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Assessing climate change impacts on hydrology: application to Zacapu and Pastor Ortiz aquifers (Mexico)

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ABSTRACT

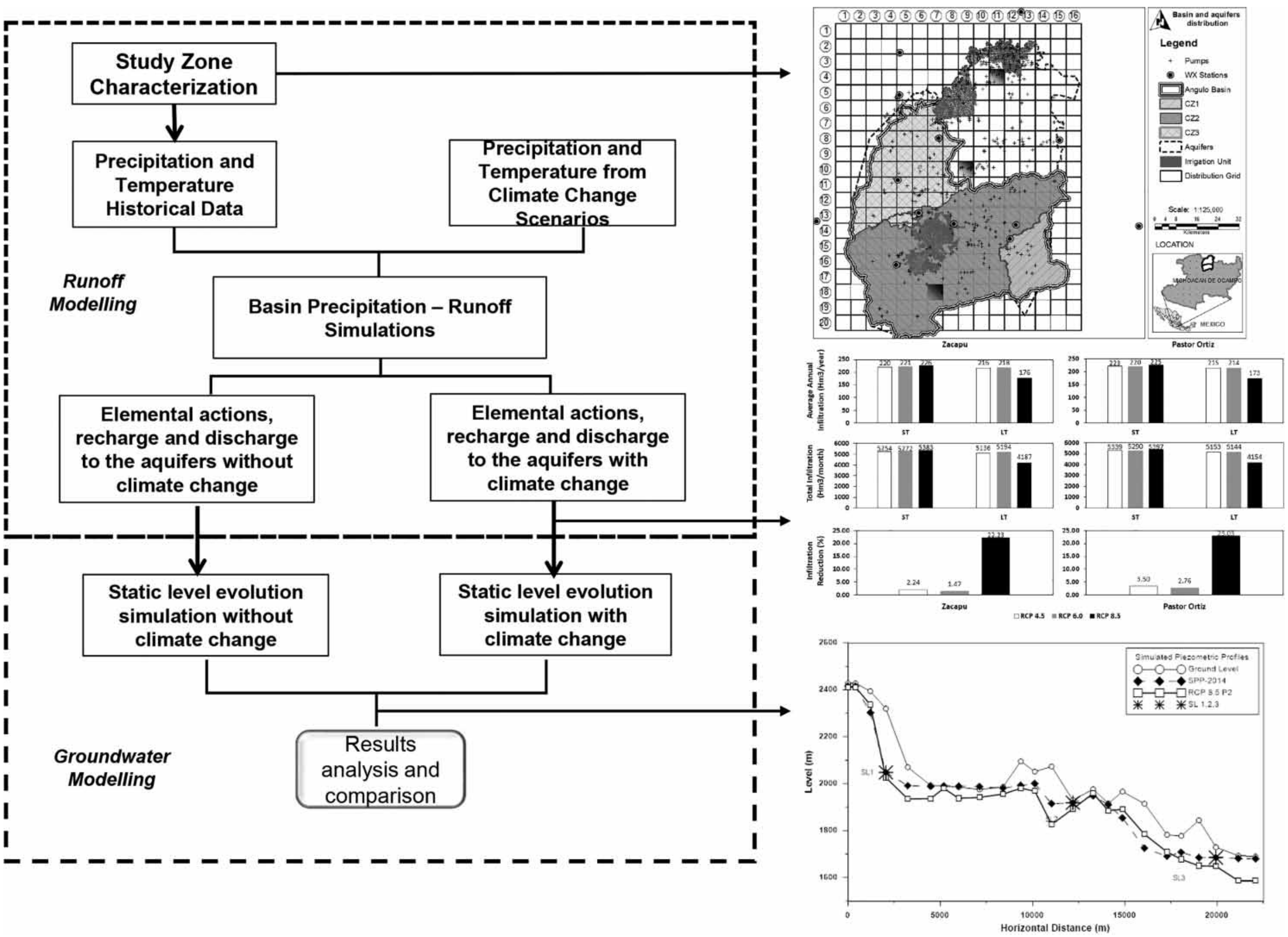
The agricultural and urban water requirements in the Angulo River basin (Mexico) along with land-use change and deforestation have caused great pressure on the region's groundwater availability. The potential climate change impact on groundwater levels of the Zacapu and Pastor Ortiz aquifers is evaluated in this study, using the climate model CMIP5, the hydrological module EVALHID, and the groundwater module AQUIVAL. The regional outputs from three Representative Concentration Pathway (RCP) climate scenarios (RCP 4.5, 6.0, and 8.5), for near future (2015–2039) and distant future (2075–2099) projections, indicate that the average annual temperature is expected to increase while a decrease in precipitation is projected over the basin. The assessment of infiltration and water level evolution in these groundwater systems indicates an infiltration reduction between 1.5 and 23%, producing a static level drop between 20 and 30 m in both aquifers.

Key words: AQUATOOL DSS, climate change, groundwater modeling, Pastor Ortiz aquifer, Zacapu aquifer

HIGHLIGHTS

- A groundwater piezometry decrease is assessed as the RCP scenarios increase.
- The most considerable effects of temperature and precipitation data are related to winter and spring.
- The precipitation behavior is similar throughout the basin, with a small increase in the RCP 6.0 scenario.

GRAPHICAL ABSTRACT



1. INTRODUCTION

During the past few years, a continuous drop in surface water resources and a rise in groundwater requirements have prevailed in Mexico, mainly due to urban area expansion along with anthropogenic activities that have modified the aquifers' natural protection (Hernández 2014). According to the National Water Commission (Comisión Nacional del Agua, CONAGUA), there is a general deficit condition for basins in the administrative hydrologic region No. 12 due to a large overexploitation in which the Angulo River basin is estimated to have a -12.3 hm^3/year deficit. (CONAGUA 2009, 2020a).

Related to the latter, the uncertainty of climate change impact on water resources is mainly due to the changes in temperature and precipitation patterns, which in turn affects runoff, groundwater recharge, and water availability (Pernia & Fornés 2009; Ostad-Ali-Askari *et al.* 2019).

Climate change scenarios in Mexico foresee a general reduction in rainfall and a rise in temperature all over the country, leading to a likely fall in groundwater availability and changes in physical–chemical composition, affecting major anthropogenic activities, and altering dependent ecosystems (IPCC 2014).

Similar responses have been reported for hydrological river basin systems (Singh & Kumar 2015). Climate change uncertainty from climatic and hydrological factors within the hydrological cycle has been analyzed in some studies (Pernia & Fornés 2009); others use projections from ensembled climate models (Jackson *et al.* 2011), with regional scenarios (Hernández 2014) and the most adverse scenarios (Minjarez *et al.* 2013; Pardo-Igúzquiza *et al.* 2019).

Therefore, a suitable management of water resources is required to ensure their protection, quantity, and quality. A first approach implies modeling the evolution of groundwater levels linked with infiltration results from a hydrological model (Molinero *et al.* 2011). Spatially distributed models are better suited to assess surface and subsurface hydrological responses requiring a large number of data (Flint *et al.* 2013; Morán *et al.* 2017); however, the data availability is mostly non-existent for most studies (Esralew *et al.* 2015). Semi-distributed models, which apply an aggregate model to every catchment subdivision, reduce data requirements since their complete and continuous hydrological cycle simulation uses a small number of parameters (Ouyang *et al.* 2014); the lack of precise data related to geological and hydrological parameters makes it necessary to use this type of model.

The EVALHID (Paredes *et al.* 2017) module, included in the AQUATOOL Decision Support System (DSS) (Andreu *et al.* 1996), enables the development of Rainfall Runoff Models (RRMs) with a semi-distributed approach, and it has been widely applied in Spain as well as in Mexico for water resources evaluation (Sahuquillo *et al.* 2010; Paredes *et al.* 2011; Hernández 2014). The Témez model (Témez 1977), which is implemented in the EVALHID, is based on the moisture balance between different water transport and storage processes that take place during different phases of the hydrological cycle by using the continuity principle and mass balance, rainfall, and evapotranspiration (ET) time series data are required as well as the sub-basin surface.

The RRM provides the aquifer inputs to the AQUIVAL (Solera 2017) module, which is also included in the AQUATOOL DSS, and is based on the eigenvalues method (Sahuquillo 1983) for (confined) linear behavioral systems in a distributed approach. Its main advantage is the low computational effort required, and it is part of the same system that simplifies data handling under a few parameters work scheme, allowing streamlined simulation and calibration processes.

In the last few decades, the development of several General Circulation Models (GCMs) has enabled creation of the most probable climatic scenarios. The IS92 emission scenarios (1992) and the IE-EE/SRES scenarios, developed by the International Panel on Climate Change (IPCC), have served as the basis for the most recent global circulation models. The ensemble of scale reduced GCMs is the instrument that can analyze mesoscale phenomena with a strong impact on meteorological parameters and derived quantities (Magaña 2010). This ensemble is also used to assess the impacts of climate change on hydrological regimes around the world (Flint & Flint 2012; Qin *et al.* 2015).

The development and updating of climate change scenarios in Mexico was tackled with the CMIP5 project, based on a regional analysis of the historical period, and the projections of 15 GCMs in the near future (2015–2039) and distant future (2075–2099). It employed a set of numerical experiments to study climate prediction, exploring the scope and limitations of global models and using different Representative Concentration Pathways (RCP 4.5, RCP 6.0, and RCP 8.5). These scenarios were proposed in the fifth Assessment Report of the IPCC, and have been used in other studies to quantify the impact of climate change (Dibesh & Dinesh 2016; Li *et al.* 2016), since they take into account regional and local weather variables from the Climate Research Unit of the Environmental Sciences School, University of East Anglia (Peterson *et al.* 1998). This is the main reason to consider the outputs from these projected scenarios.

This study aims to determine the climatic anomaly in the study region by using the RCP scenarios and apply it in an RRM of the Angulo River basin. These results are implemented in a groundwater model to evaluate the possible piezometric evolution under climate change effect in order to avoid the irreversible alteration of groundwater levels under water stress conditions, as in the Zacapu and Pastor Ortiz aquifers, whose importance for agricultural activity is vital for the Lerma-Chapala hydrological region (CONAGUA 2007, 2020b).

2. CASE STUDY

The Angulo River basin is in the northern region of the state of Michoacán. Its extension of 2,088 km^2 includes a portion of the Pastor Ortiz aquifer (1,798 km^2) and a large portion of the Zacapu aquifer with an area of 1,239 km^2 (Figure 1) located within the Hydrological Region Number 12 Lerma-Chapala-Santiago. La Patera River is the main tributary of the Ciénega wetland.

The climate in this system is classified as sub-humid, with an average annual temperature of 16 °C, 766 mm/year of average rainfall, and average potential evaporation of 1,736 mm/year. In the Pastor Ortiz aquifer, three types of climate are identified: cold, warm, and semi-warm temperate, with an average annual temperature of 18 °C, 745 mm of average annual rainfall, and average potential evaporation of 1,556 mm/year.

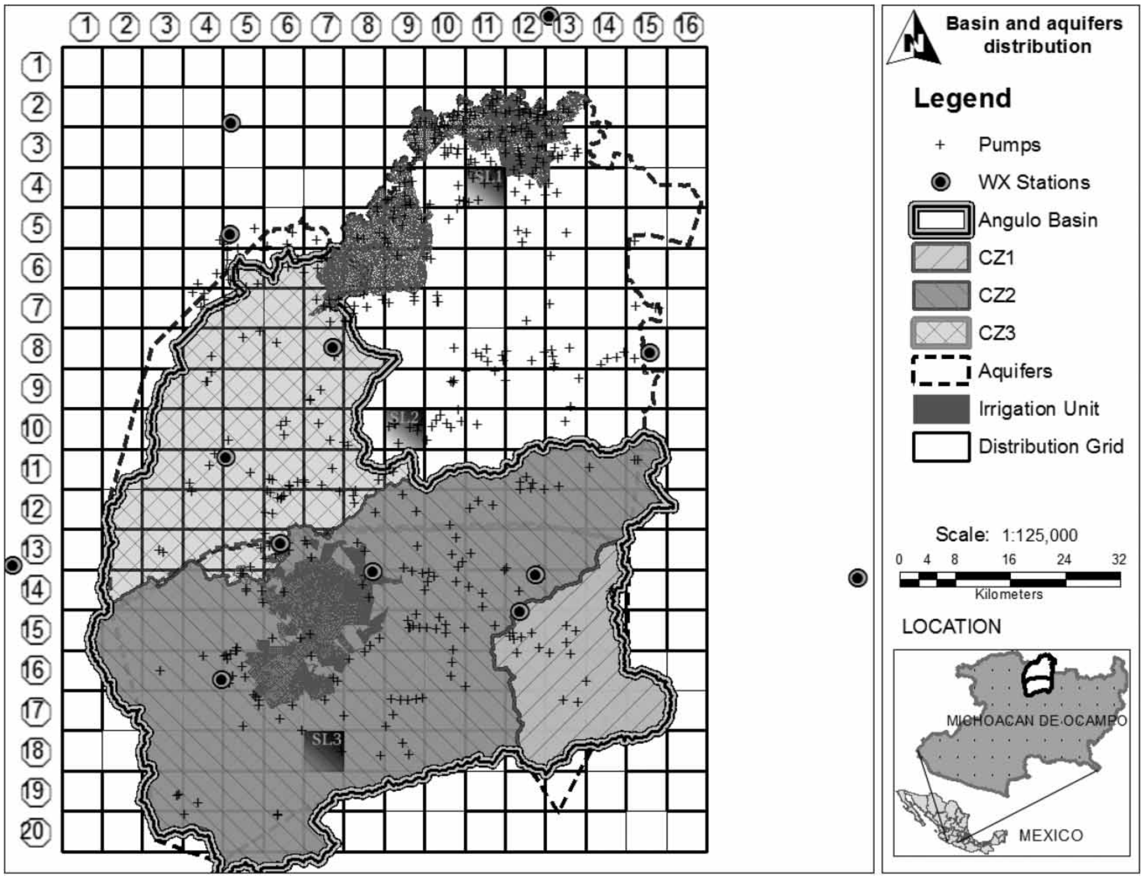


Figure 1 | Configuration of the study area.

Transmissivity is estimated from pumping tests, where values of $0.52–3.91 \times 10^{-3}$ m^2/s were observed. The contribution capacity exceeds the discharged volume, with about 4.8 Mm^3/year of the aquifer's additional availability.

The Pastor Ortiz irrigation unit covers 6,507 ha through the main Santa Ana channel which feeds the Santa Ana and Zurumuato channels at 7.0 m^3/s capacity. The aquifer is unconfined and semi-confined in local areas due to the interdigitation of fine material embedded in the main aquifer. Its regional storage coefficient approximates 0.10. The groundwater emergence is through the Pastor Ortiz valleys in the north and Ancihuácuaro in the northwest, where the effluent behavior of the Angulo River on the marginal aquifers is inferred.

An average annual recharge value of nearly 28 Mm^3/year is estimated; close to 70% is from natural infiltration, and the remaining 30% corresponds to irrigation returns. The availability of groundwater is estimated at −99 Mm^3/year; the negative sign indicates an important continuous loss in the stored reserves, implying that the aquifer is overexploited and, therefore, with zero availability.

The volumes obtained from the discharge of springs and pumping wells are 17 and 5 Mm^3/year, respectively. The water inlets and outlets are in equilibrium conditions and the aquifer is under-exploited, with 44 Mm^3/year of availability, in addition to the current exploited volume (CONAGUA 2007).

3. MATERIALS AND METHODS

3.1. Collected data

The monthly values of temperature and precipitation from the 26 meteorological stations covering the study basin were obtained from the Mexico climatic stations database known as CLIMATE Computing Project (CLICOM) by the Scientific Research Center and High Education of Ensenada (Centro de Investigación Científica y de Educación Superior de Ensenada, CICESE), whose missing data were estimated by the inverse square distance method.

Monthly runoff to the main stream of the Angulo River basin was obtained from three hydrometric stations located in the upper, middle, and lower part of the basin, corresponding to the National Surface Water Data Bank (Banco Nacional de Datos de Aguas Superficiales, BANDAS), produced by CONAGUA and the Mexican Institute of Water Technology (Instituto Mexicano de Tecnología del Agua, IMTA).

The piezometry of the aquifers was obtained through boreholes conducted in 2007 and 2014 in field visits by the groundwater monitoring network, by CONAGUA, and the Michoacana University of San Nicolás de Hidalgo.

The geological and hydrogeological parameters were determined by the thematic layers produced for the 'Hydrogeological updating of the aquifers: Maravatío-Contepec-Epitacio Huerta, Zacapu, Morelia-Queréndaro and Pastor Ortiz in the state of Michoacán' report, created in agreement between CONAGUA, IMTA, and the Environment and Natural Resources Secretary (Secretaría de Medio Ambiente y Recursos Naturales, SEMARNAT). The description of the hydraulic conductivity and the storage coefficient was also obtained in the report through pumping tests.

3.2. Climate change scenarios

The RCP scenarios refer to the global energy radiation, expressed in W/m^2, due to the increase of greenhouse gases; these have been classified according to radiative forcing (Moss *et al.* 2010).

The 'Updating of Climate Change Scenarios for Mexico as part of the products of the Fifth National Communication' was tackled by several Mexican institutions based on the previous scenarios, considering the Reliability of the Weighted Assemble (REA) of 15 mcg. This work resulted in a series of precipitation and temperature data for fictional stations, 0.5° longitude and latitude apart from each other. Sixteen of these stations that covered the study area in its entirety were considered. On the other hand, short- and long-term series cannot be used since they start from a historical base that reflects a different behavior from the data of the meteorological stations of the region. Therefore, a methodology to determine the climatic anomaly (Δ) that could occur in the study area is proposed (Figure 2).

The climatic anomaly is determined by the expression:

$$\Delta C_M = (\overline{DC}_{\text{RCP}} - \overline{DC}_{\text{REA}}) \tag{1}$$

where ΔC_M is the monthly climatic anomaly; $\overline{DC}_{\text{RCP}}$ is the average monthly climatic data of the RCP projection; and $\overline{DC}_{\text{REA}}$ is the monthly average of the climatic data of the historical base REA.

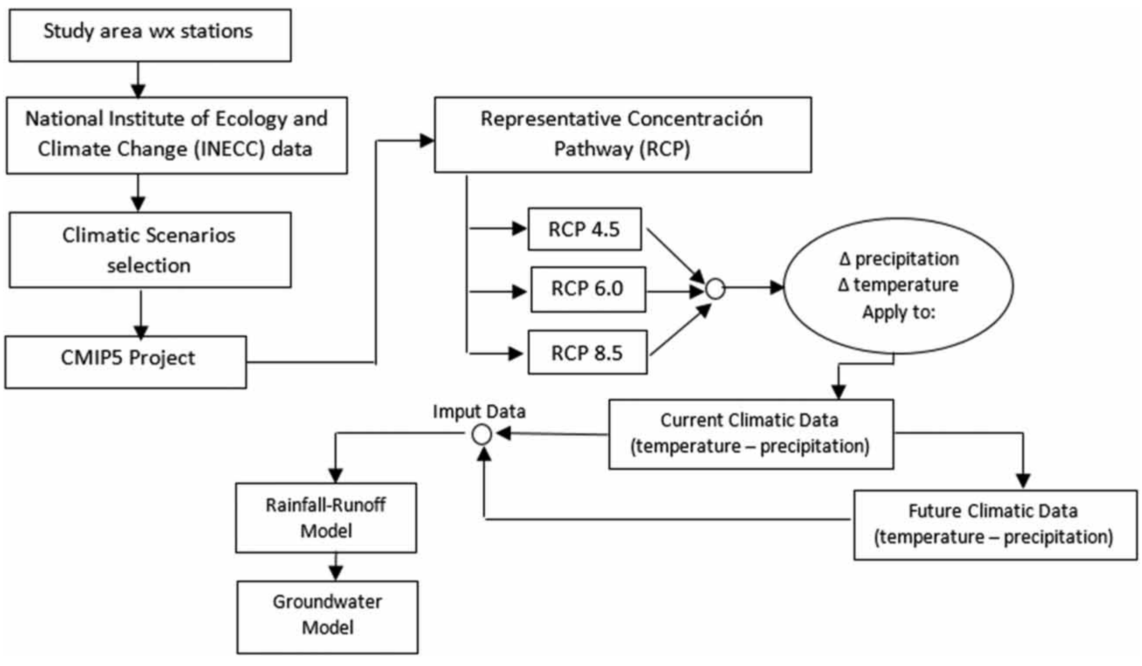


Figure 2 | Determination of the climatic anomaly.

This anomaly was applied to the climatic data of CLICOM for the analyzed historical period to produce the feasible series of precipitation and temperature of RCP 4.5, 6.0, and 8.5 scenarios in the short and long term for the selected meteorological stations.

3.3. Catchment model

The objective of the surface hydrological modeling in this work is to determine the volumes of direct recharge to the aquifer from precipitation, as it is one of the applications of the RRM. The use of few parameters and the possibility of carrying out an aggregate assessment for medium- and small-sized basins are among the advantages offered by the Témez model (Témez 1977). In the case of larger basins, it can also work as a semi-distributed model (Sahuquillo *et al.* 2010), by subdividing the system into sub-basins.

The model carries out the humidity balance constituted by precipitation (P_i) which represents the incoming flow that is distributed among a series of outflows, intermediate flows, and intermediate storage. In the Témez model, water coming from precipitation (P) is distributed into the excess (T), the real evapotranspiration (E_t), and the soil moisture (H_t).

The infiltration produced in the month t corresponds to the fraction of water that enters the soil and ends up recharging the aquifer, forming part of the surplus that does not run on the surface. The infiltration to the aquifer is a function of the surplus and a parameter called maximum infiltration ($Imax_t$), which expresses the maximum amount of water that can infiltrate the ground in a month, described by the following expression:

$$I_t = Imax_t \cdot \frac{T_t}{T_t + Imax_t} \tag{2}$$

The part of the surplus that does not infiltrate the aquifer becomes surface runoff at the end of the month t, described by the following equation:

$$Asup_t = T_t - I_t \tag{3}$$

The surface component is one of the outputs of the model that is contrasted with the records of the hydrometric stations, whose location within the surface drainage is taken as a basis to configure the micro-basin system of the model, by using a GIS. The parameters that are calibrated within the model are the maximum infiltration ($Imax$), maximum soil storage capacity ($Hmax$), excess coefficient (c), and the coefficient of underground drainage α (Témez 1977), through an automatic calibrator (García-Romero *et al.* 2019) which uses the SCE-UA UA algorithm (Shuffled Complex Evolution method developed at The University of Arizona); the quality of the calibration is evaluated by the adjustment indicators of Nash–Sutcliffe (NS) and Pearson efficiency coefficients (Duan *et al.* 1994).

3.4. Aquifer model

The discretization by finite differences used by the AQUIVAL module requires a configuration of the aquifer's extension into a grid of 4 km×4 km, generating 16 columns and 20 rows. For each cell, the interpolated values of the initial static levels, the storage coefficient, and the hydraulic conductivity are determined using GIS tools. In a similar way, the weights of the elementary actions (elements of pressure in the system) from the infiltration and extraction volumes were determined, according to the spatial distribution of 474 present uses and the irrigation zones of Zacapu, Pastor Ortíz, and Angamacutiro districts.

Cells C11-R4, C9-R10, and C7-R18 (Figure 1) were selected as calibration points for the piezometry SL1, SL2, SL3, respectively, and compared with static levels monitoring carried out in 2007 and 2014. It has been verified that hydraulic conductivity is the parameter of greatest sensitivity in the model; the calibrated values are within the limits of material classification such as lacustrine deposits and unconsolidated sedimentary rocks (Heath 2002), and for the intergranular free-porous type aquifer classification (Villanueva & Iglesias 1984). Monthly simulations of the piezometry were obtained, with an error of 0.05–0.14% in comparison to the piezometry measured in the field.

4. RESULTS AND DISCUSSION

A monthly analysis of the time series of precipitation changes for each calibration zone and projection period in percentage of change is shown in Figure 3, which presents a decrease in precipitation for most months. The highest reductions are observed in February between a 60 and 90% decrease, the smallest reductions are produced during the most humid period of the zone

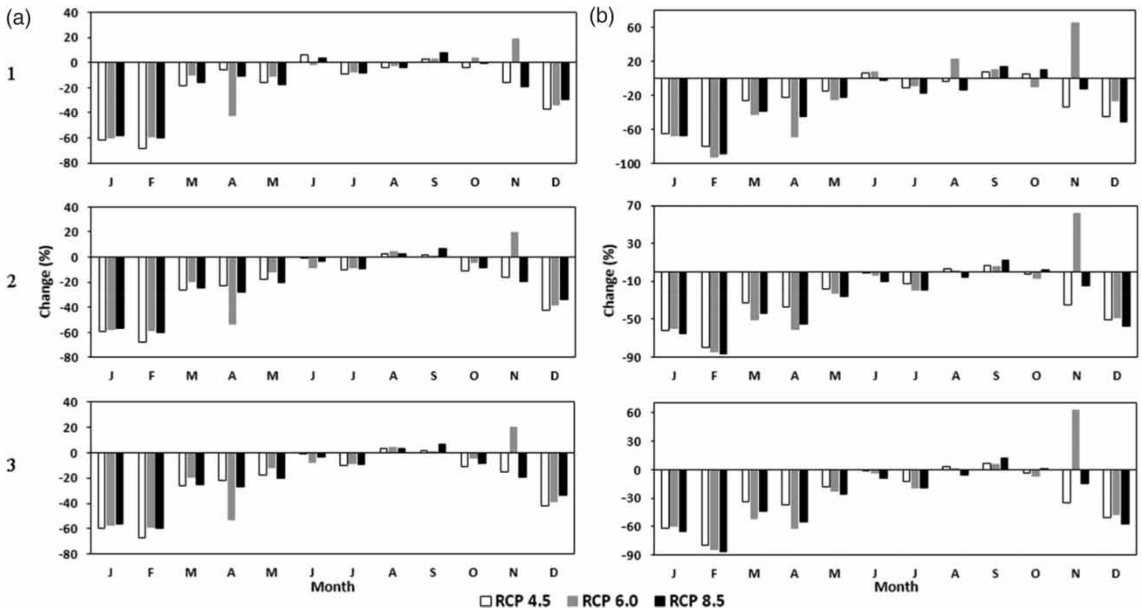


Figure 3 | Change of precipitation for RCP scenarios for the three calibration zones: (a) short term and (b) long term.

(July–November). Some increases are observed for certain scenarios; the RCP 6.0 scenario in November presents the biggest positive change as opposed to the RCP 4.5 values in the month of February.

The three zones show a similar behavior; zone 3 presents the biggest changes in the long term. A similar analysis for the temperature data shows a general increase (Figure 4), with a variation of 0.9–9% for the short term and 5–23% for the long term, with changes of lesser magnitude in the month of June.

The temperature and precipitation data affected by climatic anomaly for each of the obtained RCP scenarios were used in the EVALHID model to obtain the river basin runoff, whose percentage of seasonal reduction (Figure 5) shows that during

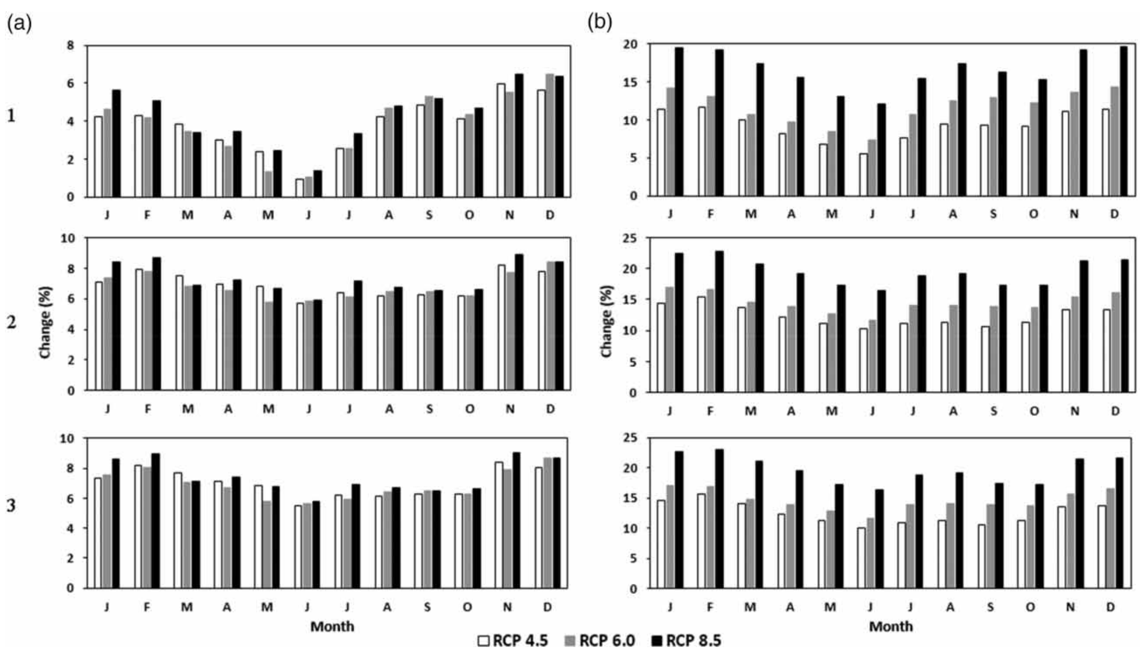


Figure 4 | Change of temperature for RCP scenarios for the three calibration zones: (a) short term and (b) long term.

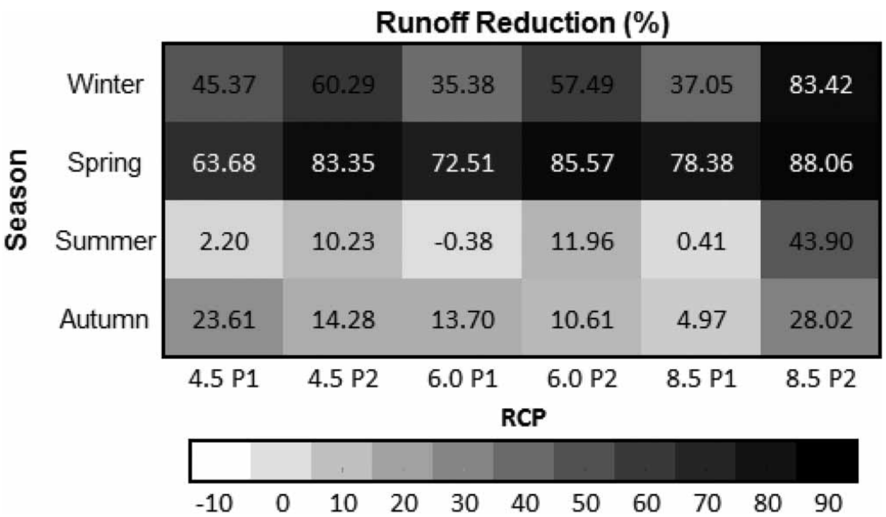


Figure 5 | Reduction of seasonal runoff for the analyzed RCP scenarios for short term (ST) and long term (LT).

winter and spring, the most considerable affections have a variation of 35–88% and in summer the least runoff affection with a range from −0.38 to 43. The monthly infiltrations into the aquifers were also determined with this model.

A general description of the total infiltration, the annual average, and the reduction percentage in each aquifer were estimated as shown in Figure 6. Infiltration values in both systems seem to not have significant differences but Pastor Ortiz have comparatively further percentage reductions for all scenarios; an interesting behavior is that RCP 6.0 presents less reduction than RCP 4.5 which could be related to the precipitation changes analyzed before.

The calculated monthly infiltration is applied as the recharge of the Zacapu and Pastor Ortíz aquifer in the AQUIVAL model, where a constant decrease in piezometry has been detected (Figure 7). With the purpose of comparing these results, a common initial static level is considered, adjusting the descriptions to the climate change short-term period (Figure 8).

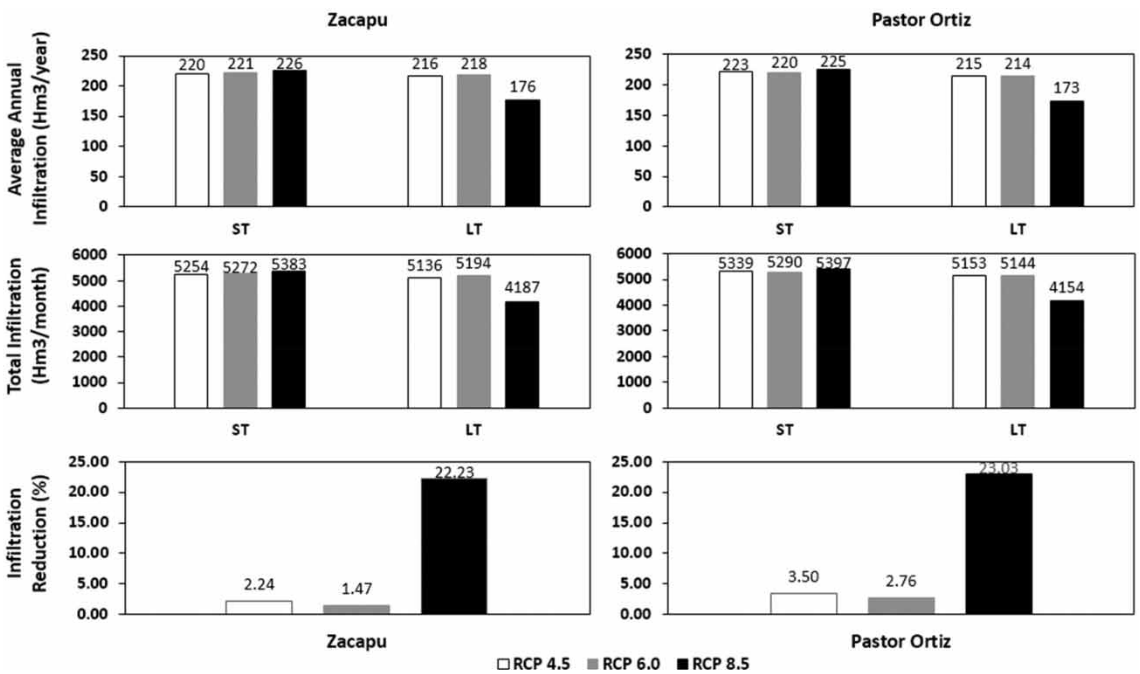


Figure 6 | Summary of infiltrations determined for each aquifer under the RCP scenarios.

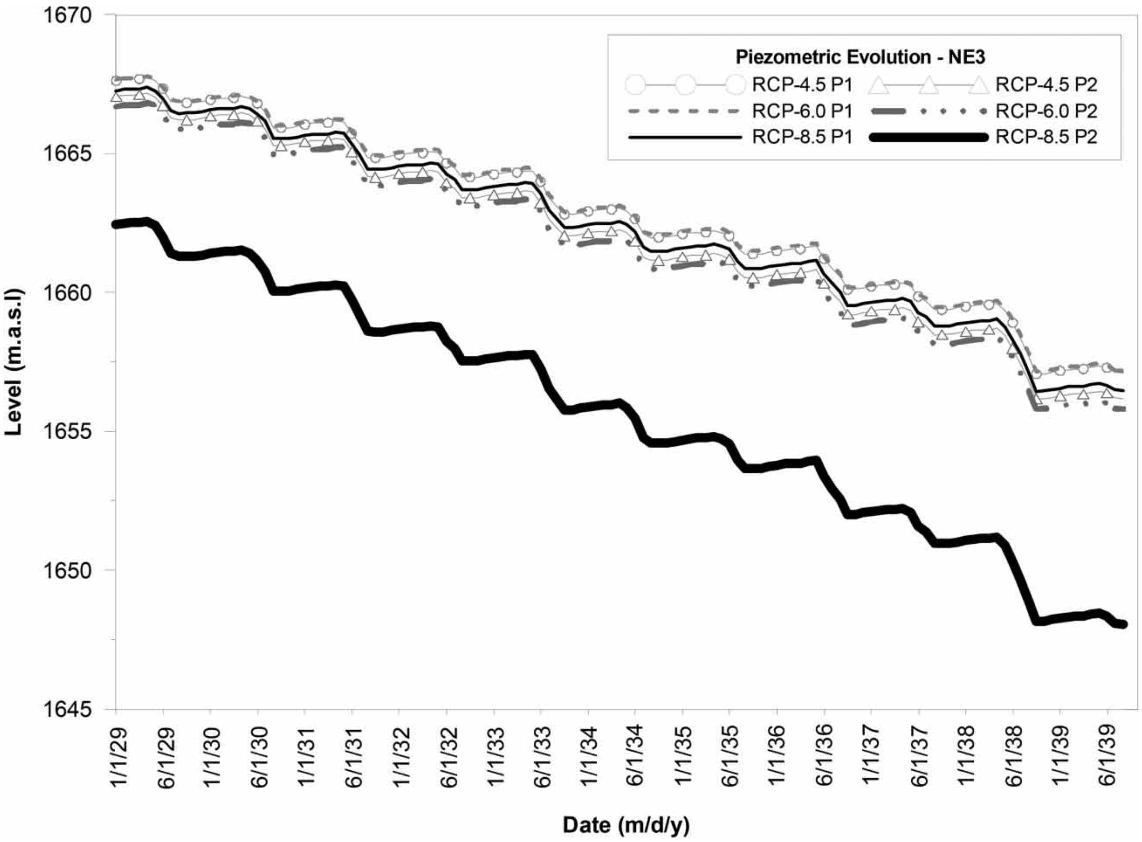


Figure 7 | Piezometric evolution of the SL3 control point for the RCP scenarios (2029–2039).

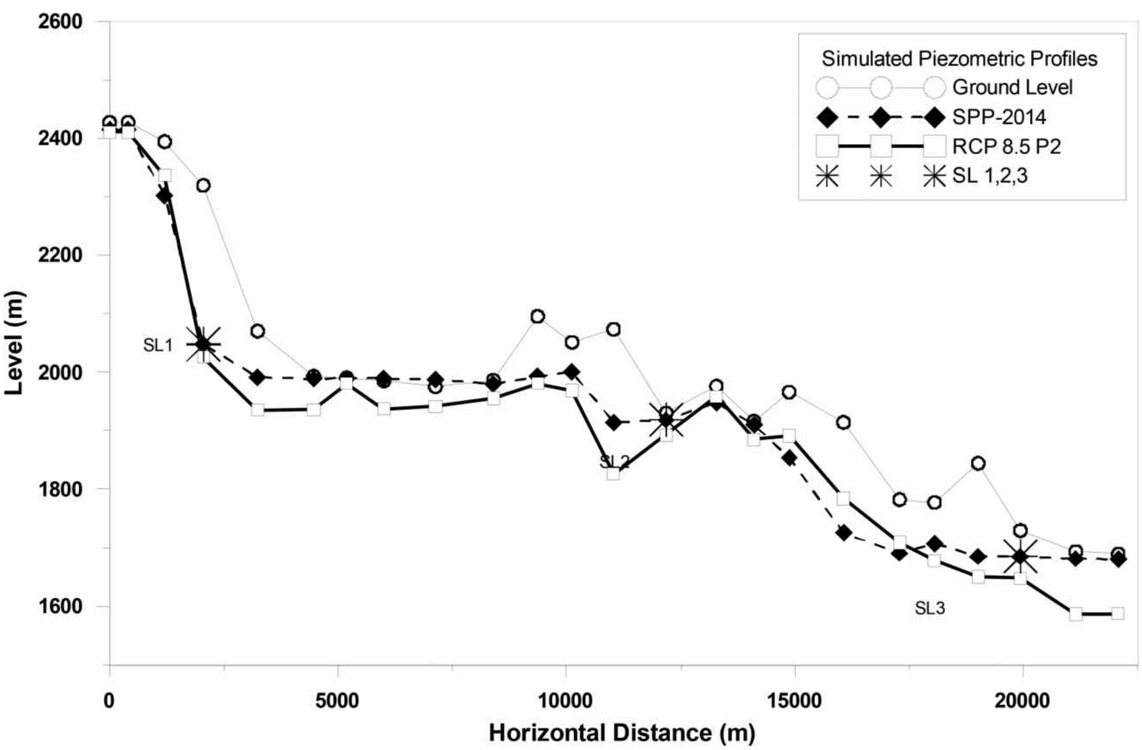


Figure 8 | Comparison of piezometric profiles simulated (RCP 8.5) and measured (2014) with respect to the ground level.

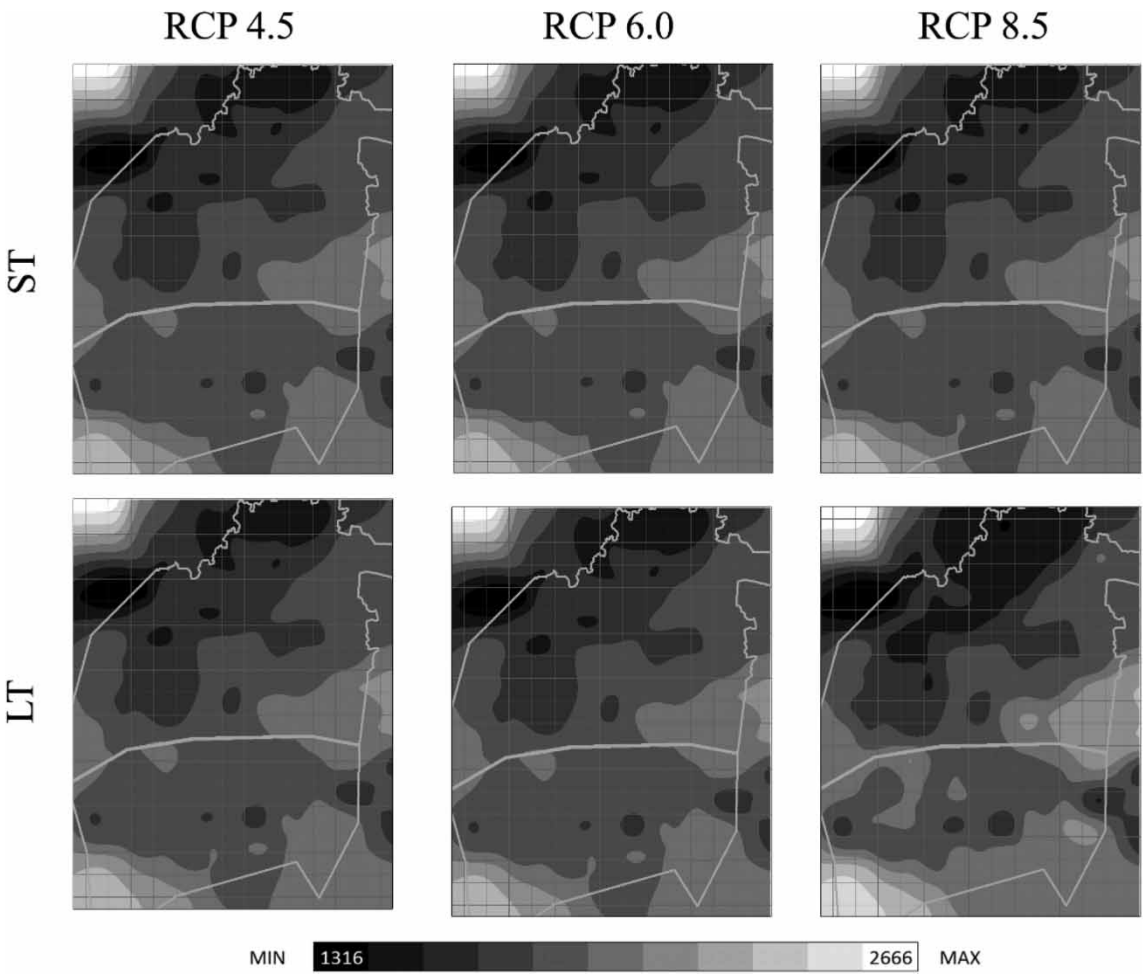


Figure 9 | Water levels simulated for short and long terms for all RCP scenarios.

As shown in the figure for the 2029–2039 period (Figure 7), the piezometry decreases as the RCP scenario increases. Paradoxically, there is little variation from one to another, except for scenario RCP 8.5 P2, where the reduction is evident, as is shown in the infiltration percentage reduction of the aquifer and water levels simulations (Figure 9), with the north region of Pastor Ortiz the most affected.

This reduction behavior is also reflected in the average elevation differences between the initial static level in 2014 and the last simulated level for the control parameters (Table 1), with the lowest reduction from the RCP 6.0 in the short term and the highest from the RCP 8.5 in the long term.

In order to obtain more accurate and descriptive simulations and results, it is necessary to implement updated and automated methods to collect information (Romero Gameros *et al.* 2021). Likewise, coupling these models in broader systems to support decisions on water management (Arreguín *et al.* 2019), a detailed analysis of the effect of the spatial variability of the climatic conditions in the region is required (Sparks *et al.* 2017), as well as precipitation influence (and the initial conditions

Table 1 | Reduction of static levels regarding the initial state for the different scenarios and projection periods

RCP ST	Reduction (m)	RCP LT	Reduction (m)
4.5	21.06	**4.5**	21.92
6.0	20.97	**6.0**	22.28
8.5	21.65	**8.5**	29.66

of humidity) in the basin runoff. On the other hand, the consideration of the magnitude and type of basin will also help to improve the parameters used in the models (Pechlivanidis *et al.* 2017), which will allow us to produce simulations in an agile way, historically describing the natural behavior of the environment, allowing system predictions under normal conditions, or later comparisons with climate change scenarios (Hervis Granda *et al.* 2019), even in systems under very different conditions to those studied (Morán *et al.* 2017).

It could be necessary to propose new options for water supply that meet the demands without overexploiting aquifers, either through the treatment of wastewater, artificial recharge of aquifers (Fernández *et al.* 2018), change of crops, protection of recharge areas, or the reduction of the volumes granted in concessions.

These results contribute to a better local water systems management, allowing us to establish better evaluations of atrophic actions coupled with superficial and underground water interactions than previous studies (Solera 2014), which focused on management through modeling but without considering climate forcing. This approach could help to develop and incorporate better hydrological simulation methods in Mexico.

5. CONCLUSIONS

Based on the proposed methodology and the obtained results, the model generated in the AQUIVAL predicts a much lower water table level than that which would occur naturally if an increase in temperatures and a reduction in precipitation did not occur, as the data generated from the RCP scenarios warn. In addition, there is a decrease in static levels as the degree of radiation increases; this is also true for long-term projections that allow us to see a diminishing evolution, which, in comparison with short-term simulations, could be interpreted as minimal. This is not the case of the long-term projection of the most drastic scenario (RCP 8.5), which shows a significant reduction of around 30 m.

The previous simulations show a direct relationship between the behavior of meteorological factors used in the runoff modeling, denoting an increase in temperature (from 17.6 to 20.9 °C), and a decrease in precipitation (from 806.4 to 735.6 mm) for the study area. This fact indicates that climate change is the main driver in piezometry change; even so, a complementary study of other factors of influence in the piezometric evolution (such as the change in land use and anthropogenic activities) could provide a clearer picture of the behavior and change of surface (Mohammed *et al.* 2016; Yan *et al.* 2016) and groundwater resources (Mack *et al.* 2013; Owuor *et al.* 2016).

Given the above circumstances, it is plausible to state that the implementation of the effect of climate change on hydrological modeling, both in surface and groundwater, provides an interesting and useful point of view on hydrological feature changes in the Zacapu and Pastor Ortíz aquifers. It has been detected that, according to what was initially proposed, climate change negatively affects these groundwater bodies, with a decrease that could be from 20 to 21 m for the short term and from 22 to 30 m for the long term. This circumstance, combined with the decline of previous periods, could result in a greater economic and infrastructural effort to maintain water use and, possibly, affect all human and natural subsystems that depend on it, mainly urban and agricultural ones. With medium-term data, the reduction of the total level could have been determined, which would possibly lead to a more aggravated state than those previously analyzed.

It is advisable to include the effects of climate change in future hydrological modeling approaches, together with the determination of climatic indexes that help to identify local affections in precipitation distribution (Shao *et al.* 2016). Moreover, an improvement in water resource systems operations could help to avoid irremediable alterations to resources and ecosystems, while projects that provide tools and strategies for adaptation are implemented.

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DECLARATION OF INTEREST

None declared.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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