Regional hydro-climatic characterization for the efficient use and management of water Study case

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ABSTRACT
Objective: To analyze official information to project future groundwater availability and demand scenarios, based on the different consumptive uses of the Alto Atoyac aquifer, in Tlaxcala, Mexico.
Design/Methodology/Approach: The methodology used in this study included a bibliographic and documentary research. Likewise, based on the Penman-Monteith equation, quantitative research was used to calculate and estimate crop irrigation requirements.
Results: The results of the availability and demand of groundwater showed a surplus of ≈23.34% in 2020. This percentage will gradually decrease in the following years until it reaches a 24.71% deficit by 2070. Consequently, a groundwater deficit in the Alto Atoyac aquifer will take place throughout the whole period (2020-2070). From 2040 to 2050, this deficit will gradually increase.
Study Limitations/Implications: Measures for a sustainable use, exploitation, and conservation of the aquifer must be urgently implemented, as a regular and frequent measurements of aquifer depletion, through measures of phreatic and dynamic groundwater levels, also regular and frequent measures of groundwater extraction, water conduction through the conveyance and distribution system, and finally amounts of water applied to all crop pattern.
Findings/Conclusions: The integration of the consulted and generated data allowed the development of groundwater availability and demand scenarios in the aquifer. In addition, comparisons between the said scenarios were established and conclusions were drawn. The growing water demand in the region —required to meet the basic needs of the localities and inhabitants and to keep driving the economic activities in the region— would have negative effects on the environment and the inhabitants, due to the overexploitation of the aquifer groundwater.

Keywords: Consumptive use, groundwater, deficit, surplus, sustainable.

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INTRODUCTION

This study is based on the growing concern among the population, several government bodies, agricultural producers, industry members, and service providers regarding groundwater. All these sectors use groundwater from the aquifers that make up the basins and sub-basins of the hydrological regions managed by the Mexican government. The concerns include the current availability and demand of groundwater and the prospects for its future availability. The prevailing conditions of the study area show a precipitation deficit all year round. However, the development of agricultural and livestock activities requires water for irrigation and animal production supplementation. The surface water stored from the Manual Ávila Camacho "*Valsequillo*" dam and groundwater from the regional aquifer are the only source of water for these activities.

Based on the analysis and comparison of the bibliographical and field data, the objective of this study was to develop a 50-year projection regarding the demand and availability scenarios of groundwater from the Alto Atoyac aquifer, considering the different consumptive uses of groundwater (agricultural, urban, and industrial).

Agriculture is the activity with the highest consumptive use of water, sometimes using over 80% of the available and officially licensed water. The requirements and irrigation water volume of each crop —included in the established crop pattern— and their irrigation system were determined. A projection of water availability and demand was developed using these results, as well as the water consumption rates of both rural and urban populations and the industries of the municipalities and communities in the area of influence of the Alto Atoyac aquifer area. Finally, this projection established the moment when the first would be exceeded by the second, causing deficits in regional water availability.

MATERIALS AND METHODS

The Alto Atoyac is classified as aquifer 2901 in the Sistema de Información Geográfica para el Manejo del Agua Subterránea of the Comisión Nacional del Agua (SIGMAS-CONAGUA). The aquifer is located in the center of the State of Tlaxcala, at 19° 10' and 19° 35' N and 97° 58' and 98° 21' W, and has an area of 2,032 km^2 (CONAGUA, 2020).

The Alto Atoyac borders with the following aquifers: Tecolutla, Veracruz (N), Valle de Tecamachalco (SE) and Valley of Puebla (S), Puebla, Emiliano Zapata (NW), Huamantla (E), and Soltepec (NE). The last three aquifers are located in the State of Tlaxcala (CONAGUA, 2020) (Figure 1).

The Alto Atoyac aquifer totally or partially covers the following municipalities: Tlaxco, Atlangatepec, Tetla de La Solidaridad, Terrenate, Tocatlán, Xaloztoc, Muñoz de Domingo Arenas, San Lucas Tecopilco, Xaltocan, Hueyotlipan, Españita, Huamantla, Ixtacuixtla de Mariano Matamoros, Santa Ana Nopalucan, Santa Apolonia, Nativitas, Tetlatlahuca, San Jerónimo Zacualpan, San Damián Texoloc, Santa Catarina Ayometla, Santa Cruz Quilehtla, San Lorenzo Axocomanitla, Tepeyanco, San Juan Huactzingo, Santa Isabel Xiloxoxtla, Xicohtzinco, San Pablo del Monte, Tenancingo, Mazatecochco de José María M., Acuamanala de Miguel Hidalgo, Teolocholco, San Francisco Tetlanohcan, La Magdalena Tlaltelulco, Tlaxcala, Panotla, Papalotla de Xicohténcatl, Totolac, Amaxac de Guerrero, Santa Cruz Tlaxcala, Yauhquemecan, Apizaco, Coaxomulco, Tzompantepec, San José Teacalco, and Zacatelco.

No ban decree has been issued for most of the aquifer area. The Alto Atoyac aquifer is managed by the Organismo de Cuenca Balsas and falls under the territorial jurisdiction of the Dirección Local of Tlaxcala. The territory of the aquifer has a partial ban, subjected to the provisions of four decrees. In a small part of its west side, a decree establishes "a ban for an undefined period to supply groundwater to the closed basin (known as Oriental) of the States of Puebla and Tlaxcala" (Official Gazette of the Federation (DOF), August 19,

Figure 1. Location of the Alto Atoyac aquifer. Source: CONAGUA (2020).

1954). Another decree in force establishes "a ban to supply groundwater to the southern part of the State of Puebla" (DOF, November 15, 1967). Regarding the central-south region, a decree extends "for an undefined period the ban to supply groundwater to the southern part of the State of Puebla, established in the decree issued on June 12, 1967, for the municipalities of Amozoc, Calpa, Totimehuacán, and Puebla" (DOF, August 30, 1969). Based on the capacity of the aquifer, this type III ban allows a limited extraction from the water table for domestic, industrial, irrigation, and other uses. Finally, a decree establishes "a ban to supply groundwater of the basins of the Tochac and Tecocomulco lagoons, in the States of Hidalgo, Puebla, and Tlaxcala" (DOF, June 17, 1957) for a small part of the western side of the aquifer. Based on the capacity of the aquifers, this type II ban only allows a limited extraction from the water table for domestic use.

Weather and aridity index

Based on data from Station 000290 30 Tlaxcala de Xicoténcatl (DGE) of the Servicio Meteorológico Nacional (SMN), Table 1 shows the weather data for the 1991-2020 period. The difference between the average annual precipitation (866.00 mm) and the total evaporation (1,380.60 mm) resulted in a 514.60 mm deficit.

Figure 2 shows the water balance of the Tlaxcala de Xicoténcatl region, developed with the weather data from Table 1. The figure includes a hydrological deficit period from October to May (*i.e.*, ≈8-month crisis).

Meanwhile, Figure 3 shows the ombrothermic diagram of the same region, from March to November, a period during which environmental humidity prevails on mean monthly temperatures.

Table 1. Weather data from Station 000290 30 Tlaxcala de Xicoténcatl (DGE) for the 1991-2020 period (Servicio Meteorológico Nacional, 2024).

NATIONAL METEOROLOGICAL SERVICE

CLIMATOLOGICAL NORMALS

STATE:TLAXCALA PERIOD: 1991-2020

STATION: 00029030 TLAXCALA DE XICOTENCATL (DGE) LATITUDE: 19"19'26"N. LONGITUDE: 98"14'48"W. HEIGHT: 2230.0 MSNM.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DEC	SUMS AND MEDIUMS
NORMAL MAXIMUM TEMPERATURE	22.50	24.60	26.50	27.90	28.00	25.90	25.00	25.20	24.40	24.70	24.10	22.90	25.14
MEDIUM TEMPERATURE	13.30	14.90	16.60	18.50	19.10	18.80	17.90	18.20	18.00	17.10	15.40	13.80	16.80
MINIMUM TEMPERATURE	4.20	5.20	6.70	9.00	10.50	11.70	10.90	11.20	11.60	9.60	6.70	4.60	8.49
RAINFALL	8.00	8.10	15.50	35.20	75.40	159.10	159.50	154.70	153.20	71.60	19.20	6.50	866.00
TOTAL EVAPORATION	85.90	105.10	141.10	151.70	151.40	125.00	124.00	117.90	105.50	103.60	86.70	82.70	1380.60

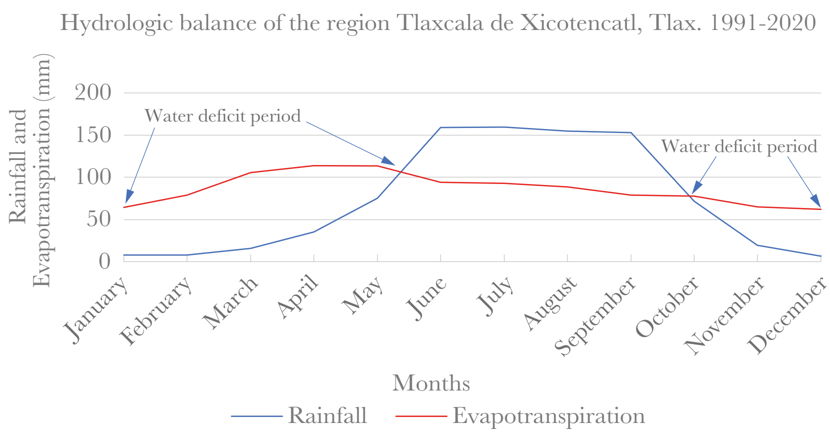

Figure 2. Water balance of the Tlaxcala de Xicotencatl region (1991-2020).

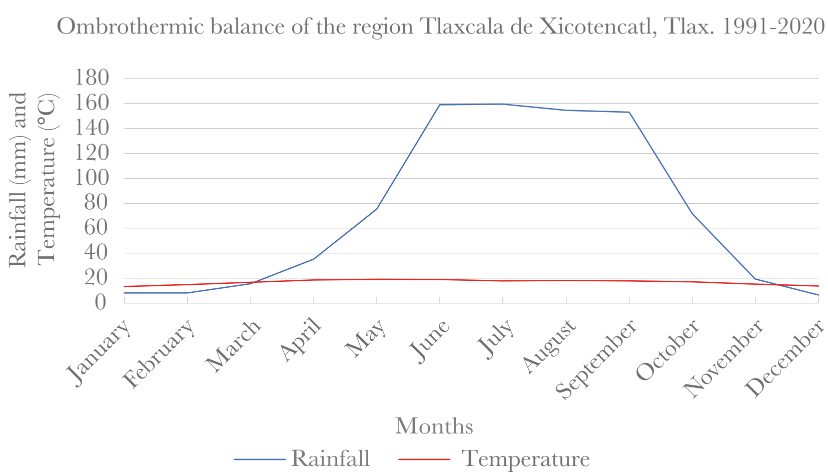

Figure 3. Ombrothermic diagram of the Tlaxcala de Xicotencatl region (1991-2020).

According to De Martonne aridity index, this is not an arid area (Table 2). Regarding the Dantín-Revenga index, the region has a lower humidity rate and, according to Gaussen, the driest months are December, January, and February (Figure 4).

Groundwater balance

The groundwater balance was established in 2,031 km^2 of the aquifer surface for which piezometric information is available. Most of the underground exploitations are located in this area (CONAGUA, 2020). Table 3 includes a groundwater balance summary of the Alto Atoyac aquifer.

Table 2. Aridity index of the Tlaxcala de Xicoténcatl region (1991-2020).

Aridity index's:		
Martonne:	More than 20: no arids.	32.31
	Between 5 and 20: arids.	
	Less than 5: more arids.	
Dantín-Revenga:	Less than 2: humid.	1.94
	Between 2 and 3: semiarid.	
	Betwen 3 and 6: arid.	
	More than 6: subdesertic.	
Gaussen:	Dry month when rainfalls are less than the double of the temperatures	

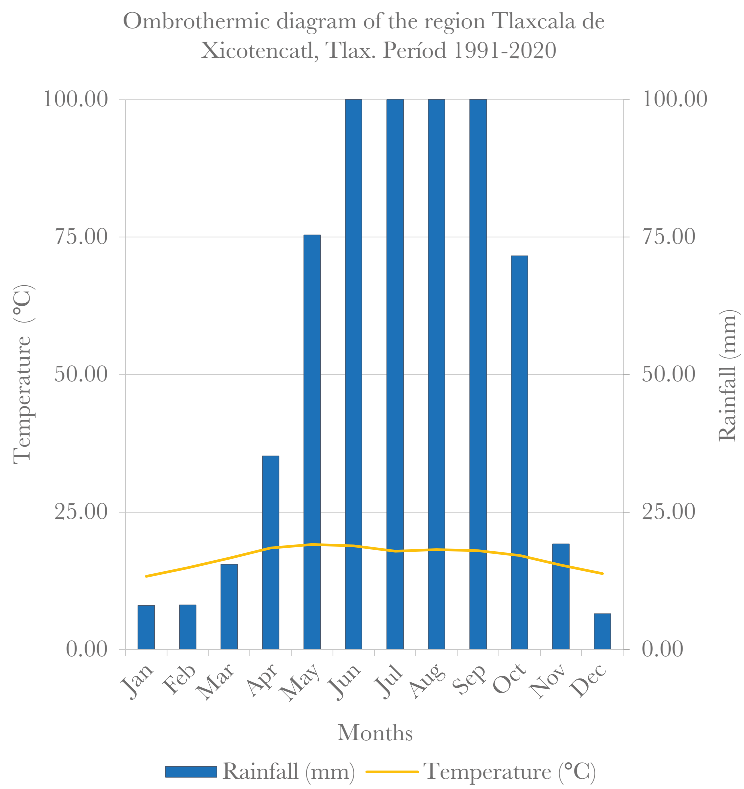

Figure 4. Ombrothermic diagram of the Tlaxcala de Xicotencatl region (1991-2020).

Table 3. Updating of the mean annual water availability in the Alto Atoyac aquifer. Figures are expressed in millions per m^3 and per year (December 30, 2020).

Code	AQUIFER	R	DNCOM	VCAS	VEAS	DAS
2901	ALTO ATOYAC	212.40	41.00	124.69	153.40	46.70

R: mean annual recharge; AND (DNCOM): allocated natural discharge; Ir (Ri): induced recharge; LGV (VCAS): licensed groundwater volume; GEVRTS (VEAS) groundwater extraction volume recorded in technical studies; MAGA (DAS): mean annual groundwater availability. These terms are defined in sections 3 and 4 of the NOM-011-CONAGUA-2015. Source: CONAGUA, 2020.

Analysis of the agricultural activity and its influence on the availability of water from the Alto Atoyac aquifer

This study required data about crop area and irrigation depths. Therefore, the analysis was partially focused on determining the water volume required for the crop pattern, established under irrigation systems, in the area of influence of the Alto Atoyac aquifer. This area was determined with data from the Servicio de Información Agroalimentaria y Pesquera (SIAP, 2022), which is a decentralized body of the Secretaría de Agricultura, Ganadería, Pesca y Alimentación (SAGARPA) of the Federal Government. The crop irrigation depths were used to calculate the said data.

Consequently, the irrigation requirements of the crop pattern were estimated in an *ex profeso* Excel spreadsheet (Villarreal, 2021), which included three estimation methods: the Blaney-Criddle method (Brouwer and Heibloem, 1986), the Penman-Monteith equation (Alle, 2020), and the Evaporimeter Tank Type A method.

Blaney and Criddle developed and improved their formula in Arizona (USA) and, consequently, it can be easily adapted to the arid and semiarid areas of Mexico, whose conditions are very similar to those of Arizona. In addition, the data used for the calculation of evapotranspiration (ET) or the consumptive use (CU) of irrigation water is easily obtained without special equipment. The factors used for this formula are mean monthly temperature, daylight hour percentages, and a coefficient that depends on the type of crop under study (López, 2016a).

The Penman-Monteith equation is the standard combined method used to estimate the evapotranspiration (ET) of a given crop. Most of the combined methods are similar, depending on the type of crop and the location of the weather instruments. This equation uses crop canopy and aerodynamic resistance to relate the height of weather instruments and the height of the crops, as well as the stomatal resistance of the minimum transpiration, which depends on crop type and height (López, 2016b).

Finally, López (2016c) pointed out that the Evaporimeter Tank Type A method has been widely used in irrigation areas with poor weather information. This author only recommends its use if the equipment is accurately calibrated.

The Penman-Monteith equation was used to estimate irrigation requirements. The total volume required by the established crop pattern had a 51.47% impact. This is the same percentage of mean efficiency of irrigation requirement established for the region by Villarreal (1994).

Building water availability and demand scenarios for the Alto Atoyac aquifer, based on agriculture, population, and industries water demand

Based on the water use of primary and secondary sectors and the water supply for the population of the localities and municipalities of the area of influence of the aquifer, a procedure was established to build the water availability and demand scenarios of the Alto Atoyac aquifer.

Population water demand

Using the *Panorama sociodemográfico de Tlaxcala, Tomo I* (2011), the population of each municipality in the area of influence of the aquifer was determined for 2010. Based on the data obtained from the Instituto Nacional de Geografía, Estadística e Informática (INEGI, 2011, 2012, 2013, 2014, and 2015), the population was also determined for the next five years (2011-2015). Finally, using information from the Consejo Nacional de Población (CONAPO, 2019), the birth rates of the municipalities under study, and lineal trends (the least square method), population growth projections were developed until 2070.

For the purposes of this analysis, the population was divided into urban (72%) and rural population (28%).

Considering that the urban population consumes 150 L of water per person and per day, the demand or consumptive use of the population was used to build the scenario. Meanwhile, the rural population consumes 75 L per person and per day. According to CONAGUA, both water consumptions are lower than the 320 L per person and per day, currently available for the Mexican population. However, these figures are closer to the 100-150 L per person and per day reported by the World Health Organization (WHO). This consumption is the minimum amount of water recommended to cover basic needs and prevent most health problems (ONU and OMS, 2011).

Industrial, public-urban, and agricultural demand

The demand or consumptive use of water for industrial and other activities accounted for 6.30% (9.68 million m^3) of the licensed groundwater volume (LGV) authorized by CONAGUA. Meanwhile, 52.80% (81.05 million m^3) and 40.90% (62.67 million m^3) of the LGV is used for public-urban consumption and agriculture, respectively.

Building water demand and availability scenarios depending on soil use (2020-2070)

The water demand and availability scenario depending on soil use (overall adujsted) for the 2020-2070 period was developed based on the hectares required for each substantive activity in the Alto Atoyac aquifer, including agricultural, public-urban, industrial, and other uses.

The consumptive use of water for substantive activities were obtained from the calculation of the water volume spreadsheets of the established crop pattern (agricultural use). These spreadsheets also include the consumptive use of the population and the industry.

The total water demand is made up of the sum of all the consumptive uses. The comparison between consumptive uses and groundwater availability —reported by CONAGUA in the *Actualización de la disponibilidad media anual de agua del acuífero Alto Atoyac, al 30 de diciembre de 2020* study— is included in the figures.

Finally, the different consumptive uses of water from the aquifer were weighted. The base line for the comparison included the sowing and harvested area, the water volume required by the established crop pattern, and the projected sowing area increases (21 and 50%) in the area of influence of the aquifer.

RESULTS AND DISCUSSION

Agricultural water demand

The 2022 crop pattern was made up of 46 annual and perennial crops, established under irrigation systems. Corn was the crop with the highest sowing area (13,934.50 ha), followed by green alfalfa (2,564.00 ha), forage oats (1,770.50 ha), green tomato (833.50 ha), and forage corn (827.00 ha). The total sowing area was 22,965.50 ha. This area produced a 16,620,562.34 t harvest, obtaining a total of MXN$909,395.99. Corn yielded MXN$365,316.96, which accounts for over 40% of the total production in the Alto Atoyac aquifer area.

The water volume was calculated for the building of the consumptive use scenarios, considering the sowing area and the water requirement of each established crop. Based on the sowing and harvesting area of each crop, the following crops and areas stood out as a result of their water volume requirement and consumptive use: corn grain, green alfalfa, forage oats, green tomato, grasslands, and prairies. Meanwhile, the rest of the crops had a similar water requirement trend. The crops grown in the area of influence of the Alto Atoyac aquifer consumed 120,290,077.00 m^3 of water in the 22,965.50 ha harvesting area. These figures account for 78.42% of the total groundwater volume extracted from this aquifer.

Public-urban water demand

The urban and rural populations consume 150 L and 75 L per person and per day, respectively. Therefore, the 973,288 inhabitants of the 45 municipalities of the Alto Atoyac aquifer required a total water volume of 45,827,265 m^3 during 2010. The population projection for 2020 recorded a local population of 1,077,134 inhabitants. This population required a total water volume of 50,716,835 m^3. Therefore, the area had 103,846 more inhabitants than in 2010 and required an additional water volume of 4,889,570 m^3. Based on the CONAPO data and the results obtained from the lineal trend (least square method), the total population of the area is projected to reach 1,409,318 inhabitants by 2070 and will require a total water volume of 66,357,742 m^3. Consequently, the area will have 332,184 more inhabitants than in 2020 and will require an additional water volume of 15,640,907 m^3.

The highest consumptive use of the total extracted groundwater (52.80%) was made by public and urban supply, followed by the agricultural and industrial sectors.

Regarding the consumptive use and soil use (adjusted) scenarios of each consumptive use of groundwater in the Alto Atoyac aquifer (2020, 2030, 2040, 2050, and 2070), the sowing area reached 22,970.50 ha in 2020. Out of this total, 3,054.00 ha belonged to urban and rural communities, while 500.00 ha were used for industrial parks and other purposes. Consequently, the consumptive use of water in the area reached 202,993,871.16 m^3. By 2070, the agricultural area, the urban and rural areas, and the industrial parks will reach 71,748.27 ha, 41,520.48 ha, and 620.00 ha, respectively. Therefore, the total consumptive use (250,673,196.55 m3) will be 47,679,325.00 m^3 higher than the total consumptive use of 2020.

The licensed volume (LGV) and the groundwater extraction volume allowed for technical studies (GEVRTS) and the mean annual groundwater availability (MAGA) will be impacted by a 0.96, 0.94, 0.92, and 0.90 factor in 2020, 2030, 2050, and 2070, respectively. The results indicated a total water volume of 200.10 million m^3 for 2020. This volume will decrease in the following years, until it reaches 149.51 million m^3 by 2070. Consequently, the groundwater surplus was 23.34% in 2020 and is projected to gradually decrease in the following years, until it reaches a 24.71% water deficit by 2070 (Table 2 and Figure 5).

Table 2. Groundwater availability and demand of the Alto Atoyac aquifer (2020-2070).

Year	Demand	Availability	%	Surplus/deficit
2020	153,400,000.00	200,100,000.00	76.66	23.34
2030	161,070,000.00	192,096,000.00	83.85	16.15
2040	169,123,500.00	180,570,240.00	93.66	6.34
2050	177,579,675.00	166,124,620.80	106.90	−6.90
2070	186,458,658.75	149,512,158.72	124.71	−24.71

Source: table developed by the authors.

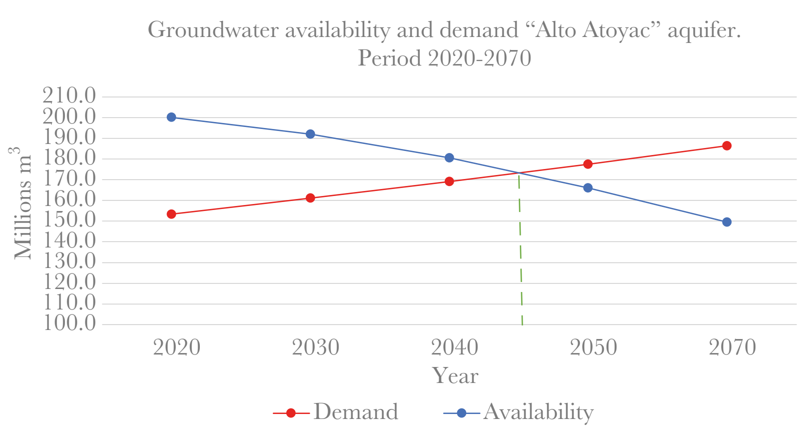

Figure 3. Groundwater availability and demand of the Alto Atoyac aquifer (2020-2070).
Source: figure developed by the authors.

CONCLUSIONS

The Alto Atoyac aquifer (number 2901) is located in an area that lacks natural water. This area has a mean annual precipitation of 866.0 mm and its potential mean annual evaporation reaches 1,380.6 mm. This situation indicates that most of the precipitation evaporates, resulting in a reduced infiltration and runoff. This situation and the growing water demand in the region —required to meet the basic needs of the localities and inhabitants and to keep driving the economic activities in the region— would have negative effects on the environment and the inhabitants, due to the overexploitation of groundwater. Therefore, the government and the population must control the extraction, use, and exploitation of groundwater. The groundwater surplus was 23.34% in 2020 and is projected to gradually decrease in the following years, until it reaches a 24.71% water deficit by 2070. By 2070, the agricultural area, the urban and rural areas, and the industrial parks will increase to 27,920.79 ha, 37,118.16 ha, and 607.75 ha, respectively, reaching a total area of 65,646.70 ha. The total consumptive use (186,458,658.75 m^3) will be 33,058,658.75 m^3 higher than the total consumptive use of 2020.

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