 1:250 000. Serie II (Continuo

Nacional) [online]. Available from: http://www.beta.inegi.org.mx/app/biblioteca/ficha.html?upc=702825266707 [Accessed 10 Mar 2018].

INEGI, 2013b. Uso de suelo y vegetación, escala 1:250000, serie V [online]. Available from: http://www.conabio.gob.mx/informacion/gis/ [Accessed 2 Nov 2016].

INEGI, 2014. *Diccionario de datos edafológicos. Escala 1:250,000 (versión 3)*. Ciudad de México, México.

INEGI, 2015. *Anuario estadístico y geográfico de Yucatán*. México.

Jauregui, E., 2005. Impact of Increasing Urbanization on the Thermal Climate of Large Mexican Cities. *Fifth International Conference on Urban Climate*, 18 (4), 247–248.

Jiménez Cisneros, B.E., Oki, T., Arnell, N.W., Benito, G., Cogley, J.G., Döll, P., Jiang, T., and Mwakalila, S.S., 2014. *Freshwater resources. In: Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York, NY, USA,: Cambridge University Press, Cambridge, United.

Kefi, S., Rietkerk, M., and Katul, G.G., 2008. Vegetation pattern shift as a result of rising atmospheric CO2 in arid ecosystems. *Theoretical Population Biology*, 74 (4), 332–344.

Kirkham, M.B., 2014. Field Capacity, Wilting Point, Available Water, and the Nonlimiting Water Range. *In*: *Principles of Soil and Plant Water Relations*. 153–170.

Kirtman, B., Power, S.B., Adedoyin, J.A., Boer, G.J., Bojariu, R., Camilloni, I., Doblas-Reyes, F.J., Fiore, A.M., Kimoto, M., Meehl, G.A., Prather, M., Sarr, A., Schär, C., Sutton, R., Oldenborgh, G.J. van, Vecchi, G., and Wang, H.J., 2013. Near-term Climate Change Projections and Predictability. *In*: V.B. and P.M.M. (eds.)]. [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, ed. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA.: Cambridge University Press, 982–985.

Klausmeier, C.A., 1999. Regular and irregular patterns in semiarid vegetation. *Science*, 284 (5421), 1826–1828.

Klein, S.A., 1977. Calculation of monthly average insolation on tilted surfaces. *Solar Energy*, 19

(4), 325–329.

Kløve, B., Ala-Aho, P., Bertrand, G., Gurdak, J.J., Kupfersberger, H., Kværner, J., Muotka, T., Mykrä, H., Preda, E., Rossi, P., Uvo, C.B., Velasco, E., and Pulido-Velazquez, M., 2014. Climate change impacts on groundwater and dependent ecosystems. *Journal of Hydrology*, 518 (PB), 250–266.

Lesser, J.M., 1976. Resumen del estudio geohidrologico e hidrogeoquimico de la Península de Yucatán. *Boletín de Divulgación Tecnica*, 10, 1–11.

Li, Z., Liu, W.Z., Zhang, X.C., and Zheng, F.L., 2009. Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China. *Journal of Hydrology*, 377 (1–2), 35–42.

Liverman, D.M. and O'Brien, K.L., 1991. Global warming and climate change in Mexico. *Global Environmental Change*, December, 351–364.

Lloyd, J.W., Drennan, D.S.H., and Bennell, B.M.U., 1966. A Ground-Water Recharge Study in North Eastern Jordan. *Proceedings of the Institution of Civil Engineers*, 35 (4), 615–631.

Lu, G.Y. and Wong, D.W., 2008. An adaptive inverse-distance weighting spatial interpolation technique. *Computers & Geosciences*, 34 (9), 1044–1055.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M., and Kjeldsen, T.R., 2014. Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. *Journal of Hydrology*, 519 (PD), 3634–3650.

Magaña, V., Amador, J.A., Medina, S., Magaña, V., Amador, J.A., and Medina, S., 1999. The Midsummer Drought over Mexico and Central America. *Journal of Climate*, 12 (6), 1577–1588.

Marín-Stillman, L.E., Pacheco Ávila, J.G., and Méndez Ramos, R., 2008. Hidrogeología De La Península De Yucatán. *Península de Yucatán*, 159–176.

Marin, L.E. and Perry, E.C., 1994. The hydrogeology and contamination potential of northwestern Yucatán, Mexico. *Geofísica Internacional*, 4, 619–623.

Martinez, S., Kralisch, S., Escolero, O., and Perevochtchikova, M., 2015. Vulnerability of Mexico city's water supply sources in the context of climate change. *Journal of Water and Climate Change*, 6 (3), 518–533.

Matonse, A.H., Zion, M.S., Schneiderman, E.M., Frei, A., Pierson, D.C., Anandhi, A., and

Lounsbury, D., 2011. Examination of change factor methodologies for climate change impact assessment. *Water Resources Research*, 47 (3).

McCabe, G.J. and Markstrom, S.L., 2007. A Monthly Water-Balance Model Driven By a Graphical User Interface. *U.S. Geological Survey Open-File report 2007-1088*, 6.

Meehl, G.A., Goddard, L., Murphy, J., Stouffer, R.J., Boer, G.J., Danabasoglu, G., Dixon, K., Giorgetta, M.A., Greene, A.M., Hawkins, E., Hegerl, G., Karoly, D., Keenlyside, N., Kimoto, M., Kirtman, B., Navarra, A., Pulwarty, R., Smith, D., Stammer, D., and Stockdale, T., 2009. Decadal predictionCan It Be Skillful? *Bulletin of the American Meteorological Society*, 90 (10), 1467–1486.

Meixner, T., Manning, A.H., Stonestrom, D.A., Allen, D.M., Ajami, H., Blasch, K.W., Brookfield, A.E., Castro, C.L., Clark, J.F., Gochis, D.J., Flint, A.L., Neff, K.L., Niraula, R., Rodell, M., Scanlon, B.R., Singha, K., and Walvoord, M.A., 2016. Implications of projected climate change for groundwater recharge in the western United States. *Journal of Hydrology*, 534, 124–138.

Messina, M.G. and Conner, W.H., 1998. *Southern forested wetlands : ecology and management*. Lewis Publishers.

Milly, P.C.D., Dunne, K.A., and Vecchia, A. V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, 438 (7066), 347–350.

Mollinga, P.P., Meinzen-Dick, R.S., and Merrey, D.J., 2007. Politics, plurality and problemsheds: A strategic approach for reform of agricultural water resources management. *Development Policy Review*, 25 (6), 699–719.

Moss, R., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L., Hibbard, K., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J.F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B., Pichs, R., Riahi, K., Rose, S., Runci, P., Stouffer, R., van Vuuren, D., Weyant, J., and Wilbanks, T., 2008. *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. Geneva: Intergovernmental Panel on Climate Change.

Mulholland, P.J., Best, G.R., Coutant, C.C., Hornberger, G.M., Meyer, J.L., Robinson, P.J., Stenberg, J.R., Turner, R.E., Vera-Herrera, F., and Wetzel, R.G., 1997. Effects of climate change on freshwater ecosystems of the south-eastern United States and the Gulf Coast of Mexico. *Hydrological Processes*, 11 (8), 949–970.

Navarro-Racines, Tarapues-Montenegro, And Ramírez-Villegas, J.E., and Ramírez-Villegas, 2015. *Bias-correction in the CCAFS-Climate Portal: A description of methodologies.* Decision and Policy Analysis (DAPA). Cali, Colombia.

Neuman, B.R. and Rahbek, M.L., 2007. *Modeling the Groundwater Catchment of the Sian Ka'an Reserve, Quintana Roo*. Austin: AMCS Bulletin 18. Association for Mexican cave studies.

Null, K. a., Knee, K.L., Crook, E.D., de Sieyes, N.R., Rebolledo-Vieyra, M., Hernández-Terrones, L., and Paytan, A., 2014. Composition and fluxes of submarine groundwater along the Caribbean coast of the Yucatan Peninsula. *Continental Shelf Research*, 77, 38–50.

Nyenje, P.M., Batelaan, O., and Okke Batelaan, &, 2009. Estimating the effects of climate change on groundwater recharge and baseflow in the upper Ssezibwa catchment, Uganda. *Hydrological Sciences-Journal-des Sciences Hydrologiques*, 54 (4).

Orellana, R., Espadas, C., Conde, C., and Gay García, C., 2009. *Atlas. Escenario de cambio climático en la península de Yucatán*. Mérida, Yucatán: Unidad de Recursos Naturales, Centro de Investigación Cientifica de Yucatán y Centro de Ciencias de la Atmosfera de la Universidad Autónoma de México.

Pechlivanidis, I.G., Arheimer, B., Donnelly, C., Hundecha, Y., Huang, S., Aich, V., Samaniego, L., Eisner, S., and Shi, P., 2017. Analysis of hydrological extremes at different hydro-climatic regimes under present and future conditions. *Climatic Change*, 141 (3), 467–481.

Pérez-Ceballos, R., Pacheco-Ávila, J., Euán-Ávila, J.I., and Hernández-Arana, H., 2012. Regionalization based on water chemistry and physicochemical traits in the ring of Cenotes, Yucatan, Mexico. *Journal of Cave and Karst Studies*, 74 (1), 90–102.

Pérez Ceballos, R. and Pacheco Ávila, J., 2004. Vulnerabilidad del agua subterránea a la contaminación de nitratos en el estado de Yucatán. *Revista UADY Ingeniería*, 8–1, 33–42.

Perry, E., Paytan, A., Pedersen, B., and Velazquez-Oliman, G., 2009. Groundwater geochemistry of the Yucatan Peninsula, Mexico: Constraints on stratigraphy and hydrogeology. *Journal of Hydrology*, 367 (1–2), 27–40.

Ponce, V.M., 1989. Basic hydrologic principles. *In*: *Engineering Hydrology: Principles and Practices*. 48–51.

Pulido-Velazquez, D., Collados-Lara, A.J., and Alcalá, F.J., 2018. Assessing impacts of future potential climate change scenarios on aquifer recharge in continental Spain. *Journal of*

Hydrology, 567, 803–819.

Pulido-Velazquez, D., Renau-Pruñonosa, A., Llopis-Albert, C., Morell, I., Collados-Lara, A.J., Senent-Aparicio, J., and Baena-Ruiz, L., 2018. Integrated assessment of future potential global change scenarios and their hydrological impacts in coastal aquifers - A new tool to analyse management alternatives in the Plana Oropesa-Torreblanca aquifer. *Hydrology and Earth System Sciences*, 22 (5), 3053–3074.

Refsgaard, J.C., Sonnenborg, T.O., Butts, M.B., Christensen, J.H., Christensen, S., Drews, M., Jensen, K.H., Jørgensen, F., Jørgensen, L.F., Larsen, M.A.D., Rasmussen, S.H., Seaby, L.P., Seifert, D., and Vilhelmsen, T.N., 2016. Climate change impacts on groundwater hydrology-where are the main uncertainties and can they be reduced? *Hydrological Sciences Journal*, 61 (13), 2312–2324.

Rodríguez-Iturbe, I., 2000. Ecohydrology : A hydrologic perspective of climate-soil-vegetation dynamics. *Water Resources Research*, 36 (1), 3–9.

Rushton, K.R., 1988. Groundwater recharge estimation (Part 2): numerical modelling techniques. *In*: *Estimation of Natural Groundwater Recharge*. Reidel Publishing Company, 223–239.

Rushton, K.R. and Ward, C., 1979. The estimation of groundwater recharge. *Journal of Hydrology*, 41 (3–4), 345–361.

Sánchez Aguilar, R.L. and Rebollar Domínguez, S., 1999. Deforestación en la Península de Yucatán, los retos que enfrentar. *Madera y Bosques*, 5 (2), 3.

Savenije, H.H.G., Hoekstra, A.Y., and Van Der Zaag, P., 2014. Evolving water science in the Anthropocene. *Hydrology and Earth System Sciences*, 18 (1), 319–332.

Saxton, K.E. and Rawls, W.J., 1986. Estimating Generalized Soil-water Characteristics from Texture. *Soil Sci. Soc. Am.*, 1031–1036.

Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häberli, C., Liniger, M.A., and Appenzeller, C., 2004. The role of increasing temperature variability in European summer heatwaves. *Nature*, 427 (6972), 332–336.

Schulz, C.J. and García, R.F., 2015. Balance hídrico y recarga de acuíferos.

SEMARNAT, 2015. Descripción del subsistema natural (Contenido Parcial). *In*: *Bitacora de ordenamiento ambiental*. Mérida, Yucatán, 24–132.

Shnerb, N.M., Sarah, P., Lavee, H., and Solomon, S., 2003. Reactive Glass and Vegetation Patterns. *Physical Review Letters*, 90 (3), 4.

Smerdon, B.D., 2017. A synopsis of climate change effects on groundwater recharge. *Journal of Hydrology*, 555, 125–128.

Solé, R. V., 2011. *Phase Transitions*. New Jersey: Princeton Univeristy Press.

Steinich, B. and Marín, L.E., 1997. Determination of flow characteristics in the aquifer of the Northwestern Peninsula of Yucatan , Mexico, 191, 315–331.

Tabari, H., Grismer, M.E., and Trajkovic, S., 2013. Comparative analysis of 31 reference evapotranspiration methods under humid conditions. *Irrigation Science*, 31 (2), 107–117.

Tabor, K. and Williams, J.W., 2010. Globally downscaled climate projections for assessing the conservation impacts of climate change. *Ecological Applications*, 20 (2), 554–565.

Taylor, K.E., Stouffer, R.J., and Meehl, G.A., 2012. An Overview of CMIP5 and Experimental Design. *Bulletin of the American Meteorological Society*, 93 (april), 485–498.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M., Bierkens, M.F.P., Macdonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen, D.M., Shamsudduha, M., Hiscock, K., Yeh, P.J.F., Holman, I., and Treidel, H., 2013. Ground water and climate change. *Nature Climate Change*, 3 (4), 322–329.

Thornthwaite, C.W., 1948. An Approach toward a Rational Classification of Climate. *Geographical Review*, 38 (1), 55–94.

Thornthwaite, C.W. and Mather, J.R., 1955. The water balance. *Publications in Climatology*, 8 (1), 1–104.

Thornthwaite, C.W. and Mather, J.R., 1957. Instructions and Tables for Computing Potential Evapotranspiration and Water Balance. *Publ.Climatol*, 10 (3), 185–311.

Torres, M.C., Basulto, Y.Y., Cortés, J., García, K., Koh, A., Puerto, F., and Pacheco, J., 2014. Evaluación de la vulnerabilidad y el riesgo de contaminación del agua subterránea en Yucatán. *Ecosistemas y Recursos Agropecuarios*, 1 (3), 189–203.

Trenberth, K.E., 2011. Changes in precipitation with climate change. *Climate Research*.

USDA (US Department of Agriculture Natural) Resources Conservation Service, 1998. *Soil Quality Resource Concerns: Available Water Capacity*. Soil Quality Information Sheet.

Valle-Levinson, A., Mariño-Tapia, I., Enriquez, C., and Waterhouse, A.F., 2011. Tidal variability of salinity and velocity fields related to intense point-source submarine groundwater discharges into the Coastal Ocean. *Limnology and Oceanography*, 56 (4), 1213–1224.

Vetter, T., Reinhardt, J., Flörke, M., van Griensven, A., Hattermann, F., Huang, S., Koch, H., Pechlivanidis, I.G., Plötner, S., Seidou, O., Su, B., Vervoort, R.W., and Krysanova, V., 2017. Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. *Climatic Change*, 141 (3), 419–433.

Villasuso, M. and Méndez, R., 2000. A Conceptual Model of the Aquifer of the Yucatan Peninsula: From Ancient Maya to 2030. *In*: W. Lutz, L. Prieto, and W. Sanderson, eds. *Population, Development, and Environment on the Yucatan Peninsula*. Vienna, 120–139.

de Vries, J.J. and Simmers, I., 2002. Groundwater recharge: An overview of process and challenges. *Hydrogeology Journal*, 10 (1), 5–17.

Wilby, R.L., Charles, S.P., Zorita, E., Timbal, B., Whetton, P., and Mearns, L.O., 2004. Guidelines for use of climate scenarios developed from statistical downscaling methods. Supporting material of the Intergovernmental Panel on Climate Change, prepared on behalf of Task Group on Data and Scenario Support for Impacts and Climate Analysis, (August), 1–27.

Zhou, G., Wei, X., Chen, X., Zhou, P., Liu, X., Xiao, Y., Sun, G., Scott, D.F., Zhou, S., Han, L., and Su, Y., 2015. Global pattern for the effect of climate and land cover on water yield. *Nature Communications*, 6, 1–9.

Table 1. Summary of Yucatan Peninsula recharge studies. *P*, precipitation, ET_a, actual evapotranspiration, *R*, recharge, NA, not available/specified)

Reference	Method	P (mm)	ET_a (mm)	R (mm)	Area
Lesser (1976)	Turc (1961)	1050	900	150	YP
Hanshaw and Back (1980)	NA	NA	NA	150	YP
Villasuso (2000)	Thornthwaite (1948)	1300	1060	240	YP
González-Herrera (2002)	AQUIFER model (1991)	1300	NA	233	Yucatan
INEGI (2002)	NA	1135	900	230	Yucatan
Pérez and Pacheco (2004)	NA	NA	NA	110 - 300	Yucatan
Albornoz-Euán (2007)	Turc (1961)	1200 - 1500	600 - 800	0 - 491	Yucatan
Gondwe et al. (2010)	Priestley–Taylor equation (1972)	1260	960	290	YP
Torres Díaz, M.C. (2014)	NA	NA	NA	198 - 276	North and center of Yucatan
SEMARNAT (2015)	Penman (1948)	1070	NA	182	YP
CONAGUA (2015a)	NA	1100 - 1430	1236	146	YP
Carballo Parra (2016)	Hargreaves (1985)	1200	NA	220 - 360	Quintana Roo

Table 2. Maximum mature root depth (m). Source: Charles (2003), Thornthwaite and Mather (1957)

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

Table 3. List of ET_O calculation methods considered in this paper

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

Table 4. Summary of GCM scenarios. Average of GCMs with uncertainty. Negative precipitation in bold.

GCM	Institute	Ensemble	Historical period	Differences RCP 4.5 with historical data		Differences RCP 8.5 with historical data	
				$\bar{T}$ (°C)	P (mm)	$\bar{T}$ (°C)	P (mm)
CNRM-CM5	Centre National de Recherches Meteorologiques	r1i1p1	1961 – 2000	0.67	12.1	0.72	38.4
GFDL_CM3	Geophysical Fluid Dynamics Laboratory	r1i1p1	1961 – 2000	1.31	59.7	1.37	38.9
HADGEM2-ES	Met Office Hadley	r1i1p1	1961 – 2000	1.31	**-67.7**	1.40	**-22.4**
MPI_ESM_LR	Max-Plank Institute	r1i1p1	1961 – 2000	0.95	**-74.0**	1.09	**-73.6**
Reliability Ensemble Averaging (REA)	weighted ensemble projection that considered fifteen GCM Cavazos *et al.*, (2013), Colorado-Ruiz *et al.*, (2018)		1971 – 2000	1.37	**-57.7**	1.43	**-58.8**
Average of GCMs				*1.12* ± 0.29	**-25.5** ± 56.0	1.2 ± 0.29	**-15.5** ± 50.0

Table 5. Groundwater recharge according to model sensitivity analysis factors. A2: Alternative ET_a (equation 19). AVG only considers HAM, HAR and BLA methods.

Method	Groundwater recharge (mm·year^{-1})			Percent change (%)	
	Conventional	A2	STC = 100	A2	STC = 100
FAO	72.5	96.7	80.1	33%	10%
THO	43.3	59.4	45.8	37%	6%
HAM	143.4	176.1	153.1	23%	7%
HAR	102.4	130.0	111.5	27%	9%
BLA	68.2	91.3	74.7	34%	10%
AVG	104.7	132.5	113.1	27%	8%

Table 6. Effects of climate change on groundwater recharge in YP. Projections shown for RCP4.5 and RCP8.5 include the uncertainty of the mean of 5 GCMs by each method and percentage change concerning current values.

		Recharge ($mm \cdot year^{-1}$)			Percentage change (%)	
ET_a calculation	Method	Current	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Conventional	HAM	143.4	101.8 ± 39.4	103.5 ± 35.7	-29%	-28%
	HAR	102.4	87.8 ± 34.7	90.3 ± 30.4	-14%	-12%
	BLA	68.2	53.3 ± 24.2	53.7 ± 21.0	-22%	-21%
	AVG	104.7	77.5 ± 32.6	79.0 ± 28.9	-26%	-25%
A2	HAM	176.1	130.4 ± 42.8	134.7 ± 40.6	-26%	-24%
	HAR	130.0	111.5 ± 40.3	116.6 ± 37.1	-14%	-10%
	BLA	91.3	70.1 ± 30.3	72.6 ± 27.9	-23%	-20%
	AVG	132.5	100.9 ± 38.3	104.6 ± 35.5	-24%	-21%
Global average		118.6	91.7 ± 39.4	94.4 ± 37.9	-23%	-20%

Figure 1. Location of Yucatan Peninsula, Mexico.

Figure 2. Water-balance model diagram. Adapted from McCabe and Markstrom (2007)

Figure 3. (a) Available water capacity (AWC). (b) Vegetation root depth category. (c) Soil-moisture capacity (STC) in the YP

Figure 4. (a) ET_a in Yucatan Peninsula by method. (b) ET_a by state and month. (See Table 3 for name method reference)

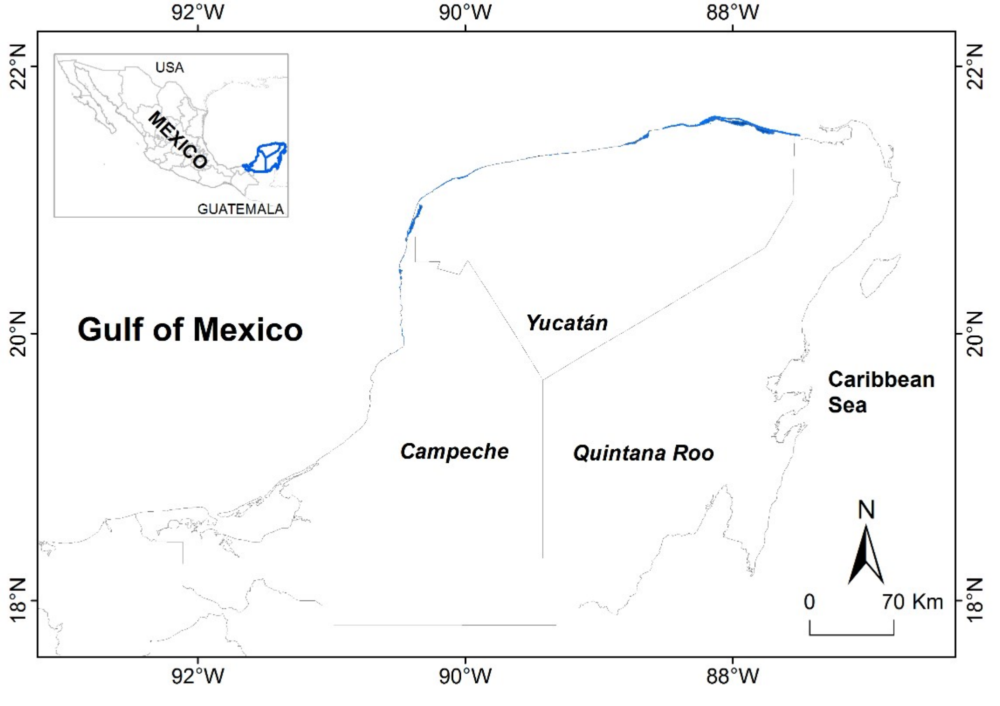
Figure 5. Recharge of groundwater (mm·year^{-1}) simulation. (a) results for ET_a methods. (b) monthly recharge for the whole area of the YP.

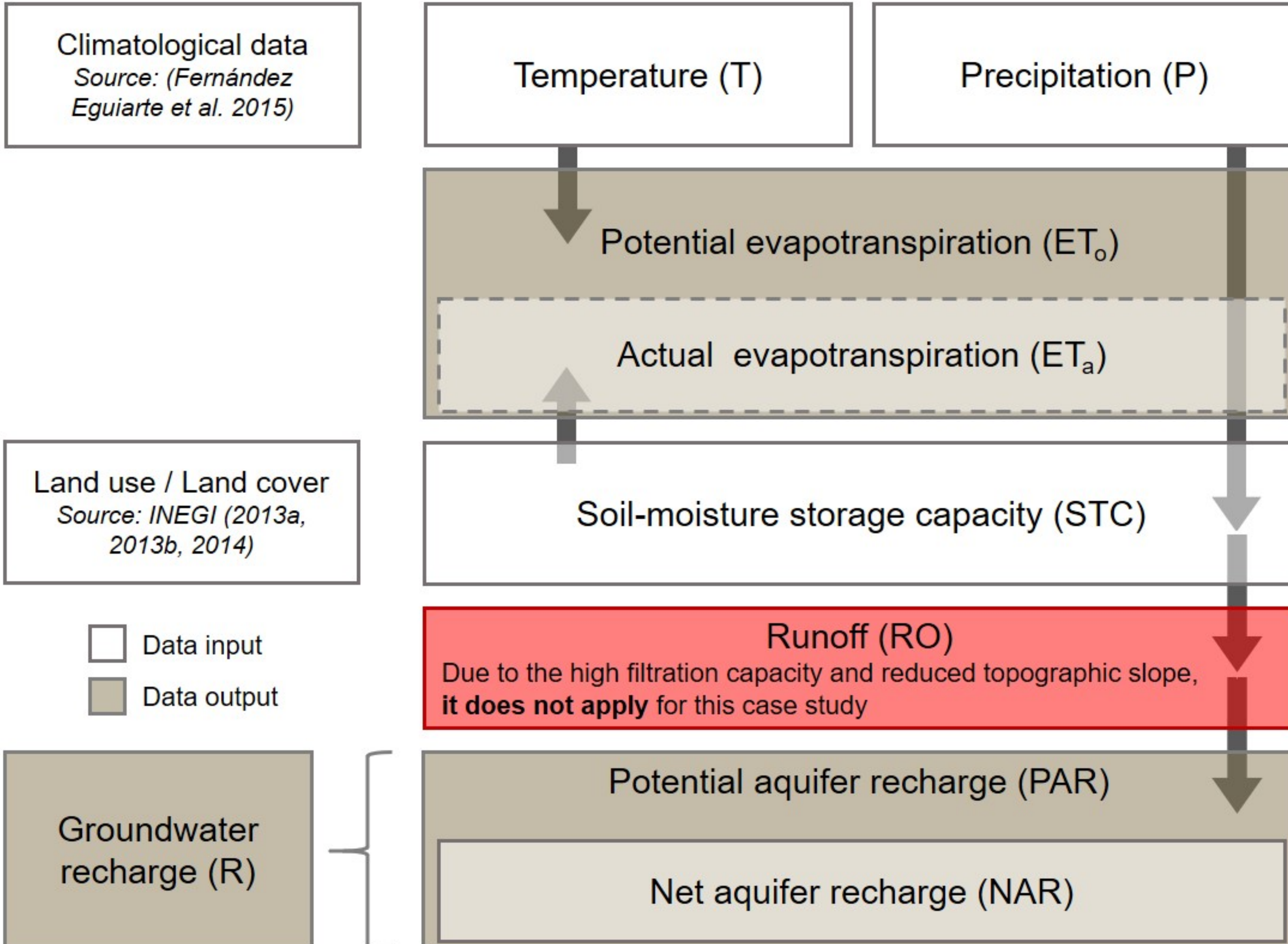
Figure 6. Correlation between precipitation P (mm·year^{-1}) and recharge R (mm·year^{-1}) for every grid (926 x 926 m approximately).

Figure 7. Boxplot differences between projections and historical recharge for GCM RCP4.5 and RCP8.5. Red dashed line: GCM average. Each mark represents the difference in the average value of each grid using the four methods described. Boxes indicate the interquartile model spread (range between the 25th and 75th quantiles). Whiskers display all points within 1.5 times the interquartile range.

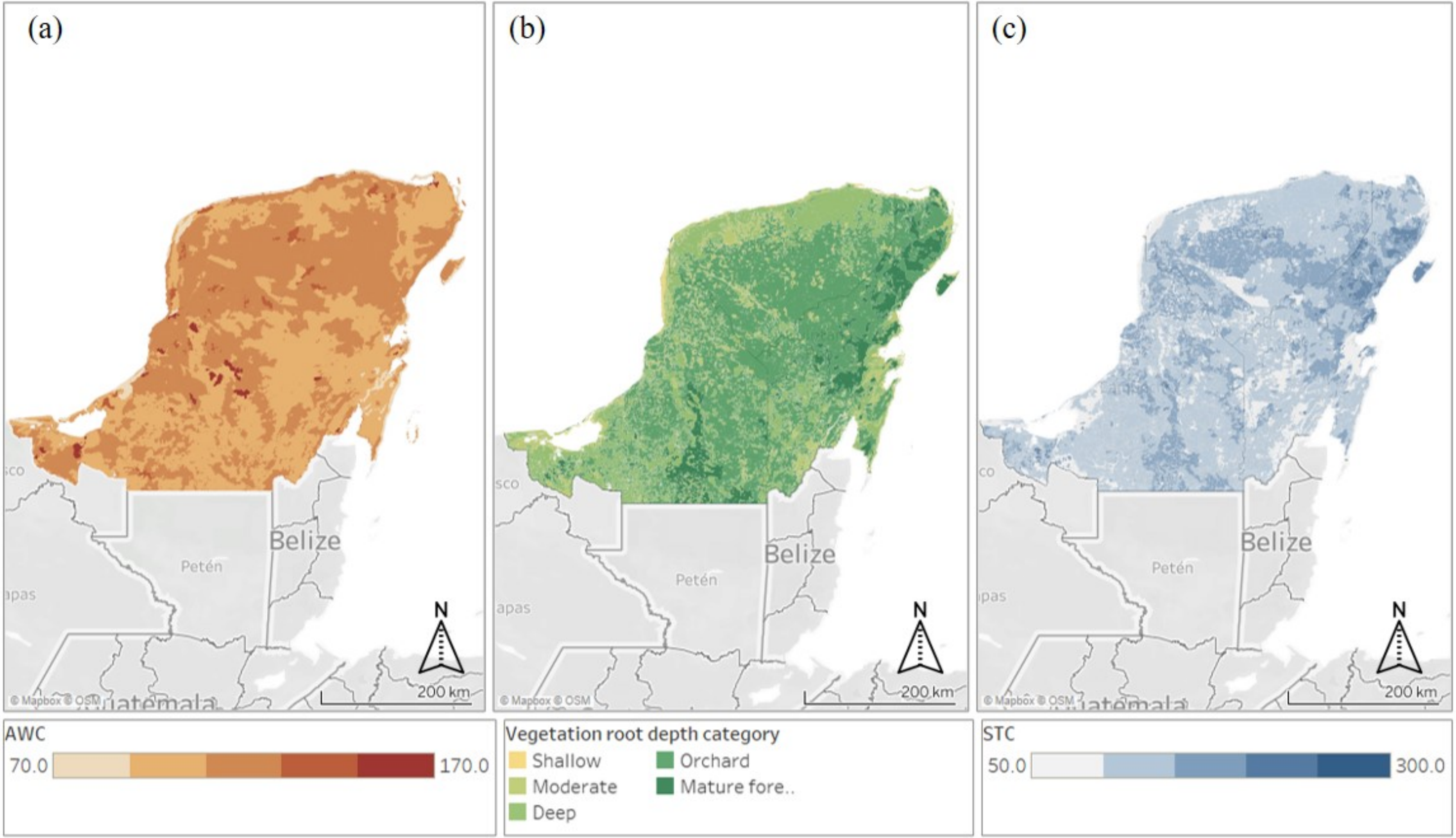
Figure 8. Spatial distribution of average differences between projections and historical data in groundwater recharge for RCP4.5 (a) and RCP8.5 (b).

Figure 9. (a) Water uses in YP by sector, size allocated volume (hm^3). (b) Ratio between recharge and uses by municipality as color. Population as size.

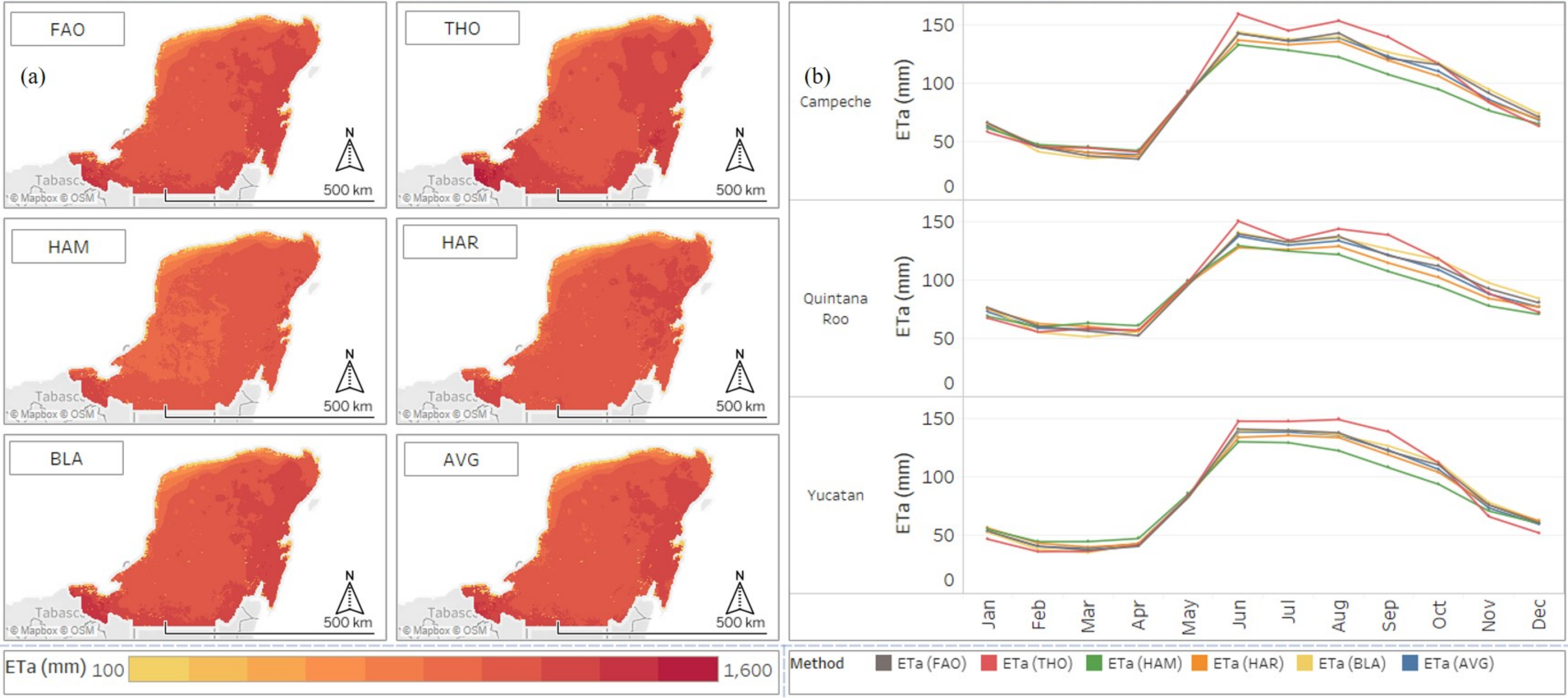

92°W
90°W
88°W
22°N
20°N
18°N
USA
MEXICO
GUATEMALA
Gulf of Mexico
Yucatán
Campeche
Quintana Roo
Caribbean Sea
N
0
70 Km



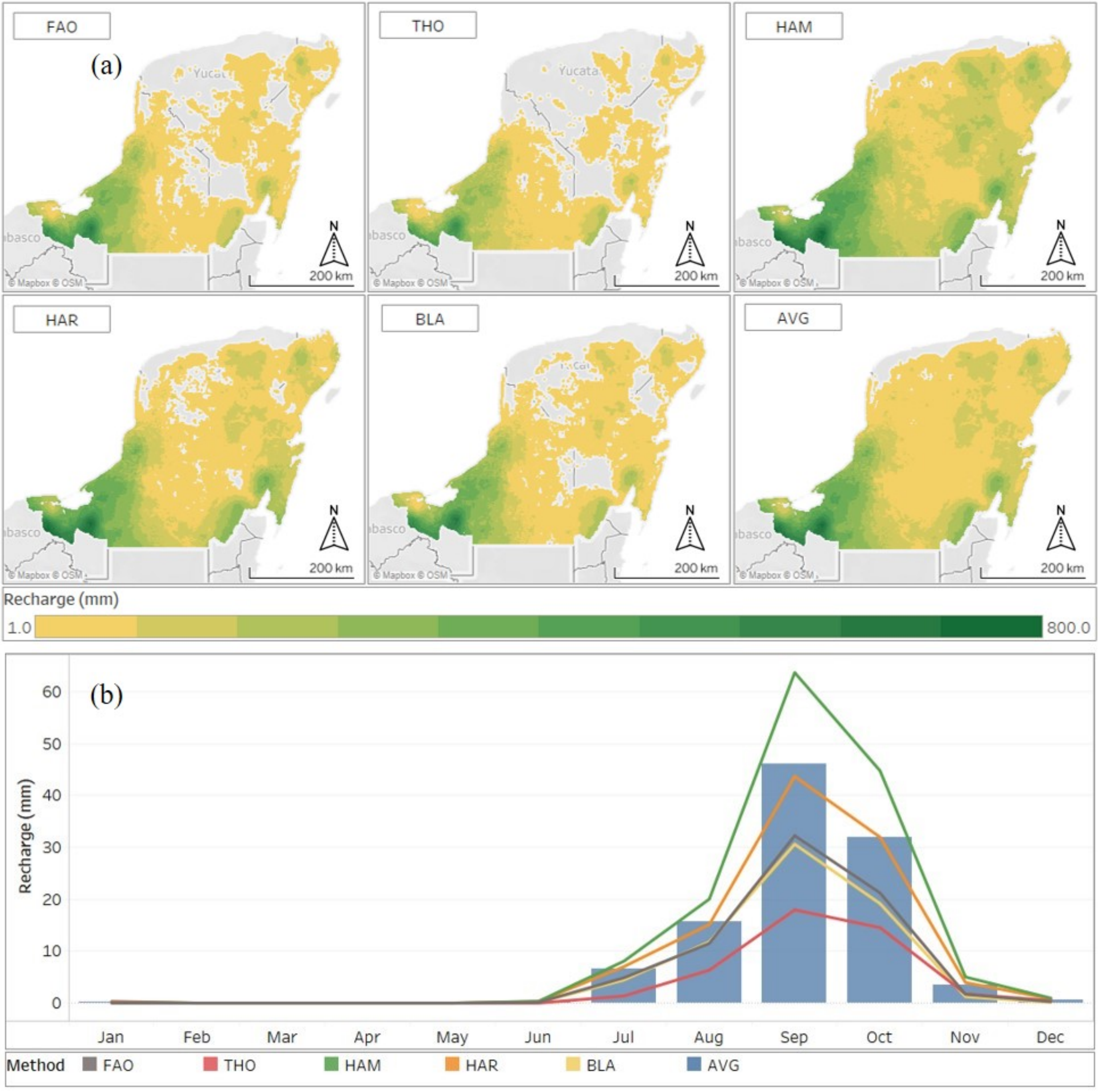
Climatological data
Source: (Fernández Eguiarte et al. 2015)
Temperature (T)
Precipitation (P)
Potential evapotranspiration (ET_o)
Actual evapotranspiration (ET_a)
Land use / Land cover
Source: INEGI (2013a, 2013b, 2014)
Soil-moisture storage capacity (STC)
Data input
Data output
Runoff (RO)
Due to the high filtration capacity and reduced topographic slope, it does not apply for this case study
Groundwater recharge (R)
Potential aquifer recharge (PAR)
Net aquifer recharge (NAR)



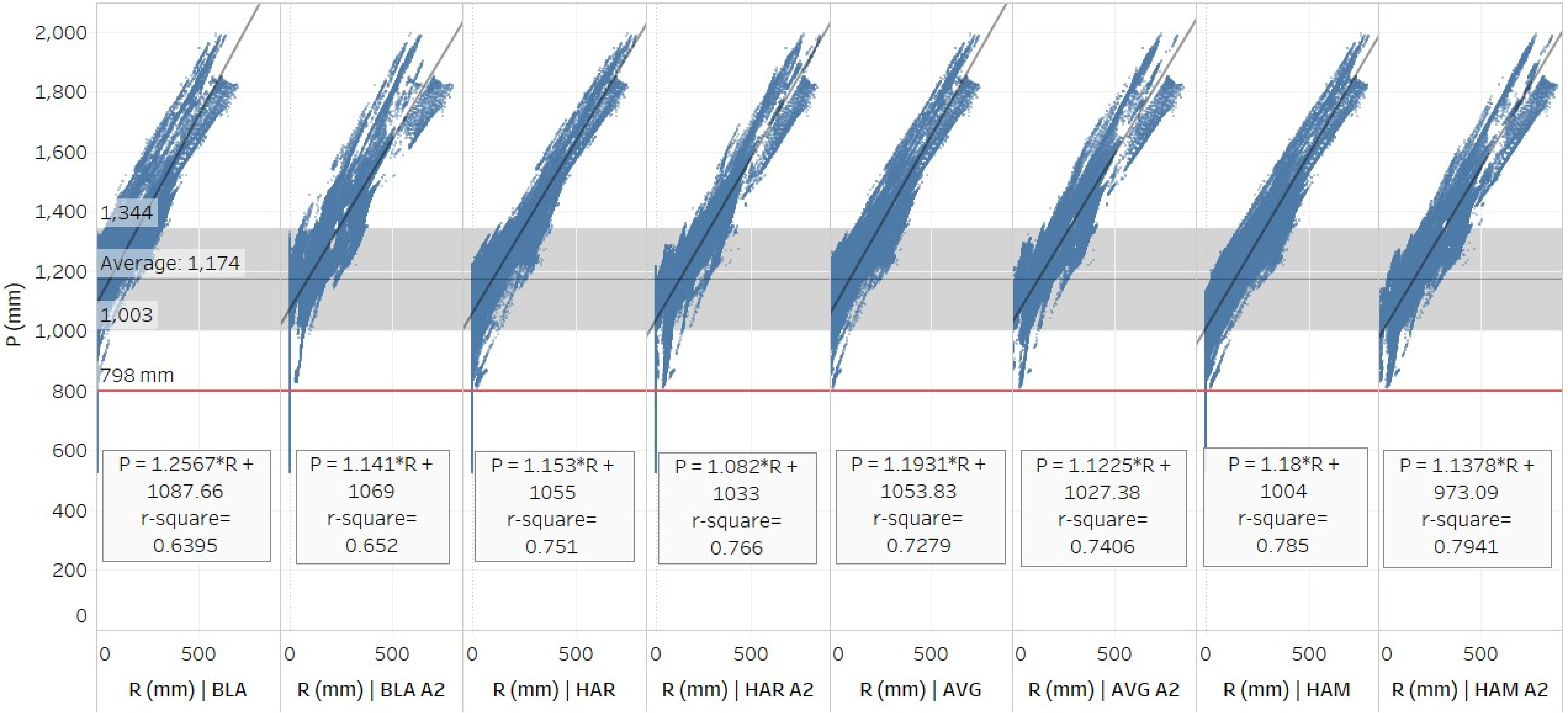
(a)
(b)
(c)
Belize
Petén
200 km
N
© Mapbox © OSM
AWC
70.0
170.0
Vegetation root depth category
Shallow
Moderate
Deep
Orchard
Mature fore..
STC
50.0
300.0

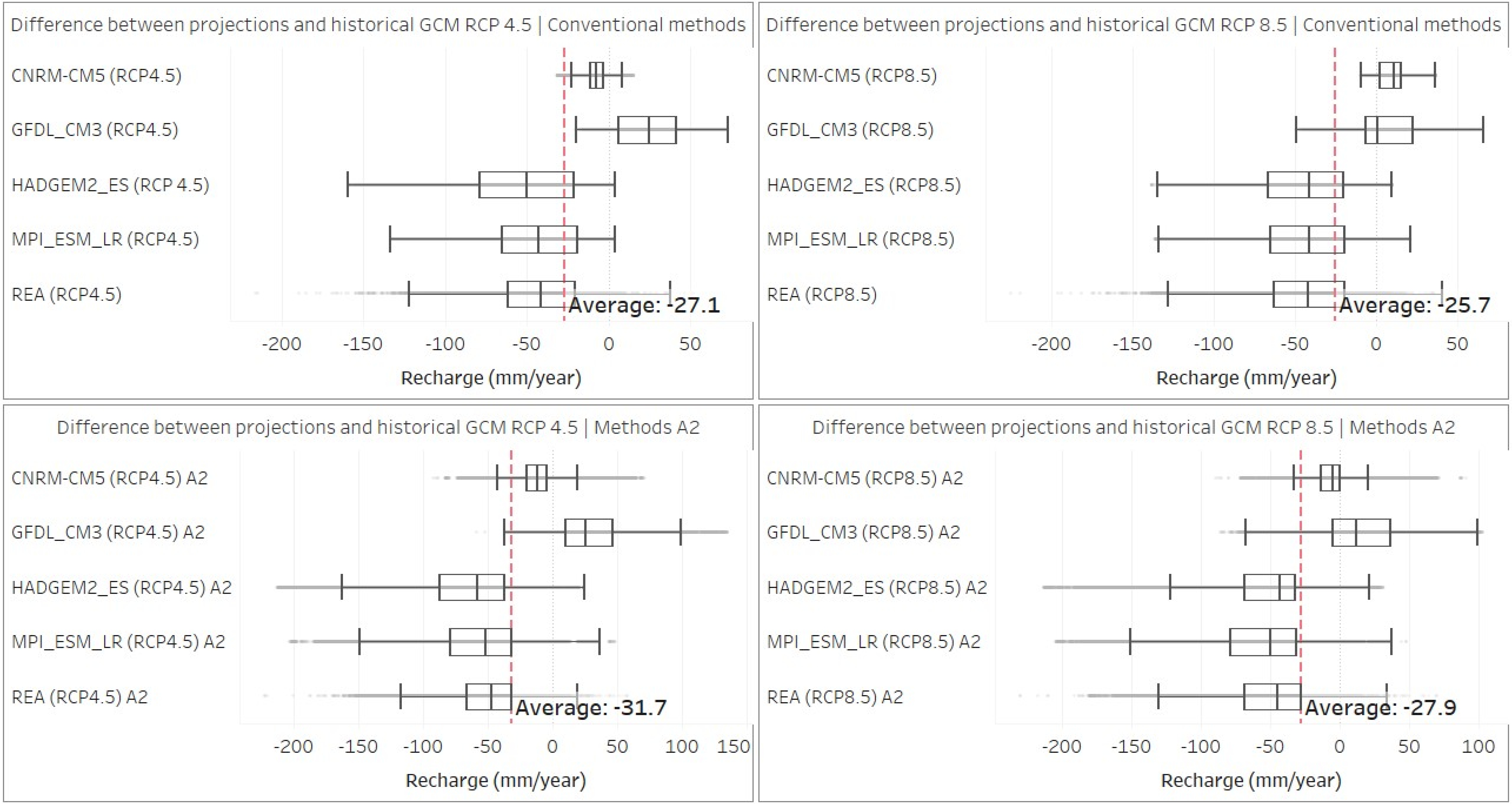


FAO
THO
HAM
HAR
BLA
AVG
(a)
500 km
Tabasco
© Mapbox © OSM
ETa (mm) 100
1,600
(b)
Campeche
Quintana Roo
Yucatan
ETa (mm)
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Method
ETa (FAO)
ETa (THO)
ETa (HAM)
ETa (HAR)
ETa (BLA)
ETa (AVG)

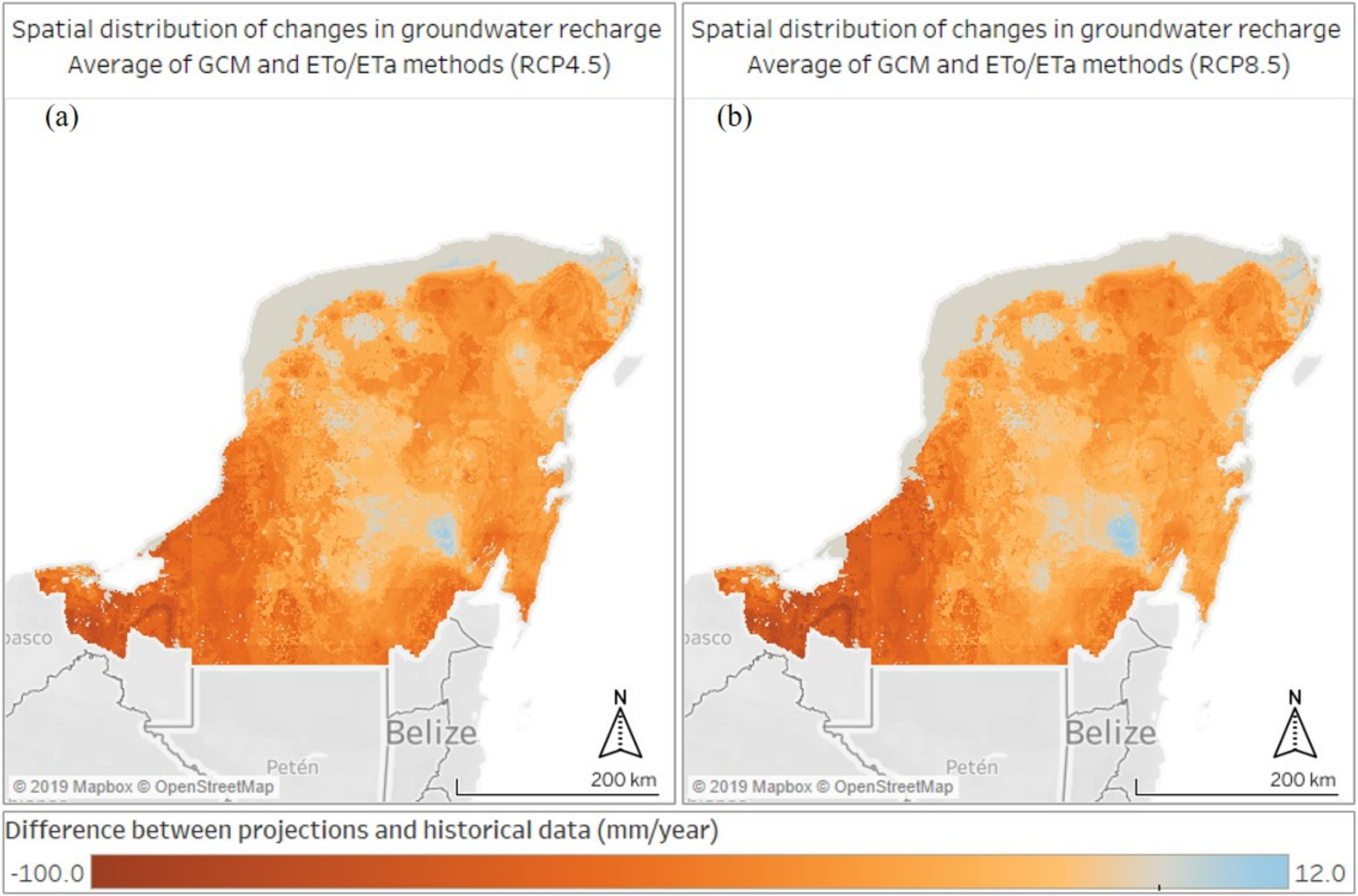


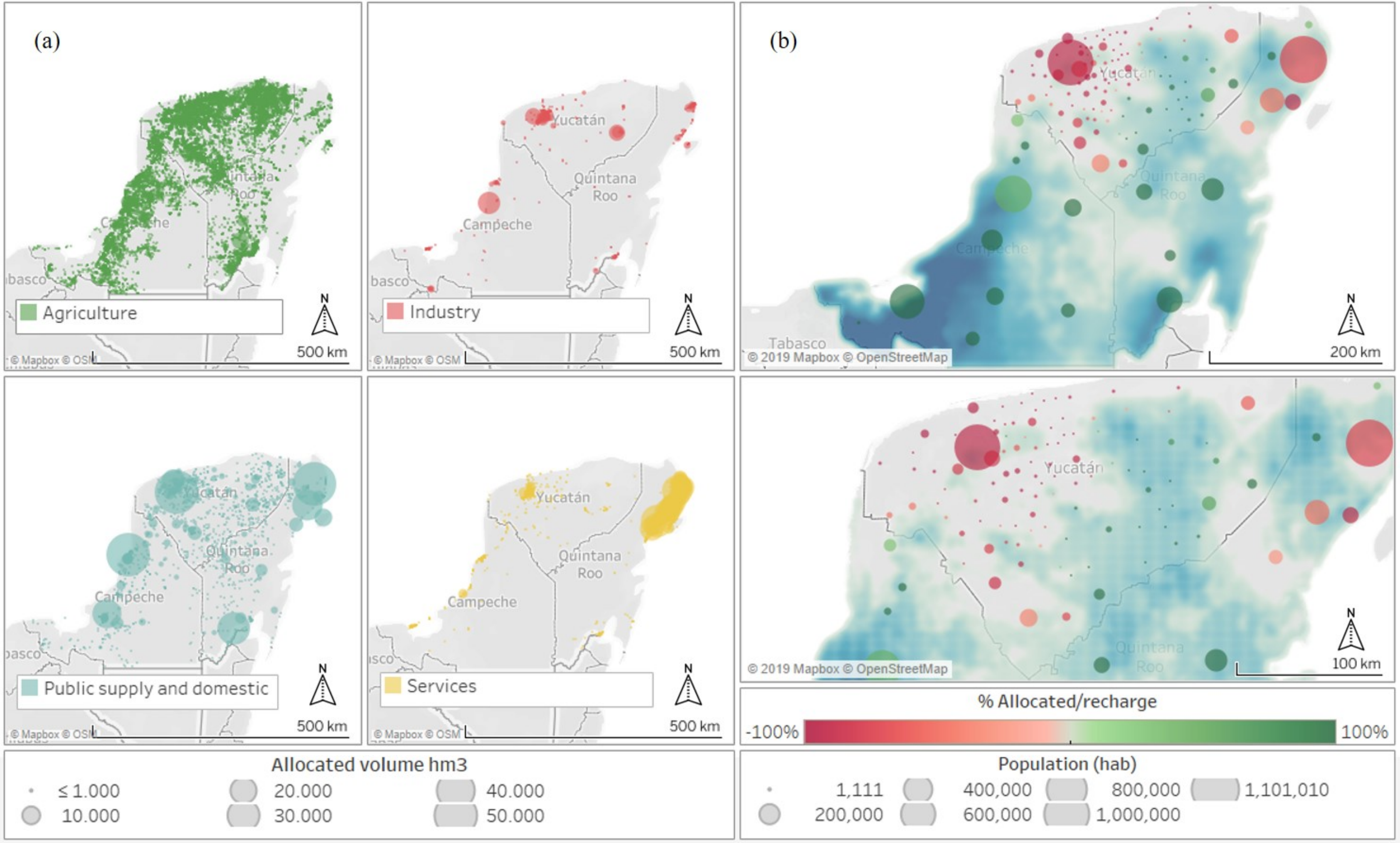
(a)
FAO
THO
HAM
HAR
BLA
AVG
200 km
N
© Mapbox © OSM
Recharge (mm)
1.0
800.0
(b)
Recharge (mm)
0
10
20
30
40
50
60
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Method
FAO
THO
HAM
HAR
BLA
AVG


P (mm)
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1,344
Average: 1,174
1,003
798 mm
P = 1.2567*R + 1087.66 r-square= 0.6395
P = 1.141*R + 1069 r-square= 0.652
P = 1.153*R + 1055 r-square= 0.751
P = 1.082*R + 1033 r-square= 0.766
P = 1.1931*R + 1053.83 r-square= 0.7279
P = 1.1225*R + 1027.38 r-square= 0.7406
P = 1.18*R + 1004 r-square= 0.785
P = 1.1378*R + 973.09 r-square= 0.7941
0
500
R (mm) | BLA
R (mm) | BLA A2
R (mm) | HAR
R (mm) | HAR A2
R (mm) | AVG
R (mm) | AVG A2
R (mm) | HAM
R (mm) | HAM A2



Difference between projections and historical GCM RCP 4.5 | Conventional methods
CNRM-CM5 (RCP4.5)
GFDL_CM3 (RCP4.5)
HADGEM2_ES (RCP 4.5)
MPI_ESM_LR (RCP4.5)
REA (RCP4.5)
Average: -27.1
-200 -150 -100 -50 0 50
Recharge (mm/year)
Difference between projections and historical GCM RCP 8.5 | Conventional methods
CNRM-CM5 (RCP8.5)
GFDL_CM3 (RCP8.5)
HADGEM2_ES (RCP8.5)
MPI_ESM_LR (RCP8.5)
REA (RCP8.5)
Average: -25.7
-200 -150 -100 -50 0 50
Recharge (mm/year)
Difference between projections and historical GCM RCP 4.5 | Methods A2
CNRM-CM5 (RCP4.5) A2
GFDL_CM3 (RCP4.5) A2
HADGEM2_ES (RCP4.5) A2
MPI_ESM_LR (RCP4.5) A2
REA (RCP4.5) A2
Average: -31.7
-200 -150 -100 -50 0 50 100 150
Recharge (mm/year)
Difference between projections and historical GCM RCP 8.5 | Methods A2
CNRM-CM5 (RCP8.5) A2
GFDL_CM3 (RCP8.5) A2
HADGEM2_ES (RCP8.5) A2
MPI_ESM_LR (RCP8.5) A2
REA (RCP8.5) A2
Average: -27.9
-200 -150 -100 -50 0 50 100
Recharge (mm/year)


Spatial distribution of changes in groundwater recharge
Average of GCM and ETo/ETa methods (RCP4.5)
Spatial distribution of changes in groundwater recharge
Average of GCM and ETo/ETa methods (RCP8.5)
(a)
(b)
Belize
Petén
N
200 km
© 2019 Mapbox © OpenStreetMap
Difference between projections and historical data (mm/year)
-100.0
12.0


(a)
Yucatán
Quintana Roo
Campeche
Tabasco
Agriculture
Industry
Public supply and domestic
Services
500 km
N
© Mapbox © OSM
(b)
Tabasco
© 2019 Mapbox © OpenStreetMap
200 km
100 km
% Allocated/recharge
-100%
100%
Allocated volume hm3
≤ 1.000
10.000
20.000
30.000
40.000
50.000
Population (hab)
1,111
200,000
400,000
600,000
800,000
1,000,000
1,101,010