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Articles

Relationship between population and static level: Alto Atoyac and Huamantla aquifers, Mexico

Relación entre población y nivel estático: acuíferos Alto Atoyac y Huamantla, México

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Abstract

In the area of the La Malinche stratovolcano the source of water is aquifer. The objective of this work was to analyze the relationship between population and water table (WT) in the Alto Atoyac and Huamantla aquifers. The following variables were used: Number of inhabitants (NH), WT annual change rates, WT annual percentage changes (APC_{WT}), and trends of WT and NH. Wells were grouped with principal components analysis (PCA). The APC_{WT} were compared with a factorial design. The WT annual change rates and APC_{WT} were -0.159 m·year^{-1} and 6.7%, respectively. The rates of change of WT, were statistically different between aquifers. The relationship between WT and NH that stands out was equal to -16.5 cm·hab^{-1}. NH trends were greater than WT trends. The factorial design showed that between the rainy and the low water seasons there were no significant differences, but between concession type there were. The PCA correlated 51 wells with one component. In summary, this study revealed that the APC_{WT} are higher in agricultural and urban areas, the WT one in the wells of industrial use is reduced five times more than in those of public use. The relationship between population and WT was clearer in the mountains than in the valleys. The PCA showed that the wells around La Malinche differ from others in the study area.

Keywords: Water use, lineal regression, principal components.

Resumen

En el área del estrato del volcán La Malinche la fuente de agua es el acuífero. El objetivo de este trabajo fue analizar la relación entre población y niveles estáticos (NE) en los acuíferos Alto Atoyac y Huamantla. Se utilizaron las siguientes variables: número de habitantes (NH), tasas de cambio anual de NE, porcentajes de cambio anual de NE (PCA_{NE}), tendencias de NE y NH. Los pozos se agruparon con análisis de componentes principales (ACP). Los PCA_{NE} se compararon con un diseño factorial. La tasa de cambio anual promedio de NE fue igual a -0.159 m·año^{-1} y 6.7% de PCA_{NE}. Las tasas de cambio de NE fueron estadísticamente diferentes entre los acuíferos. La relación entre NE y NH que resalta fue igual a -16.5 cm·hab^{-1}. Las tendencias de NH fueron mayores que las tendencias de NE. El diseño factorial arrojó que entre las temporadas de lluvia y estiaje, los PCA_{NE} no tuvieron diferencias significativas, pero entre los tipos de concesión sí los hubo. El ACP correlacionó 51 pozos con una componente. En resumen, este estudio reveló que los PCA_{NE} son mayores en las zonas agrícolas y urbanas. El NE en los pozos de uso industrial se abate cinco veces más que en los de uso público. La relación entre población y NE fue más clara en la montaña que en los valles. El ACP mostró que los pozos de los alrededores de La Malinche se diferencian de los demás del área de estudio.

Palabras clave: uso de agua, regresión lineal, componentes principales.

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Introduction

Water is an irreplaceable natural resource for living beings. Human beings need water for public, agricultural, commercial, or industrial use. The sources of the vital liquid are surface water bodies, groundwater, rainwater harvesting and treated wastewater for uses that do not require water with predetermined quality.

Throughout history, groundwater has been a primary source for sustaining humanity (Fienen & Arshad, 2016). Groundwater availability is decreasing ass tickets decrease and water outputs from the aquifer increase due to intensive extraction, especially in arid agricultural regions and urban centers (Lall, Josset, & Russo, 2020). In tropical regions of Africa, South and Central America, groundwater abstraction is scarce because surface waters are abundant and for irrigation in agriculture is not required (Margat & van der Gun, 2013).

The global groundwater extraction is 650 $km^3 \cdot year^{-1}$ (Margat & van der Gun, 2013); 70% of groundwater is used for agriculture (Fienen & Arshad, 2016) and 24% in industry (Valencia, Mendoza, Vargas, & Domínguez, 2006). Globally, groundwater contributes on average 20% for human consumption and in some countries, it can be 90% (Jakeman *et al*., 2016); 50% of the water consumed in urban areas comes from underground sources (Fienen & Arshad, 2016) and in rural areas it increases to a value of 66% (Carrard, Foster, & Willetts, 2019).

In 1910, Mexico had a water availability of more than 31 000 $m^3 \cdot inhab^{-1} \cdot year^{-1}$; in 1950 decreased to 18 000 $m^3 \cdot inhab^{-1} \cdot year^{-1}$, today is approximately 3 600 $m^3 \cdot inhab^{-1} \cdot year^{-1}$ (Palma, 2020). At present (year 2021), it is unknown with an acceptable approximation, how many Mexicans live extreme water scarcity. In cities in the north of the country, e.g., Ciudad de Monterrey, this situation became evident in 2022. Breña and Breña (2007) reported that, in 2004, 35 million Mexicans were in extreme water scarcity and 43 million with low availability.

Annually, rainfall contributes to Mexico approximately 1 449.5 km^3 of water. Of this volume, it is estimated that evapotranspiration represents 72.1%, 21.4% drains through rivers or streams, and 6.4% (92.544 km^3) infiltrates the subsoil naturally and recharges aquifers (Conagua, 2018).

In Mexico, 39.1% of water sources are groundwater and 60.9% are surface water (rivers, streams and lakes) (Conagua, 2018; Conagua, 2019), this level of extraction places Mexico in the sixth largest groundwater consuming country in the world (Margat & van der Gun, 2013). In the literature, groundwater extraction values are reported for Mexico, from 27.4 to 25 km^3·year^{-1} (Margat & van der Gun, 2013; Fienen & Arshad, 2016). Of this volume, 22 to 64% is used for public supply, 33 to 72% for irrigation in agriculture and 6 to 24% for industry (Valencia *et al*., 2006; Margat & van der Gun, 2013). However, Jiménez (2008) reports that aquifers supply about 75% of water for consumption by the population, even more; for the Metropolitan Area of the Valley of Mexico, this value increases to 80.1% and only 19.9% the source is from surface water bodies (National Research Council, 1995).

The main red flags of groundwater level decline are observed in the arid and semi-arid parts of the world, mainly as a result of high population density, heavy groundwater dependence, low and heavy rainfall that have low rates of natural recharge that drain off rapidly (Fienen & Arshad, 2016). This means that in some country's aquifers may be overexploited, as is the case in Mexico (Jakeman *et al*., 2016).

In Mexico there are 653 aquifers, 105 of these (16.1%) were placed in the category of overexploited at the end of 2017 (Conagua, 2018). The Alto Atoyac and Huamantla aquifers, which correspond to the study area of this work, are outside this classification. The data reported in the literature (Conagua, 2015a; Conagua, 2020a), indicate that the availability of water in the Alto Atoyac aquifer decreased 37.1%, from 0.0467 km^3 in 2013 to 0.0294 km^3 in 2020. For its part, the availability of water in the Huamantla aquifer increased 12.9%, from 0.0139 km^3 in 2002 to 0.0157 km^3 in 2020 (Conagua, 2015b; Conagua, 2020b). In the scenario of the La Malinche volcano area, groundwater is the predominant source, for public use (City of Apizaco, Puebla and Tlaxcala Metropolitan Area), for intensive irrigation agriculture (Huamantla Valley), and for industry (parks and industrial corridors), this because in this area there are no important surface sources of water. The objective of this work was to analyze the relationship between the population of the localities and the water table of the wells classified by their type of concession (public, agricultural, industrial), in the Alto Atoyac and Huamantla aquifers, because until now this type of study has not been done in this area.

Materials and methods

Area of study

This study was conducted in the aquifers Huamantla 2903 and Alto Atoyac 2901 in the State of Tlaxcala. These aquifers are in the Balsas River Hydrological Region, the first located in the closed sub-basin of the Totolcingo Lagoon and the second in the sub-basins of the Zahuapan and Atoyac Rivers, which flow into the Pacific Ocean (Conagua, 2020a, Conagua, 2020b) (Figure 1). The La Malinche stratovolcano is the recharge zone of these aquifers, both are free, heterogeneous, and anisotropic, constituted in its upper portion by alluvial and fluvial sediments of varied granulometry. The lower part of the Huamantla aquifer is bedded in a sequence of marine volcanic and sedimentary rocks (limestones), and the Atoyac aquifer is bedded in a sequence of extrusive igneous rocks of basalts, tuffs and andesites, more information on aquifers is found in Table 1. In the Alto Atoyac aquifer, in 2011, 890 groundwater uses were recorded, of which 600 are active wells. In the Huamantla aquifer, year 2014, 324 uses were registered, of these, 300 are deep wells (Conagua, 2020a, Conagua, 2020b).

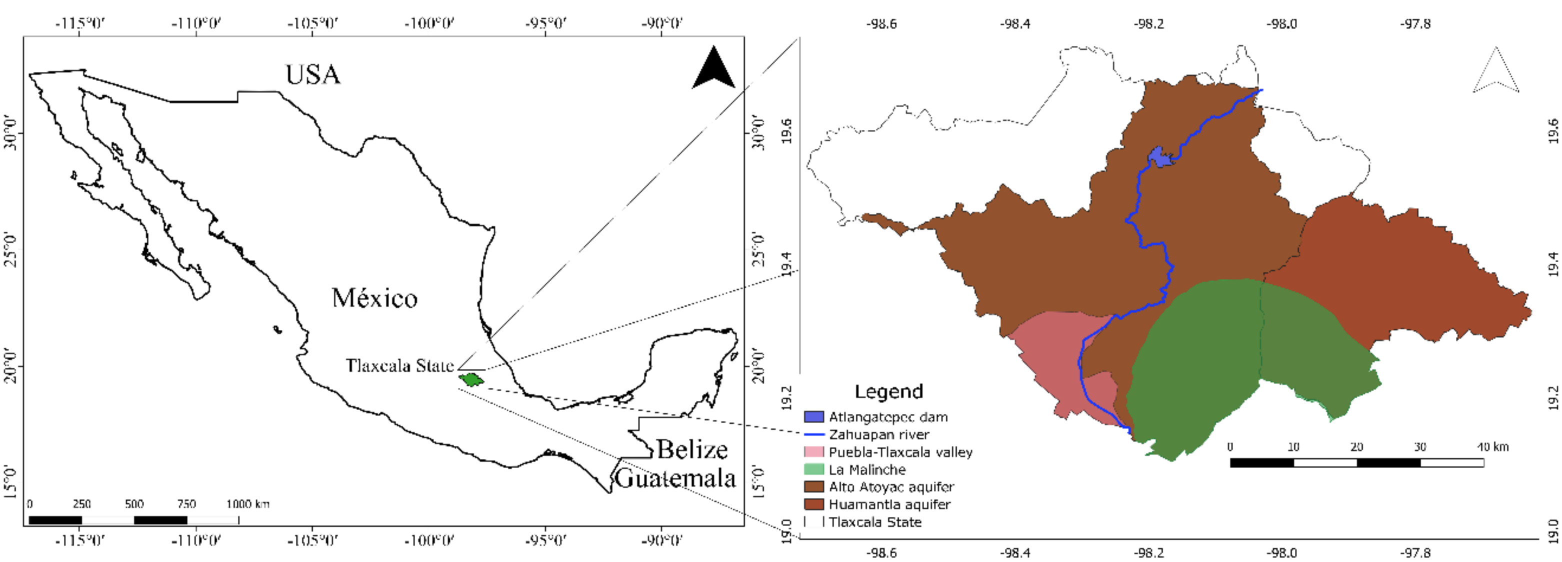

Figure 1. Study area, aquifers in La Malinche volcano, State of Tlaxcala.

Table 1. Characteristics of the Alto Atoyac and Huamantla aquifers.

Parameter	Alto Atoyac	Huamantla
Average annual temperature	16.2 °C	10 to 16°C
Average annual rainfall	878 mm	538 mm
Hydrological region	No. 18 Balsas River	No. 18 Balsas River
Basin	Alto Balsas-Río Atoyac	Alto Balsas-Cerrada Libres Oriental
Physiography	Neovolcanic Belt. Lakes and volcanoes of Anahuac	Neovolcanic Plain
Transmissivity	0.6 to 11.6 x 10^{-3} $m^2 \cdot s^{-1}$ 51.8 to 1 002 $m^2 \cdot d^{-1}$	2.7×10^{-4} to 2.4×10^{-2} $m^2 \cdot s^{-1}$ 23.3 to 2074 $m^2 \cdot d^{-1}$
Hydraulic conductivity	0.5 to 5 $m \cdot d^{-1}$	----
Storage coefficient	0.1 to 1×10^{-5}	----
Water table depth	5 to 160 m La Malinche 5 to 25 m south of the aquifer	3 to 140 m
Preferential direction of groundwater flow	North to south, with feedings from the eastern and western flanks, towards the Valle de Puebla aquifer	North and south directions converging east to Totolcingo Lagoon
Surface geology	Outcrops of volcanic rocks: rhyolites, andesites, basalts, tuffs and volcanic breccias	----
Subsurface geology	Upper part of the aquifer: alluvial and fluvial sediments of varied granulometry. Lower portion of aquifer: extrusive igneous rocks, integrated by volcanic spills, basalts, tuffs and andesites.	----
Stratigraphy	Cretaceous, Tertiary, Quaternary	Quaternary permeable alluvial (Qal) and volcanic andesitic (Qvab). Basaltic andesitic tertiary (Tvab).

Source: Conagua (2015a), Conagua (2015b).

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Number of inhabitants

The data of the total number of inhabitants (NH) of Mexico, the State of Tlaxcala, and the localities, studied in this work, were obtained from the web of the National Institute of Statistical Geography and Informatics (INEGI, https://www.inegi.org.mx/, download date March 2, 2021). In Mexico, 16 population censuses have been made from 1900 to 2020, with these data obtaining the regression equation of NH, as a function of time, and the growth rates of Mexico, Tlaxcala and the localities. With the geographical coordinates, a vectorial layer was elaborated in QGIS to put the localities over the Alto Atoyac and Huamantla aquifers. The QGIS is a freely licensed geographic information system.

Change rate of the water table

To assess the change rate of the water table (WT) with respect to time (years), it was used data from the years 1997 to 2017 from 73 wells under concession. From the Alto Atoyac aquifer there were 50 wells, 28 for agricultural use, 4 for industrial use and 18 for public use. Of the Huamantla aquifer there were 23, 16 for agricultural use, 1 for industrial use and 6 for public use. Analysis of WT fluctuation data is the most direct and simple method for estimating the volume decline of aquifer water (Fienen & Arshad, 2016). The wells analyzed are part of the groundwater monitoring network carried out, in the rainy and low seasons, the National Water Commission Local Directorate Tlaxcala. In a request to the National

Institute of Access to Information of Mexico, the National Water Commission provided WT data for each well. To these data were calculated the parameters as: minimum, maximum, average, coefficient of variation, skewness, and kurtosis. The t test was used to evaluate whether the values of WT, between the Alto Atoyac and Huamantla aquifers, are statistically different.

The change rate of WT depth (m·year^{-1}) of each well with respect to time (t), was calculated with the slope (m_{WT}) of the linear regression equation, for which the data series from 1997 to 2017 was used. The linear regression equation is described as follows (McBean & Rovers, 1998; Schuenemeyer & Drew, 2011):

$$WT = a + m_{WT}t + e_t \quad (1)$$

where

a = ordinate to the origin

$e_t \sim N[0, \sigma^2]$ = random error term

The significance of the values of m_{WT} was set to $p < 0.05$. To visualize the relative gradients of the m_{WT}, the point values of each well were represented in isolines, for this purpose a spatial interpolation was made with the technique of inverse distance weighting in the geographic information system QGIS.

Annual percentage change of WT

An estimator of WT change is the annual percentage change (APC_{WT}), which was calculated with the equation used by Andersen (2019) in econometrics. In this method, not only the initial and final values are considered, but all the values of the data series together at term $(t-1)$ of the following equation:

$$APC_{WT} = m_1(t-1) * 100 \tag{2}$$

where

m_1 = slope of the linear regression equation estimated with the following equation

$$lnWT = b + m_1 t + e_t \tag{3}$$

$lnWT$ = natural logarithm of WT

b = ordinate to the origin.

In statistics, the use of natural logarithm reduces the coefficient of variation of values (Malamud & Turcotte, 2013).

Comparison of APC_{WT}

The simultaneous and combined comparison of APC_{WT} was performed using a factorial design. Conagua reports measurements of the WT, carried out in the low water and rain seasons, in wells under concession for public, agricultural and industrial use. Considering the sampling season and concession of the wells, a two-way fixed effects factorial design was selected. The sampling season, factor A, had two levels, rain and low water. The type of concession of the well, factor B, had three levels, public, agricultural, and industrial. The two-way factorial model is represented by the following equation (Schuenemeyer & Drew, 2011):

$$APC_{WT,ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + e_{kij} \tag{4}$$

$$i = 1, \dots, a; \qquad j = 1, \dots, b; \qquad k = 1, \dots, m$$

where:

$APC_{WT,ijk}$ = annual percentage change of WT at the well ijk

μ = grand mean of APC_{WT} of all wells

α_i = effect due to the ith level of factor A

β_j = effect due to the jth level of factor B

$\alpha\beta_{ij}$ = interaction between the levels i and j of factors A and B

$e_{k(ij)}$ = error $\sim N(0, \sigma^2)$.

Evaluation of the relationship between WT and NH

For the analysis of the relationship of WT and NH by locality in the Alto Atoyac and Huamantla aquifers, the values of NH for the intercensal years from 2000 to 2020 were calculated with the regression equations described in "Number of inhabitants section".

The evaluation of the relationship between WT and NH, was performed with the linear regression equation:

$$NH = c + m_2 WT + e_t \quad (5)$$

where

c = a constant

m_2 = slope of the line that indicates the relationship between WT of a well

NH = locality near of a well

This relationship was established as valid at a significance level $p < 0.05$. Since the censuses and counts population from 1995 to 2020 provide six data, the straight segment of the exponential curve of the population as a function of time (Figure 2) was used to calculate NH of the localities in the intercensal years of this period; in this way the number of data pairs for the calculation of the correlation coefficients of NH and WT increased to 20.

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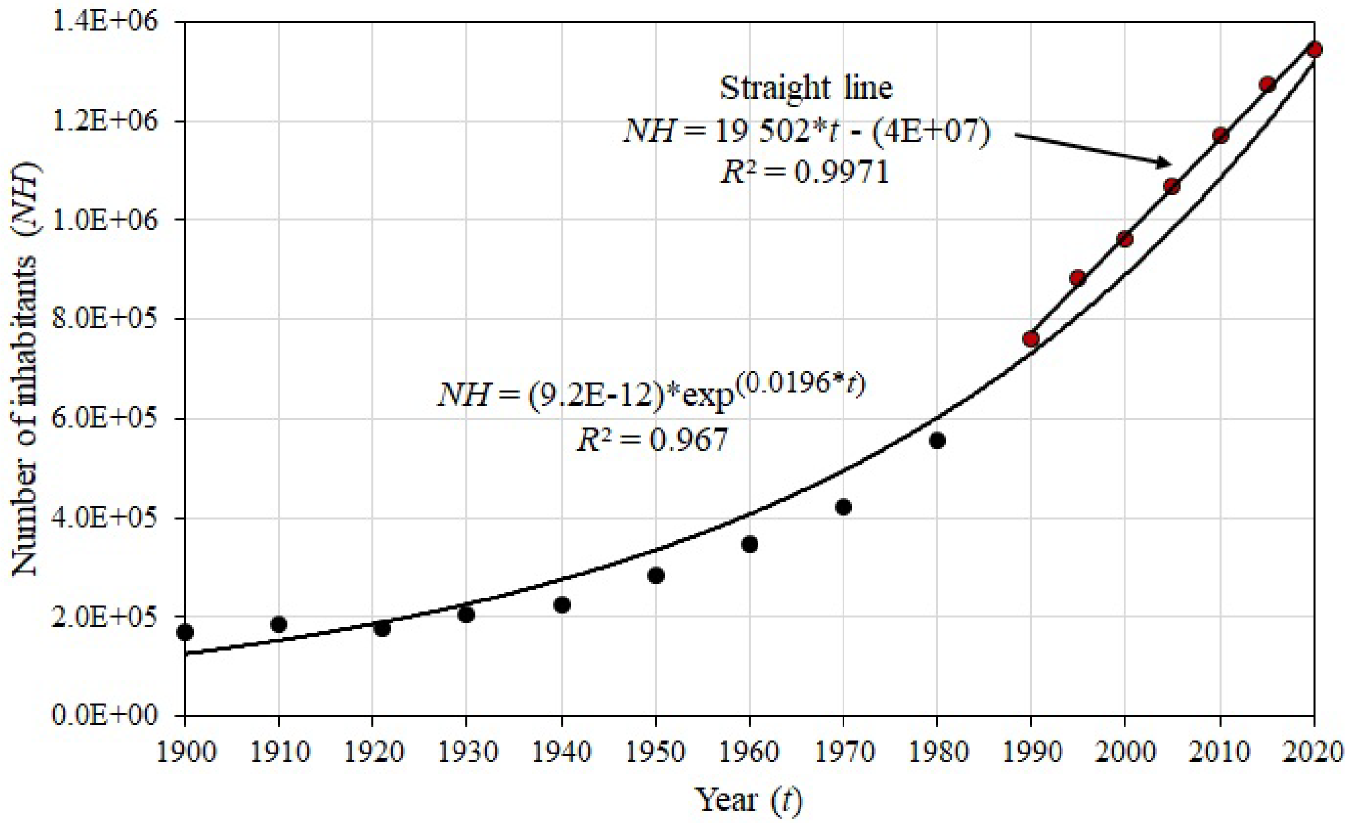

Figure 2. Behavior of number of inhabitants for the State of Tlaxcala.

Trends of WT and NH

In order to associate the trend of NH of a given locality, with the trend of WT nearby wells, it was not plausible with the raw data of these variables, because they have different units and intervals. For this reason, the data of NH and WT with the following equation were standardized:

$$Estandardized\ data = \frac{(raw\ data - average)}{standar\ deviation} \quad (6)$$

Subsequently, linear regression equations were obtained from the standardized data of NH and WT as a function of time t. The significance of the model was set at a level of $p < 0.05$:

$$NH = c + m_{NH}^{*}t + e_t \tag{7}$$

$$WT = a + m_{WT}^{*}t + e_t \tag{8}$$

Since m_{WT}^{*} tends to decrease and m_{NH}^{*} to increase over time, the values of m_{WT}^{*} were multiplied by -1. The slopes were transformed to degrees of inclination (∡), using the following expressions:

$$∡_{NH} = \text{atan}(m_{NH}^{*}) * \frac{180}{\pi} \tag{9}$$

$$∡_{WT} = \text{atan}(-1 * m_{WT}^{*}) * \frac{180}{\pi} \tag{10}$$

To determine whether the values of $∡_{NH}$ and $∡_{WT}$ have statistical differences, a t^{*} two-tailed test was used ($p < 0.05$).

Principal component analysis

The linear combination of water table of the wells was studied using principal components analysis (PCA). A linear combination is the vector of water table multiplied by a scalar, which indicates that water table values are related, otherwise, wells that are not, have a behavior that does not meet this criterion. The PCA is a mathematical procedure that transforms a system of correlated variables to another of uncorrelated variables to reduce its dimensionality and determine linear combinations (Daultrey, 1976; Schuenemeyer & Drew, 2011).

The scalars or eigenvalues (λ_i) of the principal components, which in turn represent the variances of the water table values (original variables), were calculated with the characteristic equation of the matrix $\{R\}$:

$$|\{R\} - \lambda_i\{I\}| = 0 \quad (11)$$

where:

$\{R\}$ = correlation matrix of WT

λ_i = eigenvalues of the principal components

$\{I\}$ = identity matrix

The loads or correlations of the principal components with the WT were calculated with the following matrix equation:

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$$\{L\} = \{E\} \cdot \{\Lambda\}^{\frac{1}{2}} \quad (12)$$

where:

$\{L\}$ = matrix of loads or correlations, between the principal components and the WT

$\{E\}$ = Matrix of eigenvectors associated with each eigenvalue

$\{\Lambda\}$ = diagonal matrix of λ_i, the elements outside the diagonal are zero

The mathematical operations were performed in Excel, with the Solver, MMult and Real Statistics add-ins.

Results

Number of inhabitants

The 2020 census reported that the NH one in Mexico was 126,014,024 inhabitants and the State of Tlaxcala 1,342,977. From the years 1900 to 2020, the population in Mexico increased more than 800% and in the State of Tlaxcala about 700%, in number of inhabitants these percentages were equal to 112.40 and 1.17 million inhabitants, respectively. Until 1940 the number of inhabitants remained constant, even with a decline due to the Mexican Revolution from 1910 to 1924. The behavior, from 1900 to 2020, of the number of inhabitants (NH) in Mexico and in the State of Tlaxcala was described with an exponential model as follow $NH = C \cdot e^{kt}$ ($p < 0.05$), where C and k are constant, with a straight behavior in the last thirty years, in this period of time, the NH increased 55.1% (44.7 million) and 76.4% (581 thousand), in Mexico and in the State of Tlaxcala, respectively. Particularly for the State of Tlaxcala, from 1900 to 1910 the rate of increase was 1 285 inhab·year^{-1} and for 2010 to 2020 this value increased to 17304 hab·year^{-1} (Figure 2).

Change rate of WT

The basic statistics showed that the wells of the Alto Atoyac aquifer had average, minimum and maximum WT values equal to 57, 0.9 and 184 m, respectively. For the wells of the Huamantla aquifer, the respective values were 68, 2.3 and 153 m. The coefficients of variation and skewness were higher in the wells of the Alto Atoyac aquifer (70% and 0.8) than in the wells of the Huamantla aquifer (60% and 0.2). The kurtosis values were equal to 0.5 for the Alto Atoyac aquifer and -0.6 for the Huamantla aquifer. The t-test showed that the WT values among aquifers were statistically different (p < 0.05).

The analysis showed that in the rainy season six wells had positive change rates (m_{WT}) and 67 wells had negative rates. The average m_{WT} was equal to -0.159 m·year^{-1}, the minimum of -0.838 (Huamantla 39 well), the maximum of 0.677 m·year^{-1} (Tecopilco 7 well) and standard deviation of 0.194 m·year^{-1}. The most frequent m_{WT} values were found between 0.0 and -0.4 m·year^{-1} in 87% of the wells. The value of the correlation coefficient r of the regression equation (WT *versus* time) was significant (p < 0.05) in 57 wells. In relation to the low water season, six wells also had m_{WT} positive values. The average m_{WT} value was equal to

-0.153 m·year^{-1}, the minimum of -0.820 m·year^{-1} (Huamantla 39 well), the maximum of 0.759 m·year^{-1} (Tecopilco 7 well) and standard deviation of 0.197 m·year^{-1}. The most frequent rates were found between 0.0 and -0.4 m·year^{-1} in 85% of the wells. The value of the correlation coefficient r of the regression equation was significant ($p < 0.05$) in 63 wells. Figure 3 shows the isolines of the m_{WT} values. The graph of WT, of the wells classified according to the concession type of use *versus* time (Figure 4), shows a linear trend of downward change in all wells.

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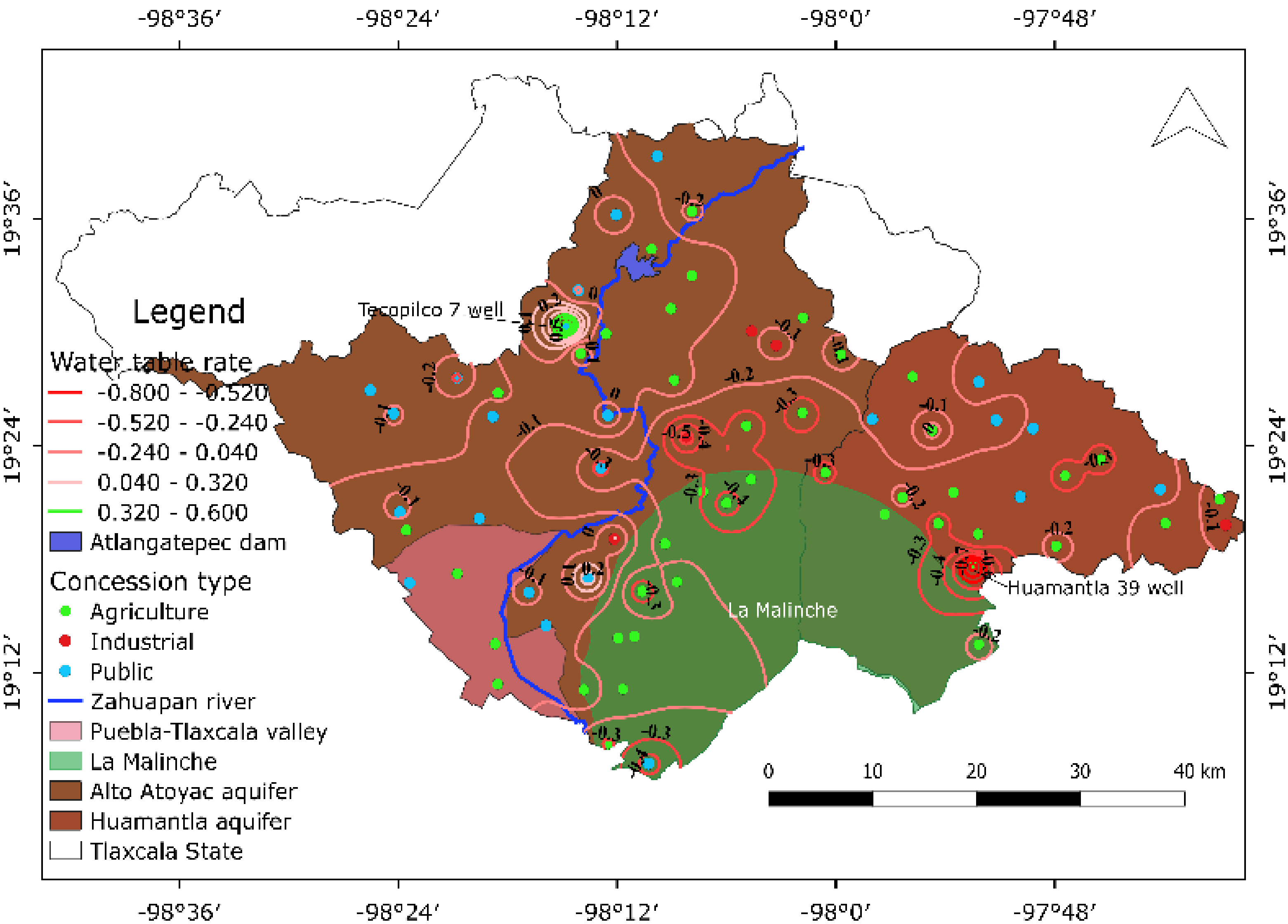

Figure 3. Isolines of the change rates of the water table (m_{WT}).

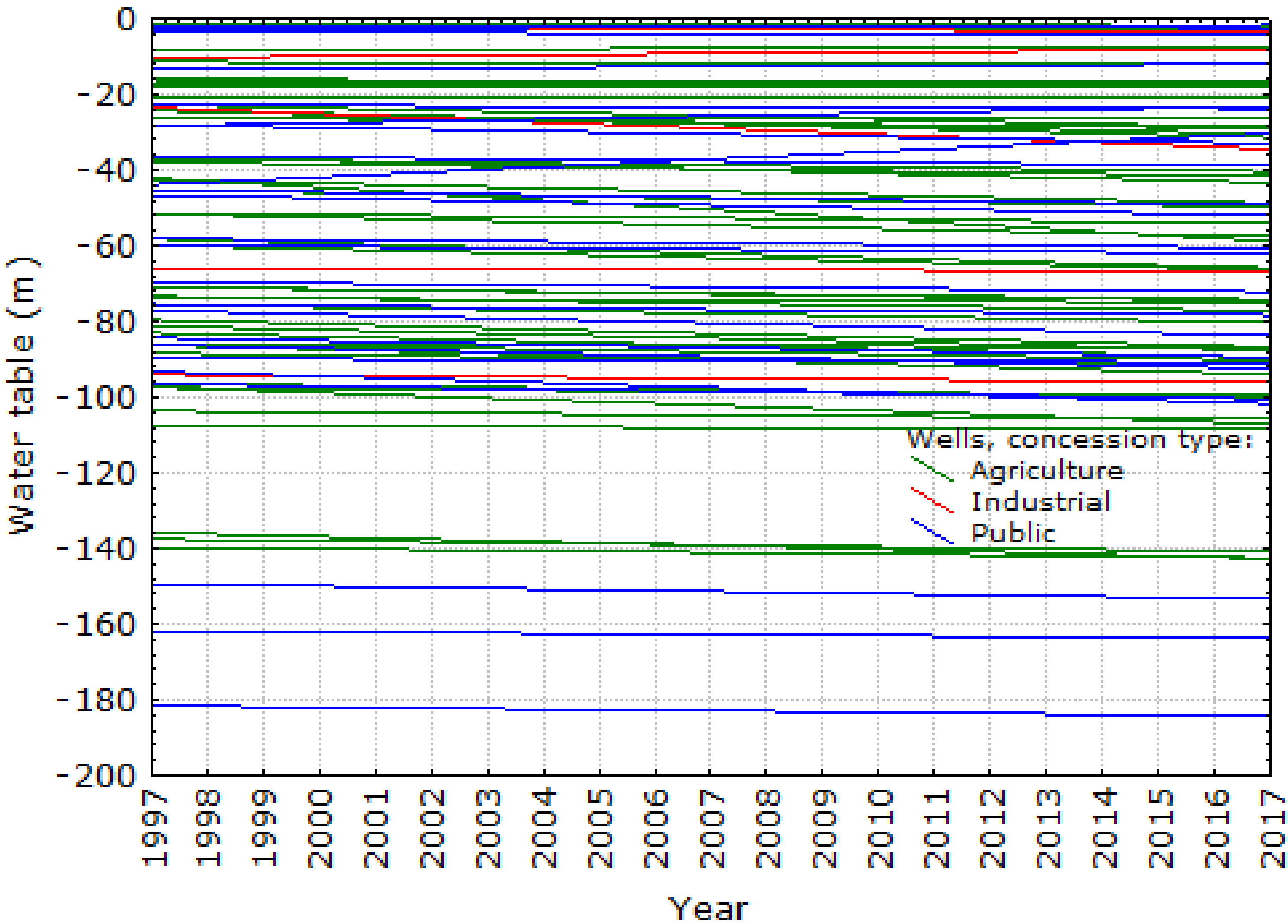

Figure 4. Water table, of wells classified by their use *versus* time.

Annual percentage change of WT (APC_{WT})

The averages APC_{WT} were equal to -6.4% (-0.159 m·year^{-1}) and -7.3% (-0.153 m·year^{-1}), in the rainy and low water seasons, respectively. The most recurrent APC_{WT} value was from 0 to -20% (from 0 to -0.4 m·year^{-}

[1]) in 80% of the wells. In six wells the APC_{WT} values were positive. The extreme values of APC_{WT} were -50% (-0.8 m·year^{-1}) in the Huamantla 39 well and ≈ 50% (0.7 m·year^{-1}) in the Tecopilco 7 well. The spatial distribution of the APC_{WT} values are found in the isolines of Figure 5. The two seasons, rain and low water, had comparable isolines.

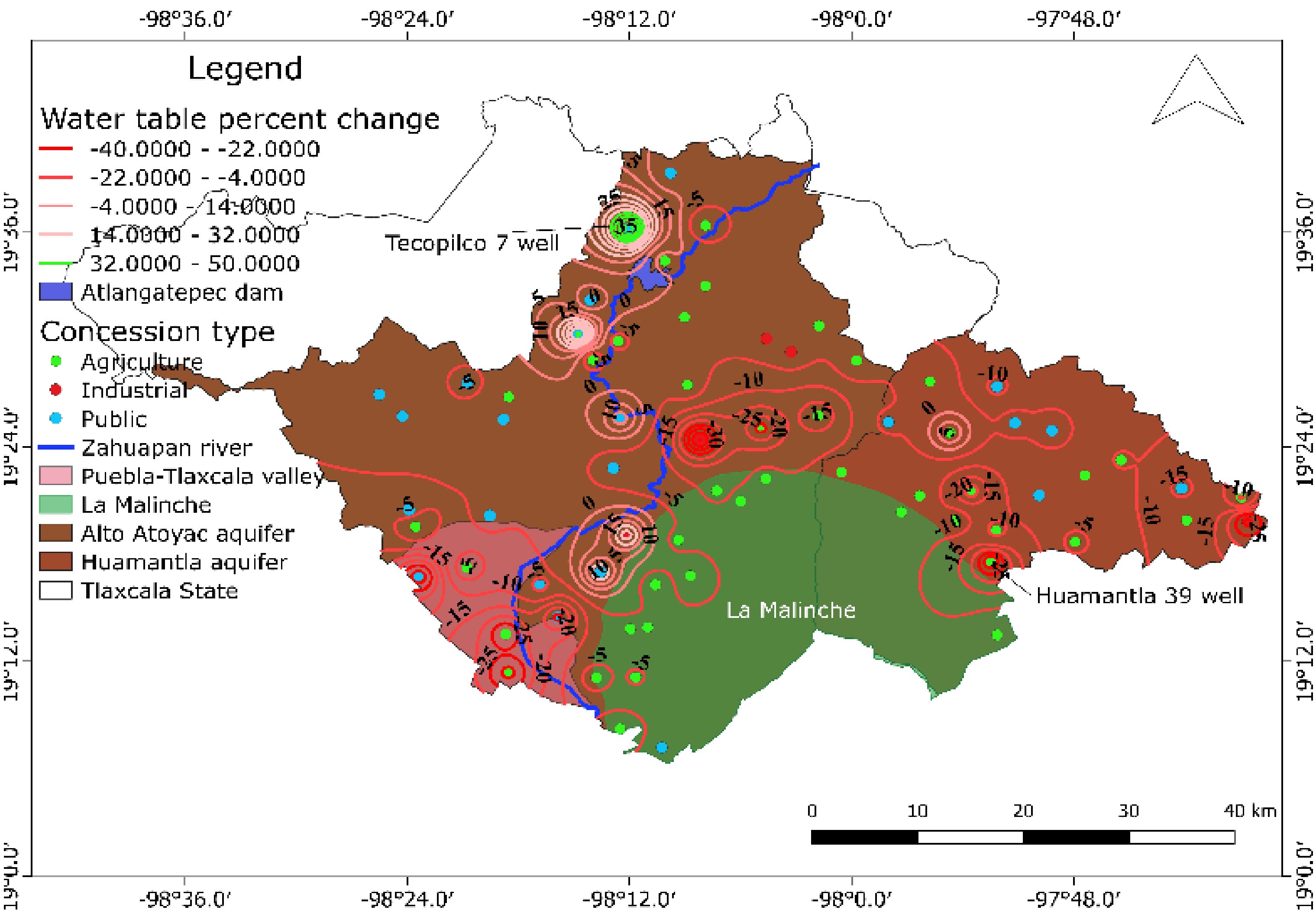

Figure 5. Isolines of annual percentage change of water table (APC_{WT}).

Comparison of APC_{WT}

The analysis of variance of the two-way fixed-effect factorial design (Table 2), to compare simultaneously and combined, the wells according to their concession type of use and sampling season, showed that APC_{WT} values in the rainy and low water seasons did not have significant differences, whose average values were -6.9% and -7.5%, respectively (Figure 6a). While those APC_{WT} of the wells concessioned for agricultural, industrial and public use had significant differences ($p < 0.05$). According to Figure 6b, these differences are since those APC_{WT} in wells concessioned for agricultural and industrial use are more pronounced than in wells for public use. The average APC_{WT} in public wells was -2.4% (n = 24), in agricultural wells it was -8.9% (n = 44) and in industrial wells -10.3% (n = 5).

Table 2. Analysis of variance of factorial design of APC_{WT}.

Source of variation	S.S.	d.f.	M.S.	$F_{cal.}$	*P*
Factor A (Season)	5.85	1	5.9	0.03	0.87
Factor B (Concession)	1427.9	2	714.0	3.44	0.03
AB Interaction	8.20	2	4.1	0.02	0.98
Residual	29026.9	140	207.3		
Total	30468.9	145			

S.S.= sum of squares

d.f.= degrees of freedom

M.S.= mean squares

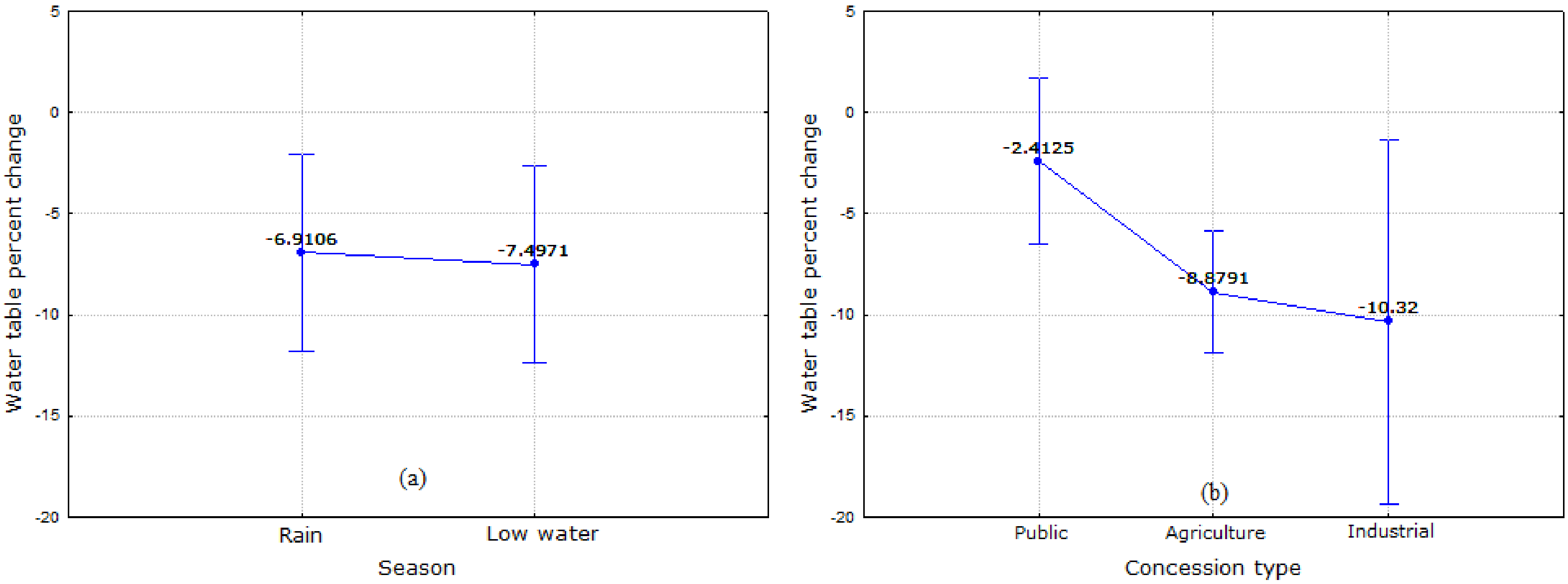

Figure 6. APC_{WT} in season and type of concession.

Relationship between *WT* and *NH*

Of the 73 wells evaluated, 59 of these were associated with NH of the surrounding localities (Figure 7), with which the values of m_2 and r for the years from 1997 to 2017 were calculated. The values of m_2, which indicate the relationship between WT of a well and that NH of a locality, were negative in 55 associations and in 4 were positive. The most pronounced negative m_2 value was equal to -16.5 cm·inhab^{-1} (Ocotitla locality), followed by a value of -4.9 in the locality of Mesa Redonda. In ten localities the values of m_2 were found from -1 to -2 cm·inhab^{-1}, in 23 it was from -1 to -9 mm·inhab^{-1} and in 20 localities it was -0.07 to -0.9 mm·inhab^{-1}. The positive m_2 values were between 0.2 to 2.6 mm·hab^{-1}. The values of

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r were significant (p < 0.05) in 43 associations of WT with NH and in 16 they were not, that is, in 73% of the cases the relationship was significant.

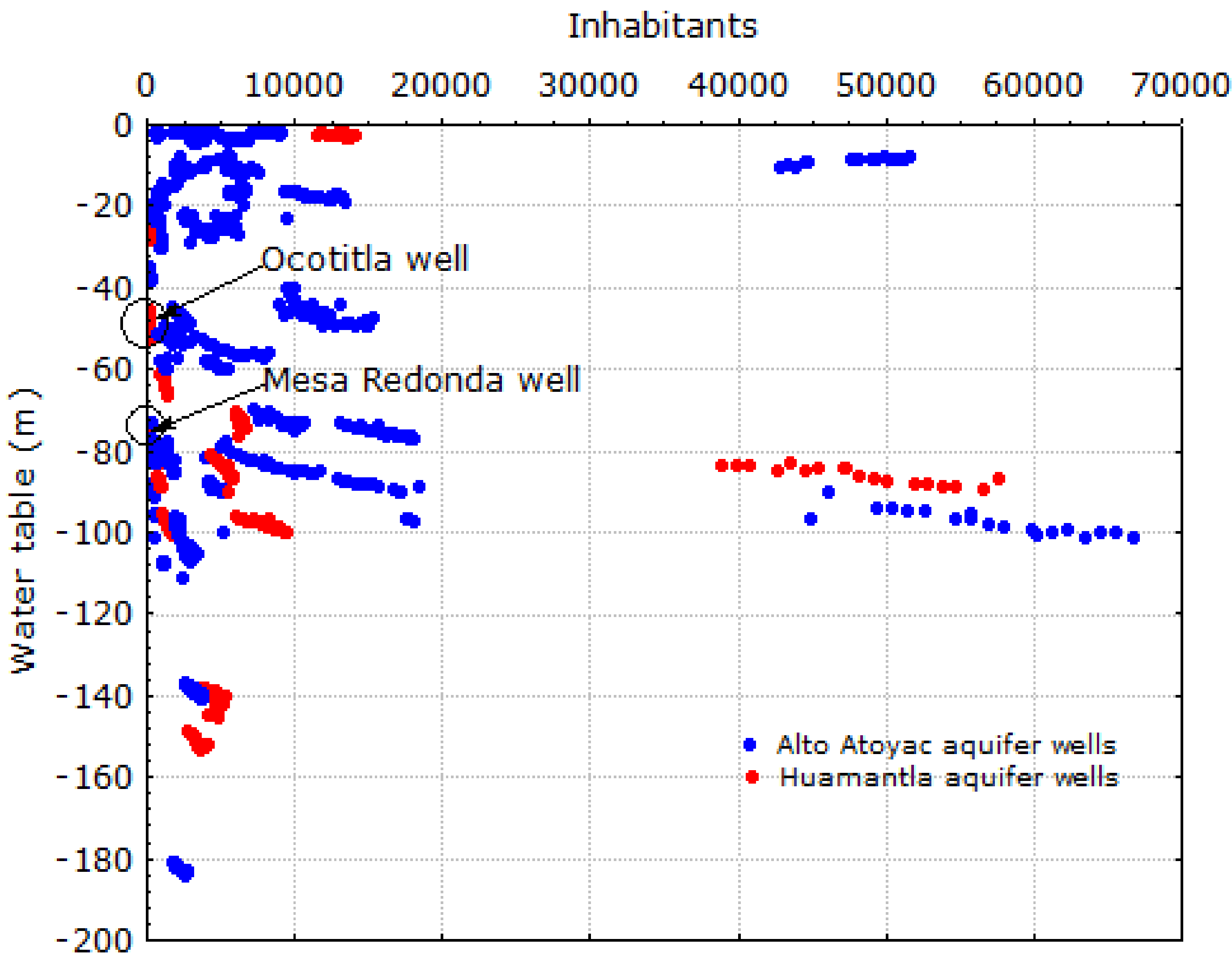

Figure 7. Relation between WT and NH.

Trends of WT and NH

The analysis of trends, negative for WT and positive for NH, with respect to time using standardized data showed that, in 30 cases, the degrees of inclination of the trend lines of the water table ($\measuredangle_{WT}$) were greater than the degrees of inclination of the lines of number of inhabitants ($\measuredangle_{NH}$) and in 25 cases the result was reversed. The average of the $\measuredangle_{WT}$ values was equal to 5.2° and the average of $\measuredangle_{NH}$ values was equal to 6.3°. The t^* two-tailed test showed that the average of $\measuredangle_{WT}$ and $\measuredangle_{NH}$ had no significant differences ($p > 0.05$), and that the average of $\measuredangle_{NH}$ was slightly higher (4.2%) than $\measuredangle_{WT}$. However, the $\measuredangle_{WT}$ values had four times greater variability than the $\measuredangle_{NH}$ values.

Principal component analysis

Figure 8, Figure 9 and Figure 10, show the result of the principal component analysis. The geographical distribution of the wells correlated with the components at values of $r > 0.8$ and $r < -0.8$ is shown in figure 8. Figure 9 shows the first ten principal components with their respective λ_i values that explain the variance of the original values and the cumulative variance on the right axis. Component 1 had a λ_1 value equal to 42.0, which represented 57.6% of the total wells, and components 2, 3 and 4 represented 6.4, 5.8 and 4.9%, respectively, components from 5 to 20, represented from 2 to 1%; 91% of the original data was represented with ten components and 100% with 20. However, only three components had loads or correlations of $r > 0.8$ and $r < -0.8$ with the original variables (water table) and five components had correlations of $r > 0.6$ and $r < -0.6$. Figure 10 shows the loads of components 1 and 2. Figure 10a for aquifer-rated wells and Figure 10b based on concession type of use. In both graphs, it observes a concentration of 47 wells (64.4%) on the right side, these had positive correlations ($r > 0.6$) with component 1, on the left side, there are four wells (5.5%), with negative correlations ($r < -0.6$) with this same component, that is, with component 1, 51 (69.9%) of the 73 wells were correlated. Two wells (2.7%) had correlations ($r > 0.6$) with component 2. With component 3, 4 wells (5.5%) were negatively correlated ($r < -0.6$), with component 4, 2 wells (2.7%) were positively and negatively correlated, with component 5 one well (1.37%) was negatively correlated and 13 wells (17.8%) were not correlated with any component.

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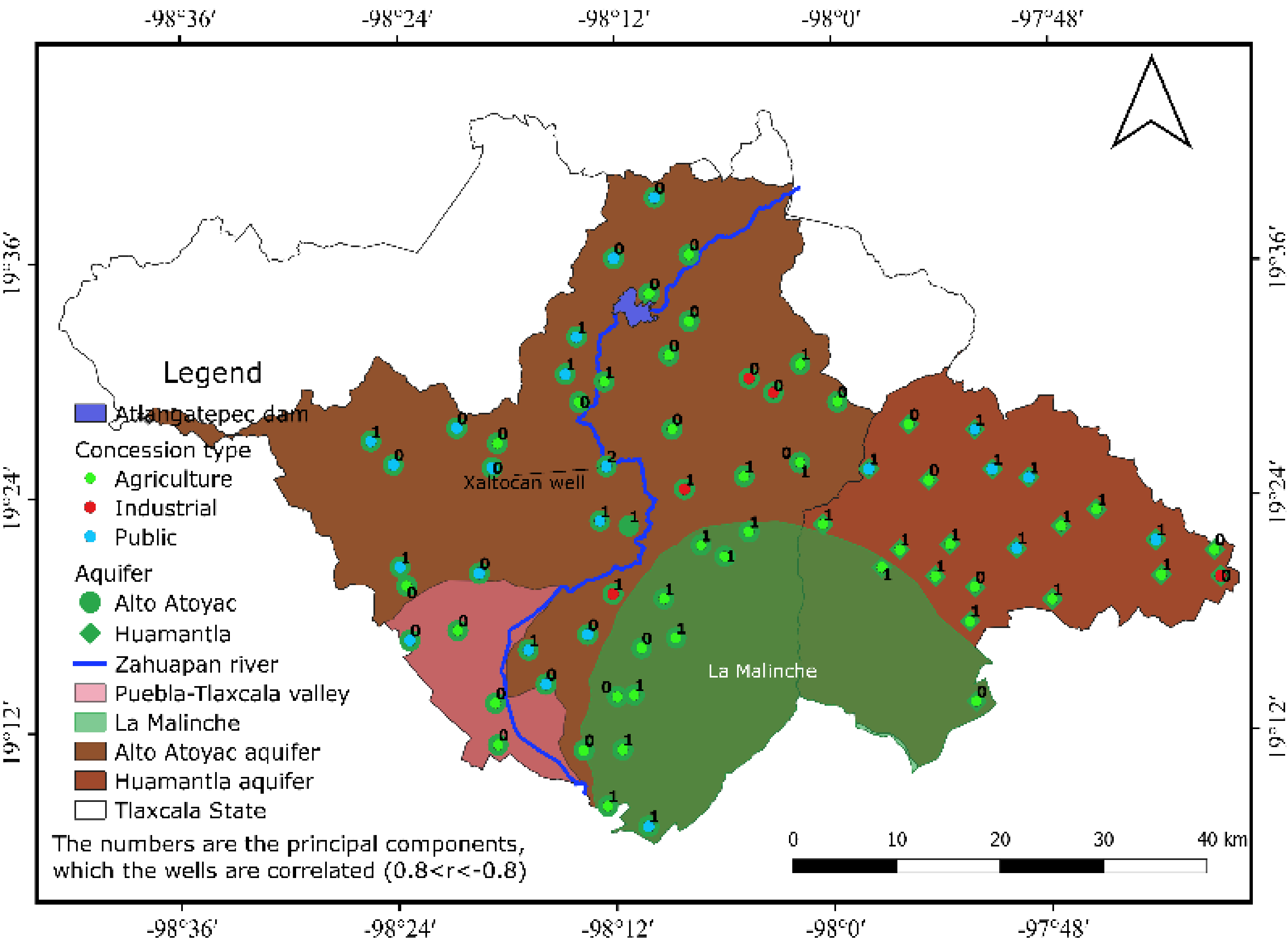

Figure 8. Wells correlated with components 1 and 2, at a value of $0.8 < r < -0.8$. Zero indicates no correlation with these components.

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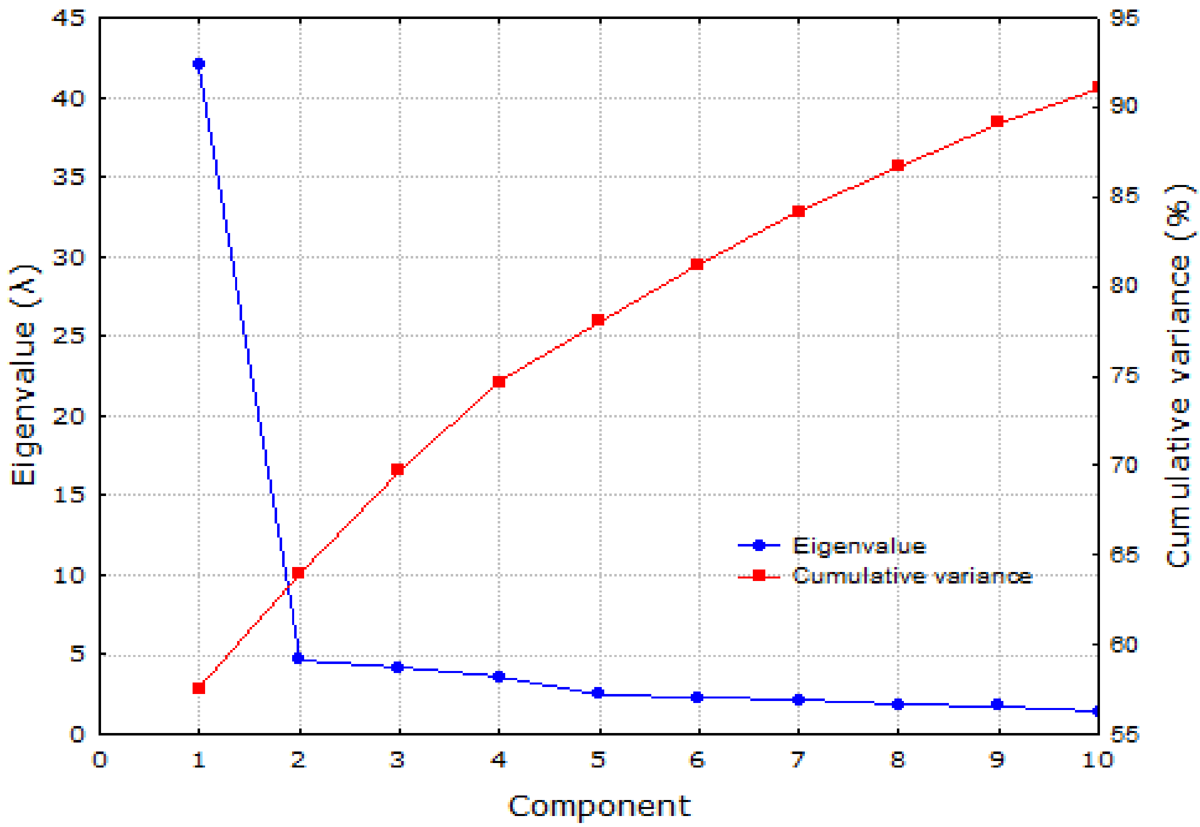

Figure 9. Variance of principal components.

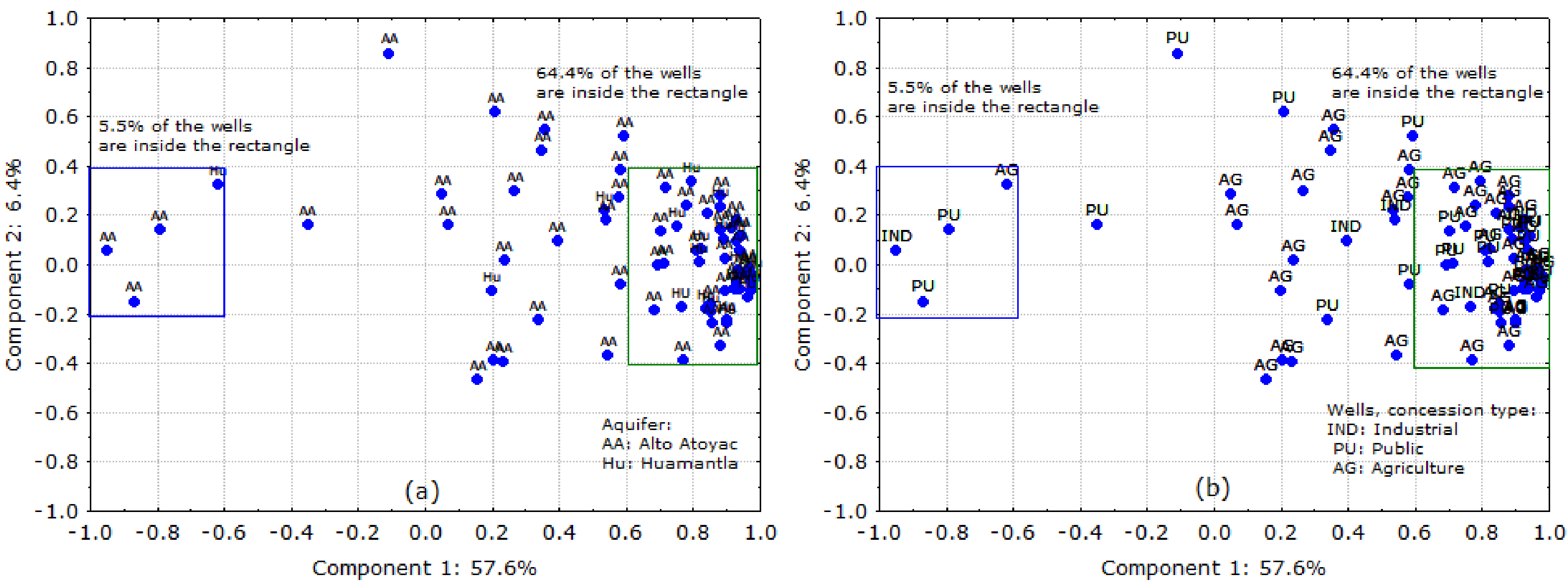

Figure 10. Correlations of components 1 and 2. Wells classified according to aquifer (a) and according to concession type (b).

Discussion

Number of inhabitants

From 1900 to 2020, the NH in the State of Tlaxcala it multiplied by seven, with an annual growth rate equal to 1.96%, which is slightly higher than the rate of 1.19% for Mexico, which is almost in the middle of the world ranking of growth rates of 116 countries reported by the WorldData.info (https://www.worlddata.info). In this same database it is reported that from 2012 to 2021 the NH in Mexico increased 11.07%, while in the State of Tlaxcala the NH from 2010 to 2020 increased 14.8%. The behavior of NH in the study area can be described with an exponential model, as can be seen in Figure 2. In the last thirty years the growth of NH was straight line adding 581 thousand inhabitants, this behavior of NH is slightly different from that of Mexico, which tends to stabilize, as shown on the page of the National Institute of Statistics and Geography of the Government of Mexico (https://www.inegi.org.mx). If the NH continues to increase exponentially, in the next twenty years approximately 400 thousand inhabitants will be added, which will bring with it greater demand and pressure on water resources.

Change rate of WT

The WT average depths indicated that the Alto Atoyac and Huamantla aquifers are comparable with those reported for the Atemajac Valley and Toluquilla, Jalisco Mexico (Hernández-Antonio *et al*., 2015), the minimum values were in wells of the Puebla-Tlaxcala Valley and the maximum values in La Malinche Volcano, which makes evident the influence of altitude and topography. The values of skewness and kurtosis indicated that WT's have normal distribution based on the criteria established by McBean and Rovers (1998) for this statistic, although the data are slightly skewed to the right ($C_s < 1$) and concentrated around the mean ($C_k \approx 0$).

The number of wells with positive and negative signs of m_{WT}, were equal in both the rainy and low water seasons. The average, minimum, maximum, standard deviation, and frequency of the m_{WT} values of the rainy season were practically equal to those of the low water season, which could be an indication that the entry of water by rainfall to the Alto Atoyac and Huamantla aquifers does not compensate for the extraction.

The rainfall in the Alto Atoyac aquifer is 878 mm per year and in the Huamantla aquifer 538 mm. The m_{WT} most extreme negative value was equal to -0.838 m·year^{-1} in the Huamantla 39 well, for irrigation in the Huamantla Valley, which approximates the value of -1 m·year^{-1} for the Metropolitan Area of Mexico City (Carrera-Hernández & Gaskin, 2007) and is comparable to the value reported by Rahman, Kamruzzaman, Jahan, Mazumder and Hossain (2016) for northwestern Bangladesh. The m_{WT} intermediate values (-0.15 m·year^{-1}), indicate that groundwater depletion in the study area is within the ranges reported in the literature (Herbert & Döll, 2019; Hu *et al*., 2019; Joshi *et al*., 2021). Particularly for the Alto Atoyac aquifer, Conagua (2015a) reported a depletion rate of 0.1-0.2 m·year^{-1}, in the period 1997-2011 and for the Huamantla aquifer a depletion rate of 0.3-0.5 m·year^{-1} (Conagua, 2015b), the t test showed that these abatement rates are statistically different ($p < 0.05$). In five wells the m_{WT} values had positive signs, these wells were found near the Atlangatepec dam and the Acuitlapilco lagoon, which means that these bodies of water raise the WT by about 0.65 m·year^{-1}. Joshi *et al*. (2021), reported groundwater level elevation values of 1.28 m·year-1. Water table elevation is reported in the literature to be correlated with surface currents and precipitation (Weider & Boutt, 2010; Dudley & Hodgkins, 2013), in our study area, the proximity of wells to water bodies may be the cause of water table rise.

Annual percentage change of WT (APC_{WT})

The APC_{WT} values during the period from 1997 to 2017 were found at around 7%. In the agricultural areas of the valleys of Huamantla and south of the Alto Atoyac basin, as well as in the urban area of Apizaco, the values of APC_{WT} were 10 to 35%, these values are high compared to those reported in the literature (0.05-0.4%), APC_{WT} values greater than 1% are considered significant (Taranaki Regional Council, 2016). The analysis of variance of two-way factorial design of APC_{WT}, showed that there are no significant differences between the seasons of the year, this result confirms that the changes of WT are not associated with the climate, mainly the rainfall (Rahman *et al*., 2016; Fienen & Arshad, 2016; Kumar, Chandniha, Lohani, Krishan, & Nema, 2018; Lall *et al*., 2020). The analysis of variance clearly showed the effect of the type of concession on the change of WT, the concessioned wells for industrial use had more pronounced APC_{WT} values, followed by those of agricultural and public use. This result shows that the WT in the wells of the industries decline approximately five times more than in the wells of public use.

Relationship between WT and NH

The analysis of the relationship (m_2) between WT and NH, showed higher values in two small neighboring towns, Ocotitla and Mesa Redonda. One possibility that in these localities the highest values of m_2, is that they are in the mountain in the upper part of the basin, north of the Huamantla aquifer, where possibly water inputs such as rainfall do not compensate for the extraction of water from the aquifer. On the other hand, the lowest m_2 values were calculated in the wells found in the valleys of the Zahuapan River and Huamantla Valley basins. In this area, it was not plausible to clearly evidence the effect of NH on the abatement of WT, although the population density is higher compared to the population that lives in the upper part of the basin, this possibly due to that the volume of water extracted by the wells is compensated by the surface and subsurface water inflows. This is argued with the result obtained in the Xicohtzingo well located at the confluence of the Zahuapan and Atoyac rivers, in which a value of m_2 close to zero and a value of r=-0.06 (p = 0.7922) were calculated.

Trends of WT and NH

The trends of WT and NH measures with the angles of inclination (∡) of the regression lines, showed that in 55% of the cases the angles of WT were greater than the angles of NH and in 45% the result was reversed. Although, the average angle of NH was slightly greater than the average angle of WT, the t^* two-tailed test showed that the angles of WT and of NH had no significant differences (p > 0.05). In the literature, it is reported, for arid and semi-arid areas, a clear relationship of aquifer depletion due to greater water demand due to population increase (Margat & van der Gun, 2013; Jakeman *et al*., 2016; Islam & Islam, 2017; Kumar *et al*., 2018; Boretti & Rosa, 2019; Elizondo & Mendoza-Espinosa, 2020; Hu *et al*., 2019). For the study area, the relationship of aquifer depletion with population growth was observed that it is not widespread in all populations and wells, this may be due to the fact that the main use of water is agricultural and that the study area is in the Mexican Altiplano, where the altitude factor and topography have a role in aquifer recharge as reported in the literature (Jakeman *et al*., 2016; Taranaki Regional Council 2016; Islam & Islam, 2017). This result implies that there are areas of this study, where there is a relationship of NH with WT, which should be treated differently from those areas where there is not, to avoid possible water shortages to the population.

Principal component analysis

Principal component analysis showed that the values of WT in 60 wells are a linear combination. A single component represented about 60% of the variance, which indicates that WT of the wells around this component are in the same dimension and their behavior is collinear. The variance representation increased to 75% with four components. With component 1, 39 wells (r > 0.8 and r < -0.8) were positively and negatively correlated, of which 23 are in the Atoyac aquifer and 16 in the Huamantla aquifer, in turn, these wells were 23 for agricultural use, 2 for industrial use and 14 for public use. Wells with values of r < -0.8 associated with component 1 had a m_{NE} positive value. With component 2, the Xaltocan well of the Alto Atoyac aquifer for public use, which is located near the Zahuapan River (Figure 8), was correlated.

The result is notorious that, of the 33 wells that were not correlated with any component (zero values in Figure 8), 27 of these were found in the Atoyac aquifer and 6 in the Huamantla aquifer, 21 are dedicated to agriculture, 3 to industry and 9 for public use. The effect of the geographical location of the wells on the correlations of WT with component 1 is evident, because the wells were found in the vicinity of the La Malinche volcano and in the Huamantla Valley. To the north and south of the Atoyac basin were the wells that did not correlate with any component. This suggests that analysis of the correlation of water table with principal components could support the study of water wells holistically and improve their management to ensure water supply to future generations.

Conclusions

The behavior of the number of inhabitants, from Mexico and Tlaxcala, was described with an exponential model, but in the last 30 years it was straight line. With this type of growth, it is estimated that in the next twenty years 400 thousand inhabitants will be added in the State of Tlaxcala, which will increase the demand and pressure on water.

The average WT rate with respect to time was equal to -0.159 m·year^{-1}. In six wells the rates were positive and in 67 wells they were negative. The WT rates between the Alto Atoyac and Huamantla aquifers were statistically different ($p < 0.05$). The average rate of WT, in terms of annual percentage change was equal to -6.4%. These values indicate that the water table decreases are comparable to those reported in the literature for other places and time, but in terms of percentage change, they are greater. In the agricultural areas and in the urban area of Apizaco the percentages reached values from 10 to 35%.

The factorial design showed that WT measured in the rainy and low water seasons there were no statistical differences, while based on concession type the differences were significant ($p < 0.05$). Graphically, it was observed that wells for agricultural and industrial use had higher percentages of change than wells for public use. The WT in industrial wells are down to five times more than in wells for public use.

The relationship between the water table and the number of inhabitants, was significant in 73% of the localities studied, the most pronounced value was equal to -16.5 cm·inhab^{-1} in a well and population located in the mountain, in 52 cases the values were found between -0.01 and -2 cm·inhab^{-1} in wells located in the valleys. The significant values of r were obtained in wells located in the mountain and the non-significant values in the valleys.

The average WT trends angles was less than the average NH trends angles. That is, WT values decrease less rapidly than the increase of NH. However, no significant differences were found between the two.

Water table of 57.6% of wells were associated with a principal component. The first four components accounted for 74.7% of the wells. However, with three components the correlations had values $r > 0.8$ and $r < -0.8$ and with five components at values $r > 0.6$ and $r < -0.6$. The wells correlated with component 1 are in the Huamantla valley and around the Malinche. The wells that had no correlation with any component are mostly located north and south of the Atoyac aquifer.

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