Research Article

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Water Balance by Planning Units in the Yucatán Peninsula

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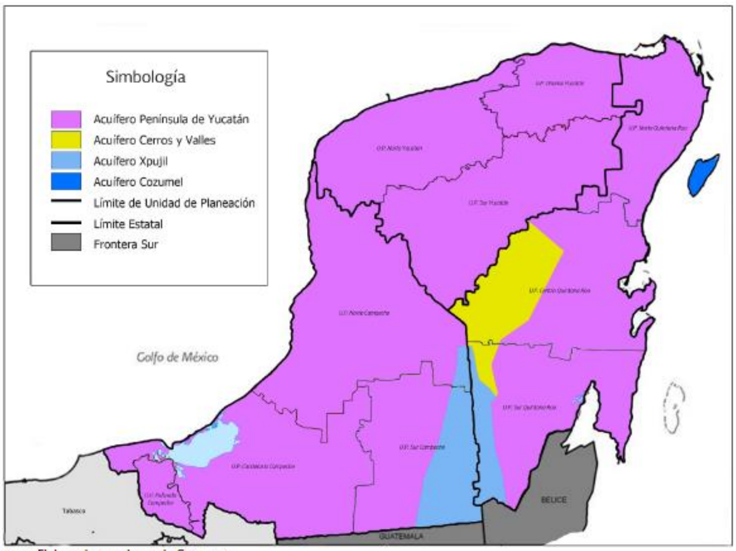
Abstract

In the official publication on Availability on September 17, 2020, a total recharge was estimated in the various aquifers considered for the Yucatan Peninsula, yielding a total figure of 25,315.70 Mm3 annually and 17,341.6 Mm3 annually for the Committed Natural Discharge (DNC).), according to what is published about the total currently extracted from the subsoil, which is 4,965.25 Mm3/year, there is an average availability of 3,008.91 Mm3/year, so, from this level of analysis, there is no restriction on granting more concessions for the use of groundwater for various consumptive uses, including agriculture and urban public consumption in the Yucatan Peninsula. However, the variability and complexity of the karst system implies that recharge is not homogeneous in the territory, so it is possible to affirm that there are subsystems with characteristics that distinguish them from others, defined as local hydrogeological subunits where extraction is exceeding the availability and the human right to water, the integrity of the health of ecosystems and the increased concentrations of contaminants are being put at risk, by exploiting water destined for Compromised Natural Discharges, which will worsen by 2050 due to the effect of change climate. In these scenarios of pressure on availability, there may be risks of salinization, scarcity, increased concentrations of contaminants, drying and salinization of wetlands, among others, associated with the consumption of water from the local DNC. This reinforces the need to deepen research on recharge in a context of climate change to incorporate it into water planning. Other research needs on the topic are the relationship between land use change and recharge in karst soil, as well as the local effects of water consumption destined for DNC in the UPs. These actions are mentioned in Chapter 5 of the PHR-PY 2020-2024, as one of the eight collective regional water management activities.

Keywords: *Water balance, availability, climate change, planning units.*

Problem Statement: Water Availability and Pumping
In Mexico, the calculation of the availability of water from an aquifer is based on NOM-011-CONAGUA-2015 "Conservation of water resources", which establishes the specifications and method to determine the average annual availability of water. national" published in the Official Gazette of the Federation (DOF) on March 27, 2015. In the publication of Availability on September 17, 2020, a total recharge was estimated in the various aquifers considered for the Yucatan Peninsula (such as Mm3 per year for Committed Natural Discharge (DNC) (figure 1).

Figure 1: Aquifers present in the Yucatán Peninsula.



Fuente: Elaborado con datos de CONAGUA.

That Committed Natural Discharge is defined in the Standard as the fraction of the natural discharge of an aquifer, which is committed as surface water for various uses or that must be conserved to prevent a negative environmental impact on ecosystems or the migration of poor quality water. to an aquifer. In the case of the Yucatán Peninsula, all three are of particular importance.

Although the availability of groundwater from the perspective of the Hydrological Region XII Yucatán Peninsula is still sufficient according to what is published in the Official Gazette of the Federation, prevention and efficiency measures must be considered. For the 3105 aquifer called the Yucatán Peninsula, there was an average availability of 5,759.22 Mm3/year according to the 2003 publication and for the last publication in 2020 an availability of 2,386.29 Mm3/year, 59% less availability in 17 years. which arithmetically would give an alarming situation in 15 years, something similar for the 2305 aquifer called Cozumel Island, which went from 92.12 Mm3/year to 29.89 Mm3/year, 67% less availability for the same period of time (Mejía Gómez, J.A. 2020, CONAGUA) (**Table 1**).

RHA	Federal entity	key	Aquifer	R	DNC	VEAS				DMA	
						VCAS	VEALA	VAPTYR	VAPRH	Positive	Negative (déficit)
				Figures in millions of cubic meters per year							
XII Yucatan Peninsula	Campeche	0405	Xpujil	2099.4	1784.1	7.116	0	0.971	0	307.21	0
	Quintana Roo	2301	Hills and Valleys	1194.2	854.9	22.59	30.32	1.485	0	284.89	0
		2305	Cozumel Island	208.7	160.4	17.70	0.0090	0.65	0	29.89	0
	Yucatán	3105	Yucatan Peninsula	21813	14542.2	4657.8	26.78	199.60	0	2386.92	0

A: Annual average total recharge; DNC: Natural discharge compromised; SEE: Volume of groundwater extraction; VCAS: Assigned concession volume of groundwater; VEALA: Volume of water extraction in areas of provisional supervision of free delivery and those registered in the Relevant National Registry; VAPTYR: Volume of water extraction pending titling and/or registration in the REPDA; VAPRH: Volume of water corresponding to reserves, regulations and water programming; DMA: Average Availability.

Table 1.- Recharge of the aquifers considered for the Yucatán Peninsula, such as Xpujil, Cerros y Valles, Cozumel Island and the Yucatán Peninsula (DOF 2020).

Reviewing the Agreements issued from 2011 to date, the recharge value has not been modified, although the annual precipitation value has been different, decreasing the committed natural discharge, increasing availability, and presenting an abrupt jump in the volume of groundwater extraction in 2020, decreasing the average availability of groundwater, as presented in the following Table 2. It is observed that the data from Beuer Gotweinn et al 2011, and Lutz, W. et al 1996 (IIASA) They are much higher given that an infiltration of just over 19% is considered, while in the Annual Agreements it is only 14%. The committed natural discharge varies in the 2020 and 2013 Agreements since they represent different percentages of the recharge, going from 76% to 68%: As can be seen, there is a lot of variability in the data, with an abrupt update, which is why it is necessary work more on this topic. At this level of the Yucatan Peninsula Administrative Hydrological Region are 4,965.25 Mm3/year, leaving an average availability of 3,008.91 Mm3/year.

Year	**Average recharge Mm3/year (Precipitation mm) % recharge**	**Committed Natural Discharge Mm3/year % of recharge**	**Total, availability Mm3/year**	**Volume of extraction of concessioned groundwater Mm3/year**	**Average availability of groundwater Mm3/year**	**Sources**
2020	25,315.70 (1,214.16 mm) 14.6 %	17,305.60 68.3 %	7,974.06	4,965.25	3,008.91	SINA-CONAGUA.Gob.mx
2018	25,315.70			1,343.50	3,487.32	SINA-CONAGUA.Gob.mx
2017	25,315.70			1,343.50	4,065.26	SINA-CONAGUA.Gob.mx
2016	25,315.70			1,343.50	4,065.26	SINA-CONAGUA.Gob.mx
2015	25,315.70			1,343.50	4,065.26	SINA-CONAGUA.Gob.mx
2014	25,315.70			1,343.50	4,560.26	SINA-CONAGUA.Gob.mx
2013	25,315.70 (1,671.53 mm)	19,411.94 76.6 %	5,903.76	1,343.50	4,560.26	SINA-CONAGUA.Gob.mx
2012	25,315.70				5,691.00	SINA-CONAGUA.Gob.mx
2011	25,315.70				5,150.00	SINA-CONAGUA.Gob.mx

2008	37,790.22 (1,259.04 mm) 19.5 %	25,697.34 Approximate 68 %	12,092.88	2,368.00	9,724.80 Approximate	Bauer Gotweinn et al 2011
1995	34,959.70 (1,283.06 mm) 19.1 %	23,772.59 Approximate 68 %	11,187.11	1,023.61	10,163.44 Approximate	Lutz, W. et al 1996 (IIASA)

Table 2.- Total value over time of the Aquifer by Hydrological – Administrative Region XII Yucatán Peninsula. (SINA-CONAGUA.Gob.mx).

Suggested hypothesis to test

Precipitation is not homogeneous in the Yucatan Peninsula, both spatially and temporally, the characteristics of the vegetation and soils differ spatially and temporally due to the change in land use, and hence also evapotranspiration, altimetry, and the presence of regional fractures. and local, faults, sinkholes, poljes and uvalas, the geological strata, the depth to the water table, the position of the saline interface, extreme temperature differences, all of them with a strong influence on karst-type geomorphological processes (PHR-PY, 2020-2024). The result of this variability and complexity implies that recharge is not homogeneous in the territory, so it is possible to affirm that in this large peninsular hydrological system, there are subsystems with characteristics that distinguish them from others, defined as local hydrogeological subunits where Extraction is exceeding availability and the integrity of the health of ecosystems and increased concentrations of contaminants are being put at risk by exploiting water intended for Compromised Natural Discharges.

Base studies for recharge analysis in hydrogeological units.

As we did not have the studies carried out by CONAGUA annually to comply with the Official Mexican Standard-011-CONAGUA 2015 and establish the availability of water, a review of available scientific information was carried out and 2 articles in indexed journals were chosen. on the characterization of the Yucatan Peninsula and the hydrological balance using geographic information systems techniques. The most complete information at the level of the Yucatan Peninsula Region on hydrological dynamics, in terms of precipitation, evapotranspiration, recharge and water extraction, are 2 works published in refereed scientific journals:

1).- Edgar Rodríguez-Huerta, Martí Rosas-Casals & Laura Margarita Hernández-Terrones (2020) A water balance model to estimate climate change impact on groundwater recharge in Yucatan Peninsula, Mexico, Hydrological Sciences Journal, 65:3, 470- 486, DOI:10.1080/02626667.2019.1702989; Website: https://doi.org/10.1080/02626667.2019.1702989

2).- Peter Bauer-Gottwein, Bibi R. N. Gondwe, Guillaume Charvet, Luis E. Marín, Mario Rebolledo-Vieyra & Gonzalo Merediz-Alonso. 2011. Review: The Yucatán Peninsula karst aquifer, Mexico. Hydrogeology Journal (2011) 19:507–524

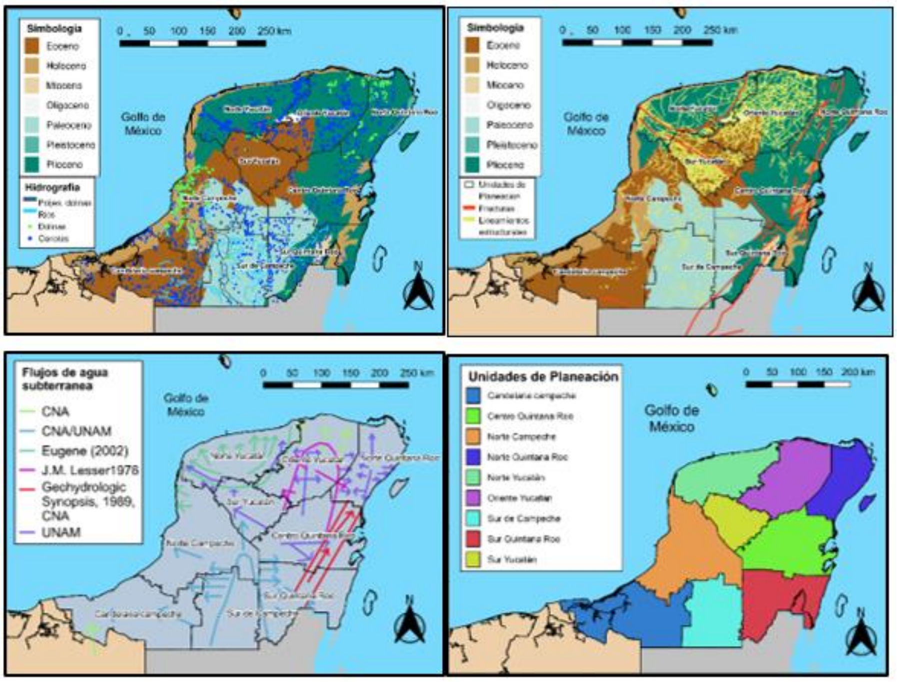
The use of this scientific information was the basis for estimating some hydrological parameters at the level of the hydrogeological subunit (or Planning Unit, as described in the Regional Water Program PY 2020-2024), which allows observing the spatial heterogeneity in the Yucatán Peninsula. , particularly the Committed Natural Discharges and the Availability of water for consumptive uses, and from here, compare against the data offered in the CONAGUA Water Information System (SINA 2020), where, after applying the NOM -011-CNA 2015 are calculated and published in the Official Gazette of the Federation year after year. For this purpose, the data from the publications in the DOF from 2013 to 2020 are reviewed, and the average annual availability is known to satisfy the new water concessions for productive projects or urban public use, which are granted considering the large karst aquifer. peninsula, but not environmental heterogeneity. This allows us to continue granting concessions in places that perhaps today are using all the available water and begin to use the water dedicated to the Committed Natural Discharge, important for the health of ecosystems and the dilution of contaminants and salts. This document supports what is mentioned in the body of the document of the Regional Water Program PY 2020-2024.

The geological environment of the Yucatan karst aquifer and the configuration of the hydrogeological subunits and Planning Units.

Although the Yucatan Peninsula is made up of a large calcareous massif, it is far from being homogeneous. Administratively, the Yucatán Peninsula incorporates 4 Hydrological Regions, a large Karst Aquifer and several Surface Basins, particularly south of Campeche, with more than 15 Hydrological Basins (PHR-PY 2020-2024). Geological structure is a dominant controlling factor in and is reflected in the evolution of landforms. Geomorphic processes leave their distinctive impression on landforms and each process develops its own characteristic set of landforms. Full interpretation of current ecosystems is impossible without a full appreciation of the multiple influences of the geological and climatic changes that occurred during the Cretaceous to Pleistocene-Holocene. Figure 2 (a, b and c) schematically presents the variations in altimetry, geology, hydrography, as well as the presence of sinkholes, poljes, faults, fractures, and preferential flows, their integration accounts for a great hydro-heterogeneity. environmental.

The particularity and importance of the hydrological basin, or in the case of the Yucatan Peninsula, the hydrogeological subunits, as a planning and development unit, lies fundamentally in that it brings together very specific natural geographic unit conditions. Among these characteristics are its character of relative independence, due to its well-defined natural limits; and its integrated functional dynamics, given fundamentally by the exchanges of matter and energy that take place in the dynamics of the components of climate and water. In this way, an analysis can be carried out of the multiple interactions and transformations of substances and energy and the complicated process of operation of these geosystems, from the mechanical movement of the loose material and the water cycle to the biotic component, the latter aspect that includes the ecological and ecosystem approach as a functional unit in the society - nature relationship. Hence the importance that, to achieve a Regional Program, one must start from hydrological basins, or in the case of the karst platform, the hydrogeological subunits (Figure 2d) associated with certain particular conditions of the territory, and administratively harmonized with the municipal levels. generating the Planning Units.

Figure 2.- a). Thematic diagrams on altimetry, sinkholes and poljes, b). geology and preferential flows, faults and fractures, c).- geomorphology, karst development and d).- Planning Units.



The water balance of the karst aquifer of the Yucatán Peninsula.

One of the steps to follow for integrated water management in the various planning units is to understand more about the basic geohydrological aspects, among which is its water balance. Previously, we commented on the balances carried out for the different aquifers of the Administrative Hydrological Region P. et la 2011, on the hydrological balance model and recharge in the Yucatan Peninsula, who studied topics such as precipitation, temperature, soil humidity, storage capacity, as well as evapotranspiration. The model consists of applying the principle of conservation of mass for the entire large basin or a part of it, influenced by certain boundary or boundary conditions and for a period of time. The difference between the inputs and outputs must be equal to the variation in storage. When the time unit is very long, the variations in storage are insignificant, so in that case the inputs would be equal to the outputs.

$$\text{Inputs} - \text{Outputs} = \Delta \text{ Storage}$$

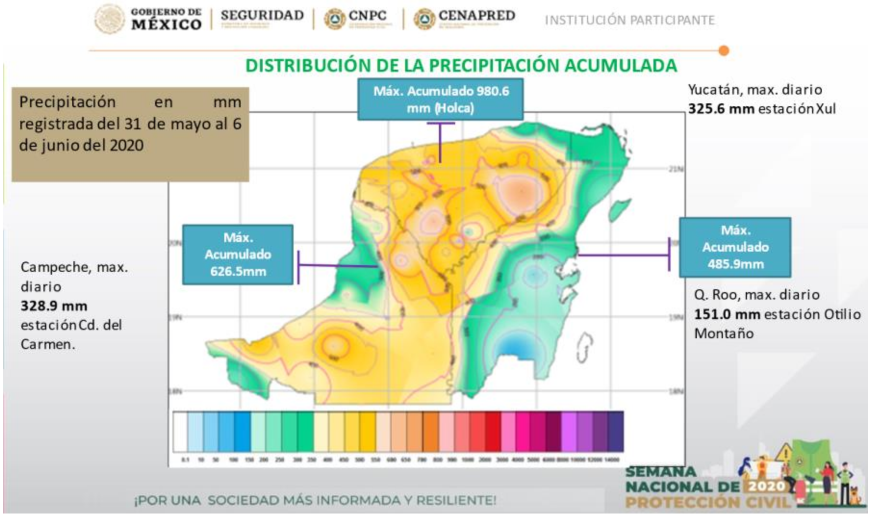
Recharge to groundwater can be explained by the pattern of precipitation. An amount of precipitation is returned to the atmosphere through evapotranspiration. Current evapotranspiration refers to the water that returns to the atmosphere through free surface evaporation from the leaves of vegetation, soil, and bodies of water. Water stored in the soil and percolating through the calcareous rock can be absorbed by plants and transpired through the leaves. The water percolated to the groundwater table that was not retained in this layer is incorporated as recharge to the groundwater table or water-saturated zone.

The model generated by the authors is exploratory, to understand more about the balance. The aforementioned authors did not consider surface runoff in their model given the great permeability and infiltration capacity of karst formations, nor did they consider inlet and outlet underground flows. With these limitations, the information generated by said authors was worked on and adjusted for the purpose of contrast with possible extraction and recharge scenarios by Planning Unit.

Hydrological balance of the Rodríguez-Huerta, E. et al 2020, and Bauer-Gotweinn, P. et la 2011 Model, for the year 2008 [1.2].

Rain is the most important of all environmental factors that influence the type of vegetation found in the territory. As the main input element and source of humidity in the previous equation, it ranges, on average, between 400 mm to 1,500 mm per year for the study area, increasing from the coast to inland, with the wet or rainy period being between May and October and the dry period between the months of November and April. However, during Hurricane Gilberto (1988), precipitation in September exceeded 500 mm in some cases, not to mention the latest events of 2020 with Storm Cristobal and subsequent hurricane and storm events that totaled more than 900 mm (Figure 3).

Figure 3: Distribution of precipitation for the year 2020 in the Yucatán Peninsula.



Source: CENAPRED, 2020

The temporal behavior of precipitation is very variable (Figure 4). The general average of the 14-year series (from 2004 to 2018) is 1,235.78 mm, and presents dry years (such as 2009) with 948 mm annual peninsular average, and wet years (such as 2013) with 1,671.53 mm peninsular average (SINA - CONAGUA.Gob.mx).

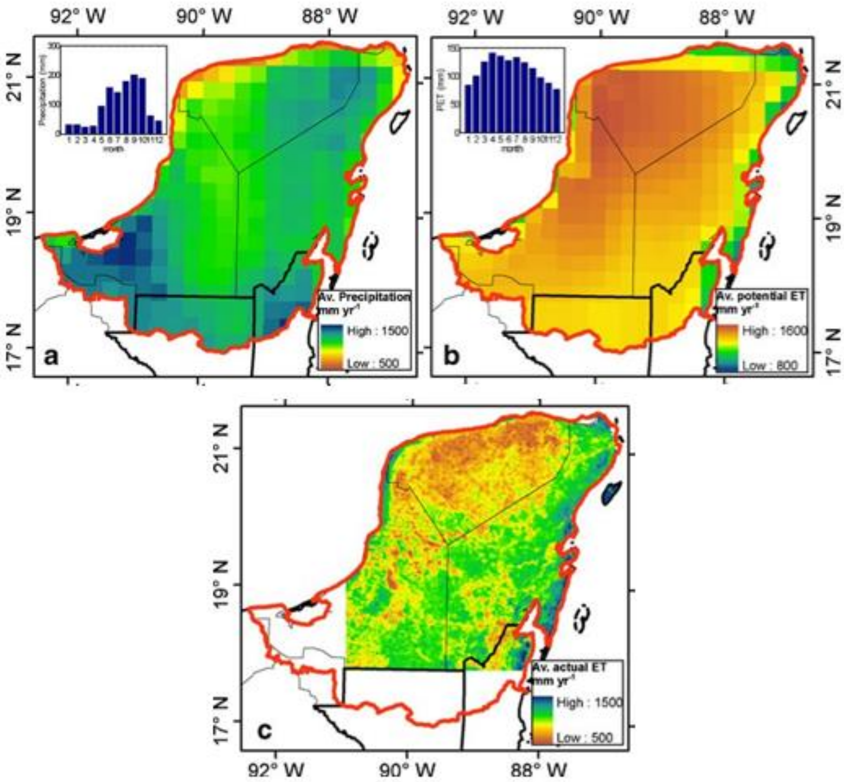
Figure 4: Annual rainfall by state of Campeche, Yucatán and Quintana Roo.

Fountain; SINA_CONAGUA, 2020.

The recharge studies by Bauer Gotweinn et al 2011, analyzed in this work, with data from 2004 to 2008, present average values of total precipitation for the four years of 1,259.04 mm (Figure 5), a value very close to the general average of the series mentioned above (2004-2018, SINA-CONAGUA.Gob.mx). The above would represent a precipitated volume in the Yucatan Peninsula of 177,888.08 Mm3/year.

Continuing with the work of Rodríguez-Huerta et al, 2020, and Bauer Gotweinn et al 2011, they estimated that the average annual potential evapotranspiration (ET) for the Yucatán Peninsula varies from 850 to 1,600 mm/year, with a weak NW-SE with greater potential evapotranspiration in the NW, decreasing towards the east and south coast (Figure 6). Potential ET was calculated from the operational surface analysis data set, provided by the European Center for Medium-Range Weather Forecasts (ECMWF2010). Actual evapotranspiration was determined for the period 2004 to 2008 from remote sensing data. The average annual real evapotranspiration for the Yucatan Peninsula varied spatially between 350 and 2,500 mm/year. Actual evapotranspiration has distinct spatial variability, with higher actual evapotranspiration along the coasts and relatively low actual evapotranspiration in the drier and less vegetated state of Yucatán (Figure 5).

Figure 5.- a). Precipitation map (TRMM-3B42, average 1998-2008), b). Potential evapotranspiration map (PET, ECMWF, average 2000-2008), c). Real evapotranspiration map (average 2004-2008).



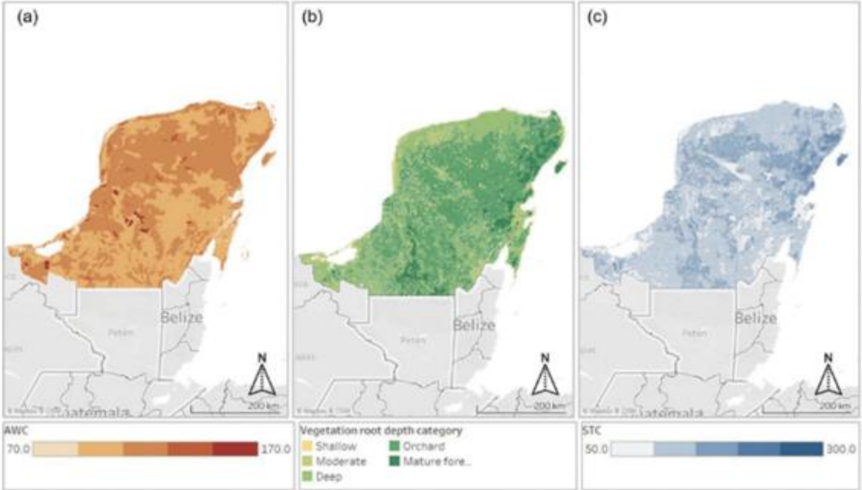
Source: Bauer Gotweinn et al 2011 [2]

According to Bauer Gotweinn et al 2011 [2], the water table in the coastal plains of the Yucatan Peninsula is quite shallow (less than 10 to 20 m underground in most places). Therefore, phreatic evapotranspiration is expected to be a term not available in the water balance of the karst aquifer in the region. Field evidence from divers from caves and quarries in the Yucatan Peninsula show trees developing extensive vertical root systems that can reach the water table. Phreatic evapotranspiration is difficult to measure and quantify directly. Querejeta et al. (2007) [3] report the results of a study in northern Yucatán (approximate location 20.8˚N, 89.5˚W) using stable isotopes of oxygen in water (18O) to discriminate between different water sources used by vegetation. Contrary to their expectations, they found that the isotopic signature of stem water was different from the isotopic signature of groundwater and similar to the isotopic signature of soil water for all times, including the dry season. The finding indicates an insignificant use of groundwater for the investigated locality and plant species.

Actual evapotranspiration determined with remote sensing techniques was correlated with groundwater depths and the study area in southern Quintana Roo was simulated (BRN Gondwe, Technical University of Denmark, unpublished data, 2010) [4]. The results indicate that the actual evapotranspiration is close to the potential evapotranspiration for water table depths less than 10 m below the surface. The ratio of actual evapotranspiration to potential evapotranspiration decreases between water table depths of about 10 to about 30 m and stabilizes for deeper water tables. Vegetation growing in localities where the water table is less than 10 m therefore never appears to suffer water stress, while vegetation can use significantly elevated amounts of groundwater up to a groundwater depth of 30 m (without However, the water potential that the plant can generate and its capillary water circulation apparatus that can overcome the force of gravity also has an influence. However, these observations contradict what is observed in the low deciduous forests of the northwest of the Yucatan Peninsula and with those results reported by Querejeta et al. (2007) [3]. The magnitude and dynamics of phreatic evapotranspiration in the Yucatan Peninsula require further investigation.

The authors mention that there is a direct correlation between precipitation and vertical recharge. However, they observed that there is a limit value at which, below that value, no recharge is possible, and this is 798 mm/year. This result suggests that the entire territory below this value will not receive a significant vertical natural recharge from precipitation, derived from infiltration into the soil and its percolation into the water table. The soil is assumed to have a field or water storage capacity, which varies according to variations in precipitation and evapotranspiration, while remaining within the maximum moisture capacity in the soil before reaching the wilting point. vegetation (Figure 6).

Figure 6.- a): Capacity of water available in the soil, b). - Depth of the roots of the vegetation and, c). - Capacity to store water (field capacity)



Source: Bauer Gotweinn et al 2011 [2], Rodriguez Huerta et al 2020 [1].

This depends on two factors, the depth of penetration of the roots of the vegetation and the water storage capacity (Figure 7), which is related to the characteristics of the soil such as texture, and the percentage of organic matter or sands, silts and clays. Given the irregular thickness and thinness of its soil, the infiltration of water from precipitation is very rapid, due to the presence of fractures and the secondary development of karst, so the water drains into the aquifer (Figure 7).

Recharge and availability values published in Bauer Gottwein et al 2011 and Rodríguez-Huerta, E. et al 2020 and REPDA from 2008 [1,2].

Rodríguez-Huerta et al, 2020 and Bauer Gotweinn et al 2011 [1,2], used various methods to evaluate the current recharge of the Yucatán Peninsula. The most important recharge areas for the date of the study are in the southwestern and northeastern part of the states of Campeche, in Candelaria and Laguna de Terms, and Yucatán, between the municipalities of Cenotillo and Tizimín, respectively. In the rest of the areas, vertical recharge is not significant, and even in some coastal areas of the Peninsula they do not receive any vertical recharge, however, they can receive recharge via underground flows [5,2,6], which in this case are not considered (Figure 8a). It is also notable that recharge occurs between the months of June to November, with September being the month with the greatest contribution to vertical recharge to groundwater (on average 46 mm/year) in the RHA-XII-PY [7].

This map by Peter Bauer-Gottweinn et al 2011 [2] was reworked for the Regional Water Program project, georeferencing the base image in Tiff format on the Shape file of the limit of the Yucatan Peninsula and also with the limits of each Planning Unit. The polygons corresponding to the mm of recharge were drawn for the different areas presented by said modified map. According to the colors of the interval, the mm of recharge were identified, ranging from -500 to 500 mm, as shown in the following Figure 8b.

Therefore, on the prepared map you can see the mm of recharge in the different areas of the peninsula. The percentage of recharge occupied by the different values (100, 200, 300, 400, 500 mm) with respect to the total surface of the planning unit was obtained. In this case, it is observed that, for the Candelaria planning unit, in the state of Campeche, 61.55% of its territory presents a recharge of 500 mm or more. Subsequently, the total recharge was calculated as shown in the following Table 3.

Planning Unit	Total, area (km2)	Recharge 2004-2008 (mm)	Surface of recharge (km2)	Percentage recharge	Recharge in Mm3
Campeche	**57,634.42**				
CampN	22,349.62	100	6,791.18	30.39	679.12
		200	1,836.65	8.22	367.33
		300	8,350.91	37.36	2505.27
		-500	535.11	2.39	-267.55
		500	4,354.38	19.48	2177.19
		subtotal			5317.31
CampC	21,280.82	100	5301.30	24.91	530.13
		200	105.95	0.50	21.19
		300	2376.06	11.17	712.82
		500	13097.47	61.55	6548.74
		400	398.40	1.87	159.36
		subtotal			7972.23
CampS	14,003.98	100	9,397.20	67.11	939.72
		200	53.91	0.38	10.78

		300	3,590.83	25.64	1077.25
		500	962.03	6.87	481.01
		subtotal			2,508.76
Quintana Roo	**44,809.22**				
QRooN	11,002.53	100	2,502.91	22.75	250.29
		0	4,782.24	43.46	0.00
		300	2,387.68	21.70	716.31
		500	1,315.91	11.96	657.96
		400	0.34	0.00	0.13
		subtotal			1624.69
QRooC	17,792.14	100	9,381.49	52.73	938.15
		0	1,755.41	9.87	0.00
		200	365.85	2.06	73.17
		300	3,776.63	21.23	1132.99
		500	2,512.75	14.12	1256.38
		subtotal			3400.69
QRooS	16,014.55	100	5,106.99	31.89	510.70
		0	2,841.95	17.75	0.00
		300	4,939.38	30.84	1481.81
		500	3,126.09	19.52	1563.04
		subtotal			3555.56
Yucatán	**41,776.95**				
YucN	16,638.43	100	3,120.89	21.32	312.09
		300	4,317.77	29.50	1295.33
		-500	1,002.87	6.85	-501.44
		500	4,758.03	32.50	2379.02
		400	470.6	3.21	188.24
		-300	929.01	6.35	-278.70
		subtotal			3394.54
YucO	16,783.68	100	1,233.85	7.35	123.38
		300	1,052.45	6.27	315.73
		500	13,011.86	77.53	6505.93
		400	1,485.49	8.85	594.20
		subtotal			7539.24
YucS	8,354.84	100	2,638.20	31.58	263.82
		300	3,224.67	38.60	967.40
		500	2,491.95	29.83	1245.98
		subtotal			2477.20
Total		Total			**37,790.22**

Source: Prepared and modified with data from Bauer (2011) [2].

Table 3.- Recharge values per Planning Unit according to the modified recharge map.

Several authors mention that the effective recharge to the groundwater table is equivalent to 14 or 17% of the precipitation [8,9,4]. In the case of the work of Rodriguez Huerta et al (2020) [1] and those of Peter Beuer-Gottwin et al 2011 [2], recharge represents 21.2% of the precipitation. Despite the basic nature of the Rodríguez-Huerta et al, 2020 [1] model (since it does not consider underground flows towards the coast), it allows generating a local hydrological footprint to determine the possibility of satisfying local needs using the theoretical recharge values within of the administrative borders of the Planning Units and only exploiting the available groundwater without affecting the committed natural discharges (Table 3).

In the following Figure 9, the total recharge per planning unit (Mm3/year) is observed through variation ranges that go from 1,624.69 Mm3, which would be the lowest recharge and which corresponds to the North of Q. Roo, to 7,972.23 Mm3, which would be the largest vertical recharge corresponding to Candelaria Campeche.

In this way, the total vertical recharge for the Yucatan Peninsula amounts to 37,790.22 Mm3 annually (Beuer Gotweinn et al 2011) [2]. Very similar values resulted in the work of Lutz, W. et al 1996 (IIASA) [10]. Following the description of the work of Beuer Gotweinn et al 2011 [2], it is mentioned that the groundwater that is recharged in the karst aquifer of the Yucatán Peninsula finally flows in three large water channels, which are the coastal outflow (DNC), pumping and evapotranspiration.

Beddows (2004) [11] measured coastal groundwater flow at major submarine springs on an 80 km stretch of coast in southern Quintana Roo and calculated average fluxes of approximately 0.73 m3s-1 per km of coastline. Using the recharge estimate of Lesser (1976) [8], the average coastal output would be around 0.27 m3s-1 per km of coast. Based on these results, Beddows (2004) argued that the overall average groundwater recharge for his study area near the Caribbean coast may be between 30 and 70% of average precipitation. Gondwe et al. (2010b) [12] calculated the average groundwater recharge rate equal to 17% of the mean annual precipitation, which is consistent with the estimate of Lesser (1976) [8]. The study also suggested limited average recharge rates on the Caribbean coast. The different available offshore estimates were reviewed and compared with the results of regional groundwater models (BRN Gondwe, Technical University of Denmark, unpublished data, 2010) [4], and for that study area, the coastal flow equivalent to ~ 0.3-0.4 m3s-1 per kilometer of coastline, which is in the same range as estimates by Hanshaw and Back (1980) [9] based on field measurements. The magnitudes of groundwater recharge to the karst aquifer and coastal outflow from the aquifer to the ocean require further investigation.

Continuing with the data derived from the scientific research of Bauer Gotweinn et al 2011 [2], adapting it to the Planning Units, it is observed in Table 4 that, for each of the Planning Units, the values (Mm3/year) of total recharge, committed natural discharge, total availability, extraction volume for the year 2008, average availability, and pressure on total availability have been calculated, following the proportions to define the Committed Natural Discharge published in the Availability Agreement that is published in the Official Gazette of the Federation every year. It is notable that the main recharge occurs in the planning units of Candelaria Campeche (river zone), and the east of Yucatán, and the minor ones in the State of Quintana Roo, particularly the north of Quintana Roo with 1,628.37 Mm3/year. Continuing with the analysis of the work of Bauer Gotweinn et al 2011 [2], the extraction granted to the year 2008 (year of preparation of that study), totaled the amount of 2,120.30 Mm3/year. There were 28,442 wells registered in the Yucatan Peninsula for that year, with the UP Norte Yuc being where 46% of the total wells were concentrated, while the UP Sur Camp only had 50 wells that extracted 1.07 Mm3/year. The maximum extractions occur in the North of QRoo and North of Yucatán, with 486.79 and 497.65 Mm3/year (tabla 4).

REPDA Wells (Period From 1966 to 2008)		
Planning Unit	No. of Wells	Extraction Volume
		Mm3/Annual
Candelaria Campeche	1,602	83.36
Centro de Q. Roo	812	39.65
Norte de Campeche	2,755	282.65
Norte de Q. Roo	1,940	486.79
Norte de Yucatán	13,100	497.65
Oriente de Yucatán	5,009	269.73
Sur de Campeche	50	1.07
Sur de Q. Roo	1,096	128.36
Sur de Yucatán	2,078	331.04
Total	28,442	2,120.30

Source: REPDA, 2020.

Table 4.- Number of Wells and total extraction values of concessioned water for the year 2008 adjusted to the Planning Units.

In Table 5, the water balance carried out with the extraction data is presented. It is possible to observe that, for that year of 2008, there was availability in the different aquifers and particularly in the calculation by Planning Units. However, it is also observed that the pressure on the total availability of the aquifer in the UP Norte QRoo amounts to 86.75%, so it is only 13.25% away from being occupied by the various productive and urban public sectors, placing the discharge at risk. Committed Natural (ecosystem health and dilution of contaminants) in the near future. Other Planning Units where the pressure on availability is medium refers to that of the North and South of Yucatán, which reaches the figure of 43.04% and 39.23% respectively, so there is still availability of the resource, but already for 2008 The growth of capital cities and tourism development was seen in an upward manner. At the peninsula level, the pressure on total availability for the year 2008 would be 16.06%, with great potential.

Planning unit	Total, area (km2)	Total, annual recharge per unit Mm3/year	Committed natural discharge (Mm3/year)	Total, availability Mm3/year	Annual extraction volume Mm3/year	Average availability Mm3/year	Pressure on total availability %
Candelaria Campeche	21,280.82	7,980.30	5,256.36	2,723.94	83.36	2,640.58	3.06
Sur de Campeche	14,003.98	2,506.71	1,652.46	854.24	1.07	853.17	0.12
Norte Campeche	22,349.62	5,319.06	3,508.89	1,810.32	282.67	1,527.64	15.61
subtotal Campeche	57,634.42	15,791.83	10,374.19	5,417.63	367.08	5,050.55	6.76
Norte Yucatán	14,638.43	3,396.11	2,239.67	1,156.43	497.65	658.78	43.03
Oriente Yucatán	16,783.68	7,535.87	4,967.96	2,567.91	269.73	2,298.18	10.52
Sur Yucatán	8,354.82	2,473.02	1,629.19	843.83	331.04	512.79	39.23
Subtotal Yucatán	39,776.93	13,404.82	8,830.47	4,946.45	1,098.42	3,848.03	22.20
Norte Q. Roo	11,002.53	1,628.37	1067.24	561.13	486.79	-74.34	86.75
Centro Q. Roo	17,792.14	3,398.29	2,241.81	1,156.48	39.65	1,116.83	3.42
Sur Q. Roo	16,014.55	3,555.23	2,338.12	1,217.11	128.36	1,088.75	1.01
Total Quintana Roo	44,809.22	8,558.56	5,645.96	2,912.59	654.80	2,257.79	22.48
Total Península	142,220.57	37,790.22	25,697.73	13,200.29	2,120.30	11,079.99	16.06

Table 5.- Pressure on water availability in the Yucatan Peninsula and Planning Units with data from Beuer Gotweinn et al 2011 and extraction volume from REPDA 2008.

In this case, if we consider that, in the Yucatan Peninsula, the surface area occupied by the various wetlands (Regional Water Program PY, 2014-2018), and using the value of the committed natural discharge, derived from Bauer Gotweinn et al 2011 (25,697.73 Mm3), aimed at the health of ecosystems and the dilution of contaminants, would represent a water column (or average depth) for all of them of 0.75 m accumulated in the year (Table 6).

Type of wetlands in the region	Quantities	Area (km2)
Palustres	180	25,976.7
Lacustres	49	439.3
Fluvial/Riparian	106	1,867.0
Estuarines	90	7,076.4
Created/Artificial	7	60.9
Total	432	35,423

Source: Water Atlas 2014, CONAGUA.

Table 6.- Types of wetlands in the PY

Recharge and availability values published in the Official Gazette of the Federation 2020 and REPDA for the year 2020.

As mentioned above, from the last publication of the Availability on September 17, 2020, a total of 17,341.6 Million m3 per year for the Committed Natural Discharge (DNC) were considered for the Yucatan Peninsula considering the 4 aquifers (405, 2301, 2305 and 3105) shown in Table 1. In this case the base values for 2020 refer to a precipitation of 1,214.16 mm, considering that only 14.6% percolates as recharge to the water table, and of this recharge value, 68.3% has been considered as the volume of the committed natural discharge. It was already commented that the Committed Natural Discharge should be considered as the fraction of the natural discharge of an aquifer, which is committed as surface water for various uses or that must be conserved to prevent a negative environmental impact on ecosystems or the migration of water from poor quality to an aquifer. The recharge of the aquifers considered for the Yucatán Peninsula, such as Xpujil, Cerros y Valles, Cozumel Island and the Yucatán Peninsula yield a total figure of 25,315.70 Mm3 annually (Table 1). As mentioned previously, in the Agreements issued from 2011 to date, the recharge value has not been modified and therefore precipitation and other variables that influence this balance have not been modified either (Table 2).

However, and in order to envision a scenario for 2020, these data were spatially distributed according to the conditions represented in the model by Planning Units, in the map modified in this study by Bauer Gotweinn et al 2011 [2], based on their map of recharge, assuming the distribution of precipitation, evapotranspiration and spatial recharge remain constant and is distributed according to the percentage of recharge in each planning unit derived from the balance of the year 2008 presented above, but with the precipitation value , recharge and availability of notices published in the Official Gazette 2020. This exercise is only to generate a first vision of spatial heterogeneity and the capacities to sustain development without compromising the quality and health of ecosystems and the human right to water in quality and quantity.

The analyzes carried out in the Public Water Registry (REPDA) for the year 2020, show a concessioned annual extraction value of 4,637.68 Mm3 at the level of the Peninsular karst aquifer, (with a total commitment of 4,965.25 Mm3/year, which includes extractions from other aquifers and concessions pending titling). It is observed that the highest extraction occurs in the Planning Units with the main urban and metropolitan centers as shown in Figure 10 (Campeche, Mérida and Cancún). While the lowest values are found in the southern UP of Campeche (Calakmul) and the Center of Quintana Roo (Felipe Carrillo Puerto).

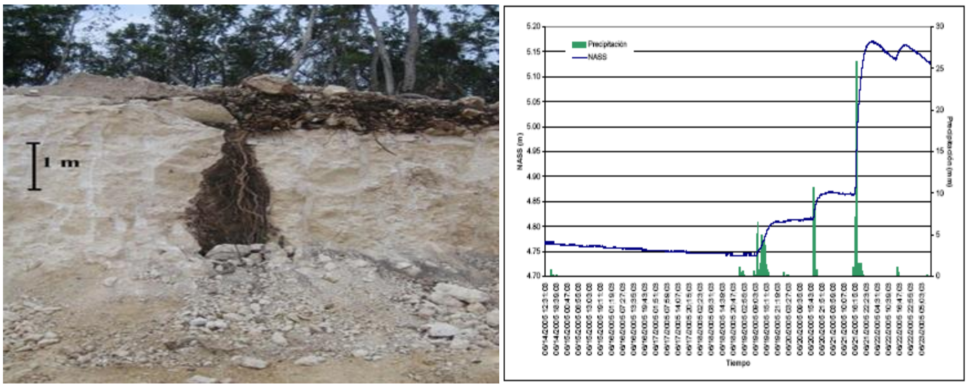
The number of wells has increased enormously to reach the figure of 48,610 concessions granted today, and the State of Yucatán stands out with 46% of the water extracted and 66% of the total registered wells, while the other two states They share about 25% of the extraction each and a little more than 10% of the number of wells (Table 7). This accounts for the specific weight of Yucatán in the context of water resource use.

Planning unit	Total, area (km2)	Annual extraction volume mm3/year	Number of wells
Candelaria Campeche	21,280.82	83.36	3,444
Sur de Campeche	14,003.98	1.07	103
Norte Campeche	22,349.62	282.67	6,715
subtotal Campeche	57,634.42	367.08	10,262
Norte Yucatán	14,638.43	497.65	19,445
Oriente Yucatán	16,783.68	269.73	9,194
Sur Yucatán	8,354.82	331.04	3,499
Subtotal Yucatán	39,776.93	1,098.42	32,138
Norte Q. Roo	11,002.53	486.79	2,926
Centro Q. Roo	17,792.14	39.65	1,030
Sur Q. Roo	16,014.55	128.36	2,254
Total Quintana Roo	44,809.22	654.80	6,210
Total Península	142,220.57	2,120.30	48,610

Source: REPDA, 2020

Table 7.- Number of Wells and total extraction values of concessioned water for the year 2020.

Figure 7.- a). Vegetation that takes advantage of groundwater sources for phreatic evapotranspiration. Open pit gravel quarry in the vicinity of Tulum (~20.2955°N, 87.5028°W). The scale is approximate, b). Relationship between precipitation and elevation of groundwater level in the State of Yucatán. (monitoring well. UADY, Faculty of Engineering)



Source: Bauer Gotweinn et al 2011 and UADY-FI

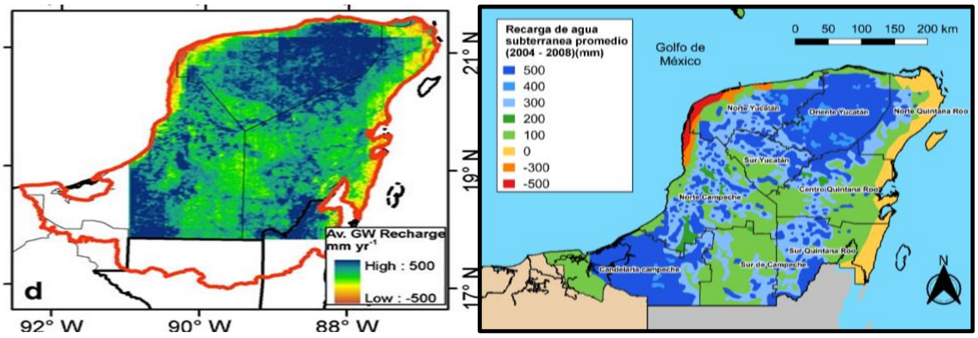
If we calculate the pressure on the current total availability (2020), it is observed in Table 8 that at the Yucatan Peninsula level, of the 7,974.06 Mm3/year of total availability and the concessioned extraction values (REPDA 2020) of 4,965.25 Mm3 /year, implies a pressure of 62.26%, so there would still be 3,008.91 Mm3/year available for other activities. Let us remember that in 2008 the pressure on availability was just over 16%.

Planning Unit	Total, Area (Km2)	Total, Annual Recharge Per Unit Mm3/Year	Committed Natural Discharge (Mm3/Year)	Total, Availability Mm3/Year	Extraction Volume Mm3/Year	Average Availability Mm3/Year	Pressure on Total Availability %
Candelaria Campeche	21,280.82	5,316.29	3,631.02	1,685.27	301.75	1,383.52	17.89
Sur de Campeche	14,003.98	1,680.62	1,147.86	532.76	8.98	523.78	1.68
Norte Campeche	22,349.62	3,562.07	2,433.87	1,129.20	987.77	141.43	87.47
Subtotal Campeche	57,634.42						
Norte Yucatán	14,638.43	2,274.00	1,553.14	720.86	859.92	- 139.06	119.29
Oriente Yucatán	16,783.68	5,050.54	3,449.51	1,601.03	675.66	925.37	42.20
Sur Yucatán	8,354.82	1,659.47	1,128.43	531.04	595.09	- 64.05	112.06
Subtotal Yucatán	39,776.93						
Norte Q. Roo	11,002.53	1,088.38	743.36	345.02	807.71	- 462.69	234.10
Centro Q. Roo	17,792.14	2.278.12	1,555.95	719.77	58.55	660.62	8.14
Sur Q. Roo	16,014.55	2,381.87	1,626.81	755.06	342.24	421.82	45.32
Subtotal Quintana Roo	44,809.22						
Total, Península	142,220.57	25,315.70	17,305.60	7,974.06	4,965.25	3,008.91	62.26

Table 8.- Pressure on water availability in the Yucatan Peninsula and Planning Units with DOF 2020 data and REPDA 2020 extraction volume.

The remaining average availability would still seem acceptable, since there would still be almost 27.8% of water available, however, if we bring the analysis closer to the Planning Unit level, we see that the Planning Units of the North and South of Yucatán, as well as the Planning Unit Planning of the North of Quintana Roo would already be using the waters of the Compromised Natural Discharge up to 462 Mm3, exerting a pressure on availability of more than 200% (Table 8). The Northern Campeche Planning Unit would be close to its available capacity.

Figure 8.- a). Groundwater recharge map (2004-2008 average) for the Yucatan Peninsula. All quantities are given in mm per year; b). Modified groundwater recharge map (2004-2008 average) for the Yucatan Peninsula. All quantities are given in mm per year.



Source: Bauer Gotweinn et al 2011 and own elaboration modified from Bauer-Gotweinn et al 2011

If we consider that, in the Yucatan Peninsula, the surface area occupied by the various wetlands, the value of the committed natural recharge, derived from DOF 2020 (17,305.60 Mm3), aimed at the health of ecosystems and the dilution of contaminants, would represent a water column (average depth) for all of them 0.50 m. This would imply a strong decrease in the discharge of freshwater to the estuarine coastal system, so the salinization of these ecosystems would be at increasing risk.

Final reflections and climate change.

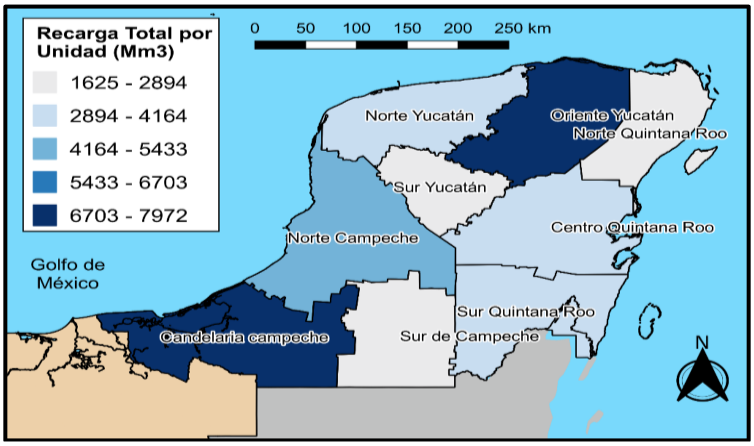
Derived from this exercise, environmental heterogeneity and social appropriation are recognized through the extraction of water from this great hydrological system at local levels, and that requires increasing research and technological development projects to improve understanding at the local level of the Water Units. Planning and achieving better management of water resources, protecting compromised natural discharges, important for the health of ecosystems and the dilution of contaminants and the human right to water in quantity and quality.

The adjusted model of water recharge data presented in scientific publications accounts for the spatial distribution of the various hydrological parameters, which are representative for that year of 2008. A limitation of the model is that it does not include surface runoff nor does it take take into account underground flows. However, it gives a good idea of the average annual spatial distribution of precipitation, evapotranspiration and recharge, key concepts in the hydrological balance. The fact stands out that both in the hydrological balance presented by the DOF 2020, and in the publication Bauer Gotweinn et al 2011, for data from 2008, the average annual total precipitation for the entire Yucatan Peninsula was 1,214.16 mm for the first and 1,259.04 mm, the second. Very similar in amount of rain sheet. However, there is a large difference in the volume calculated for aquifer recharge due to the proportion of precipitation used for each scenario (DOF 2020 and Bauer Gotweinn 2011). This has a very important impact on the final availability calculation, as shown in the following Table 9.

Hydrological parameter	**Bauer Gotweinn 2011**	**DOF 2020**	**Comment**
Precipitation (mm)	1,259.04	1,214.16	There is no significant difference
Percentage ratio for recharge %	21.2	14.7	A difference of 6.5 percentage points
Recharge Mm3/year	37,790.22	25,315.70	It represents a difference of 14,474 Mm3/year
Percentage ratio for committed natural discharge %	68	68	In this case the percentage value was maintained in both cases
Committed Natural Discharge Mm3/year	25,697.34	17,341.6	It represents a difference of 8,355.74 Mm3/year
Total availability Mm3/year	12,092.88	7,974.06	It represents a difference of 4,118.89 Mm3/year
Concessioned extraction Mm3/year	2,120.30	4,965.25	The increase from 2008 to 2020 is more than 100%
Registered wells (REPDA)	28,442	48,610	More than 20 thousand wells
Pressure on total availability at the RHXII level, Yucatán Peninsula %	16.06	62.2	A significant increase
Pressure on total availability at the UP Norte level QRoo %	86.75	234.10	The variation is enormous, availability is exhausted and the committed natural discharge is consumed

Table 9.- Hydrological parameters for calculating water availability for the Bauer and Gotweinn 2011 and DOF 2020 scenarios

Figure 9.- Total recharge per planning unit (Mm3/year).



Source: self-made.

It is necessary to reflect much more on the issue of recharge and the proportion of precipitation that actually enters the aquifer, and generate scientific knowledge to improve the calculations for each PU. This is in the perspective that, in a period of 12 years, more than double the amount of water consumed in 2008 has been granted concessions and more than 20 thousand wells are in operation. Therefore, the pressure on the total availability of water went from 16% to more than 62%. Increasingly closer to the threshold to guarantee the health of ecosystems and the dilution of contaminants, as well as the human right to water. However, it is notable that in both scenarios (2008 and 2020) some Planning Units were at 13% of average availability in 2008, but that by 2020 they have occupied the total availability and consume the natural discharge compromised for health. of ecosystems, the dilution of pollutants and the human right to water in quality and quantity, this condition is maintained even in the event of greater recharge. These results generally show the local complexity of the hydrological system and the way in which estimates are made in the water balance, and also gives an example of 2 different periods (2008 and 2020) and the speed of change that has occurred. Regarding the use of water, related to the volume and number of wells registered and their differentiated distribution in the peninsular territory, therefore the approach of the analysis at the level of the Planning Units must be encouraged for adequate local water management.

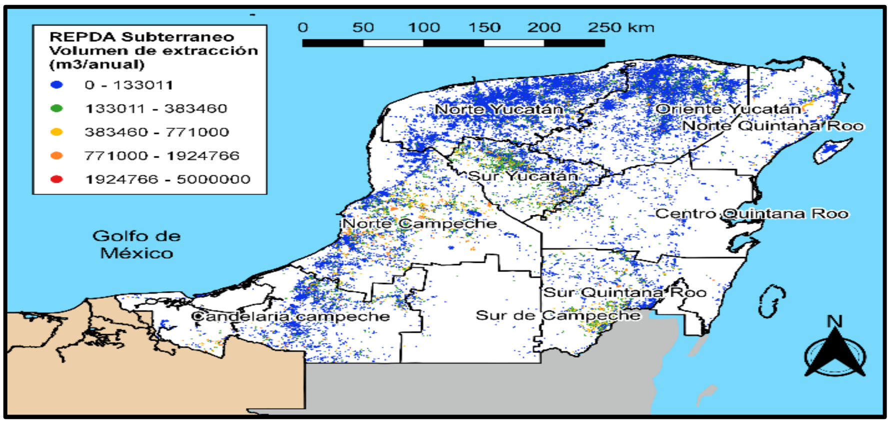
Year 2050. Climate change and socioeconomic development. According to the PHR PY 2020-2024, extraction will increase as the population increases, as well as agricultural, tourist and industrial activity. By 2050, an increase in the PY population of 36% is projected compared to 2020 (CONAPO, 2018). Due to the demographic effects of the Mayan Train, an increase in the population in the PY by 2050 of 64% compared to 2020 was estimated using data from UN-Habitat (2019). To estimate the social extraction of water from the aquifer associated with said population increase, three correlation models were implemented (PHR-PY 2020-2024). As mentioned previously, the UP QRooN, according to REPDA data (2020), is already consuming water destined for the Committed Natural Discharge (DNC) corresponding to the territorial extension of the UP. By 2050, five PUs could be in conditions of consuming water destined for the DNC (Table 10) if the current trends of total annual extraction per inhabitant are maintained. In particular, UP QRooN stands out for the high rates of water consumption in the tourism sector, which could extract up to four times more of the available water (in this case with a pressure on availability of more than 400%).

Planning Unit	Population	Recharge	DNC	Total availability	Annual withdrawal	Average availability	Pressure on total availability %
CampN	951,397	2,729	1,801	928	1,646	-719	177%
CampC	610,465	4,094	2,702	1,392	469	923	34%
CampS	59,559	1,286	849	437	13	424	3%
QRooN	2,361,418	835	551	284	1,176	-892	414%
QRooC	242,791	1,743	1,151	593	94	499	16%
QRooS	634,041	1,824	1,204	620	698	-77	112%
YucN	2,599,627	1,742	1,150	592	1,409	-817	238%
YucO	499,479	3,866	2,552	1,314	974	340	74%
YucS	296,200	1,269	837	431	744	-312	172%
Total	**8,254,977**	**19,388**	**12,796**	**6,591**	**7,224**	**-631**	**110%**
Change compared to 2020	**64%**	**-48.7%**			**62%**	**-108%**	**216%**

Notes: Population data to 2050 projected through CONAPO (2021) and demographic effects of the UN Habitat Mayan Train (2020); Projected total recharge data using baseline from Bauer-Gottwein et al. (2011) and methodology for calculating the recharge decrease of Rodríguez-Huerta et al. (2020b); It is considered that the DNC remains the same proportion of the total recharge of CONAGUA (2015).

Table 10.- Scenario of groundwater availability by 2050 under the effects of climate change in the RCP8.5 scenario and the development of the Mayan Train in Mm3/year.

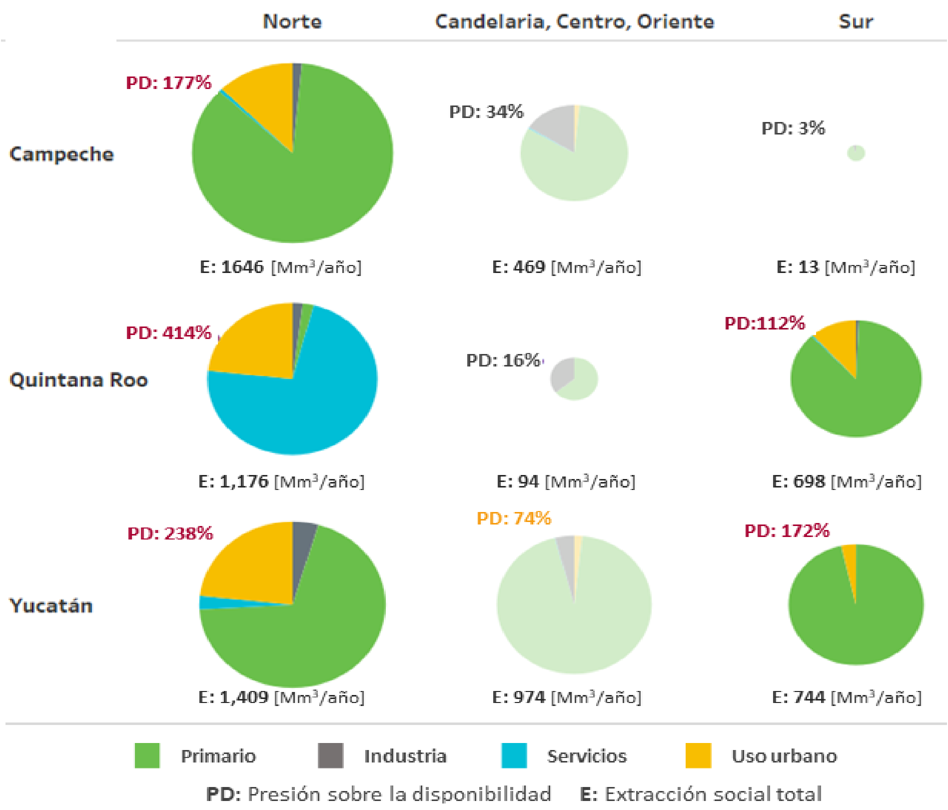
Figure 10.- Spatial distribution of wells with water concession registration in the Yucatán Peninsula, year 2020.



Source: own elaboration derived from REPDA data, 2020.

As can be seen in Figure 11, water consumption in agriculture is the main cause of water consumption of the future DNC of the resource in three UPs. In the UP QRooN, the use for services, such as hotels, golf courses, sports centers, among others, would be mainly responsible for DNC water consumption that exceeds 266% of future available water.

Figure 11.- Pressure on the availability and distribution of water uses by 2050 by Planning.



Note: Considering effects of climate change and the Mayan Train.
Source: Own elaboration with extraction values from Scenario A and population growth estimates from CONAPO (2020), demographic effects of the Mayan Train from UN Habitat (2020) and estimates of the reduction in the recharge of Rodríguez-Huerta (Annex 10 PHR- PY 2020-2024).

In these scenarios of pressure on availability, there may be risks of salinization, scarcity, increased concentrations of contaminants and desiccation and salinization of wetlands, among others, associated with the consumption of water from the local DNC.

Therefore, water planning that considers the effects of climate change and demographic trends is imperative to avoid social, environmental and economic risks derived from excessive water extraction. Furthermore, due to the dynamics of groundwater flows in the PY, the consumption of DNC water in a UP can also generate social and environmental consequences in neighboring UPs. This interconnection reinforces the need for an integrated regional vision, both of the problem and of water planning and management, in a context of climate change.

It can be seen that the decrease in recharge due to the effects of climate change is the main cause of the increase in pressure on future availability. This reinforces the need to deepen research on recharge in a context of climate change to incorporate it into water planning. Other research needs on the topic are the relationship between land use change and recharge in karst soil, as well as the local effects of water consumption destined for DNC in the UPs. These actions are mentioned in Chapter 5 of the PHR-PY 2020-2024, as one of the eight collective regional water management activities.

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The role played by each co-author
Author: Description and analysis of all information, water balance calculations
Co-author: Water balance calculations and cartography

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