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# SPATIO-TEMPORAL EFFECT OF CLIMATE CHANGE ON WATER BALANCE AND INTERACTIONS BETWEEN GROUNDWATER AND SURFACE WATER IN PLAINS

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## ABSTRACT

The analysis of the impact of climate change on water resources in plains requires integral simulation tools that quantify topographic complexity and the strong interaction of groundwater and surface water components (GW-SW). The objective of this study is to implement a coupled hydrological-hydrogeological model under climate change scenarios in order to quantify the spatio-temporal dynamics of water balance and GW-SW interactions for the upper creek basin of Del Azul, which is located in the center of the province of Buenos Aires. The simulation was carried out for a baseline scenario calibrated and validated for the period 2003-2015 and contrasted with two scenarios of the regional climate model CCSM4, RCP (4.5 and 8.5) simulated for the period 2020-2050. First, the annual and monthly anomalies of precipitation, temperature, surface runoff, evapotranspiration, soil moisture, recharge, flow, as well as the discharge, head level and reserves of groundwater are studied. Then the spatio-temporal anomalies of the GW-SW interaction were analyzed and finally wet and dry periods by means of the standardized precipitation index and the annual water balance were studied. Simulation results show that climate change will significantly alter the spatio-temporal patterns of the GW-SW interaction as well as the water balance. These showed monthly, seasonal and annual variations. They show an increase in most of the components of the water balance towards the middle of the 21st century, except soil moisture. Regarding GW-

SW interactions, the average annual discharge of the aquifer to the stream is expected to increase by 5% with RCP 4.5 while it will increase 24% with RCP 8.5. The recharge from the stream to the aquifer is expected to increase by 12% with RCP 4.5 while a decrease by 5% with RCP 8.5. Concerning the SPI related to the water balance for the period 2020-2050, alternations of both the time and the length of dry and wet periods are expected for the two scenarios, with RCP 4.5 low frequency of wet episodes, but with a greater severity and permanence in time in contrast to RCP 8.5 that presents less frequency in dry periods, but with high permanence and severity. Climate change could alter groundwater mainly through changes in the recharge, leading to modify groundwater levels and this will cause GW-SW flow to be reversed in some sectors of the stream by increasing or decreasing groundwater discharge into the stream.

**Nomenclature**

| | |
|---|---|
| ***Abbreviations and acronyms*** | |
| *BCSD* | Bias Correction by Spatial Disaggregation |
| *CCSM4* | Community Climate System Model fourth version |
| *CMIP5* | Coupled Model Intercomparison Project Phase Five |
| *GCM* | General Circulation Model |
| *NEX-GDDP* | NASA Earth Exchange Global Daily Downscaled Projections |
| *RCM* | Regional Climate Models |
| *RCP* | Representative Concentration Pathway |
| *SPI* | Standardized precipitation index |
| ***Variables*** | |
| *ET* | Actual evapotranspiration [mm] |
| *GW-SW* | Groundwater and surface water |
| *PCP* | Precipitation [mm] |
| *PET* | Potential evapotranspiration [mm] |
| *RCH* | Recharge [mm] |
| *SURQ* | Surface runoff [mm] |
| *SW* | Soil moisture [mm] |
| *TMP* | Temperature [° C] |
| ***Parameters*** | |
| *K* | Hydraulic conductivity [m/d] |
| *Sy* | Storage coefficient [-] |
| ***Statisticals*** | |
| *NS* | Nash and sutcliffe efficiency |
| $R^2$ | Coefficient of determination |
| *RMSE* | Root mean square error |

**Key words**

Climate change; SWAT-MODFLOW coupling; stream-aquifer interaction; water balance; plain areas; coupled numerical modeling.

## 1. INTRODUCCIÓN

The vulnerability of water resources due to climate change (Vörösmarty et al., 2000; Barros et al., 2015) and population growth (Vitousek et al., 1997) poses future risks for the social, economic and ecological viability of Great plains (Parton et al., 2007). One of the largest plains on the planet is located in southeastern South America called the Pampas plain with an area of 700,000 km$^2$. This area experiences important climatic variability (Lovino et al., 2018) with major changes in precipitation due to the displacement of the South Atlantic anticyclone. This has generated positive precipitation trends that have increased approximately 30% of annual rainfall since 1960 (Barros et al. 2008; Minetti and Vargas, 2009; Maenza et al., 2017) and the frequencies of heavy rains from thresholds ranging from 50 to 150 mm (Barros et al. 2015). These changes have increased the agricultural frontier, mainly the cultivation of soybeans, passing from 1.8 to 20 million hectares 1980-2005 (Mercau et al., 2007) because the Pampas plain depends heavily on rainfall for rainfed agriculture (Gutowski et al., 2003). Viglizzo et al. (1995) makes an analysis to estimate the association between precipitation and land use for the period 1960 to 1990 and states that there is a positive correlation between annual precipitation and the relative increase in the area of cultivation in the Pampas plain. This increase in agricultural extension is also related to exogenous influences such as direct sowing, input costs and the price of grain (Polsky, 2004). According to Barros et al. (2015), there are also positive trends in temperature in central Argentina in the period 1901-2012, having the average temperature increased by about 0.5 ° C. According to Rusticucci and Tencer (2008) and Rusticucci et al. (2016) minimum temperatures and heat waves have also been increasing over the years.

According to future climate projections under the models of the Coupled Model Intercomparison Project Phase Five (CMIP5) (Taylor et al., 2012) the positive rainfall trends experienced since 1960 in central Argentina will not change during this century (Maenza et al., 2017). According to Barros et al. (2015) positive temperature trends are expected until the end of the century. For a scenario of mitigation emissions of Representative Concentration Pathway (RCP) 4.5 (538 ppm $CO_2$), an increase greater than 1 °C is expected and with a scenario of non-mitigation of emissions RCP 8.5 (936 ppm $CO_2$) increases above 2 °C are expected.

The potential impacts of the future radiative forcings will trigger problems that will affect the supply of drinking water (Vörösmarty et al., 2000), frequency of droughts and floods (Easterling et al., 2000; Trenberth, 2011), alterations in GW-SW interactions (Saha et al., 2017), changes in water quality (Murdoch et al., 2000; Whitehead et al., 2009), salinization (Yeo, 1998; Nielsen and Brock, 2009), erosion (Peizhen et al., 2001; Nearing et al., 2004), changes in agricultural production (Parry et al., 2004; Olesen et al., 2011), changes in biodiversity (Sala et al., 2000; Peterson, 2003), ecosystem fragmentation (Honnay et al., 2002; Opdam and Wascher, 2004), alterations in the seasonality of the streamflows (Ali et al., 2019 ), changes in water available to renewable energy generation (Kuriqi et al., 2019a; Kuriqi et al., 2019b), increase in epidemiological diseases (Hunter, 2003; Greer et al., 2008; Luber and McGeehin, 2008) and population migration (Reuveny et al., 2007).

Aquatic ecosystems located in plains such as wetlands, lakes, aquifers and streams, are highly dynamic and respond to extreme climatic fluctuations (Covich et al., 1997). These climatic fluctuations condition the processes of the water balance (e.g., runoff, evapotranspiration, recharge), and the mechanisms of interactions between groundwater and surface water (GW-SW) as the recharge-discharge of water from a system (Sophocleous, 2002). Knowing the water balance and future GW-SW interactions is important for the interpretation of the possible mechanisms that would control the spatio-temporal distribution of vegetables formation and food production since they are strongly controlled by the climate and the hydrology (Stephenson, 1990). The variation of the depth of the water table plays a very important role in the maintenance of ecosystems (Russo and Lall, 2017) and in the dynamics of climatic extremes (droughts and floods) in plains, due to the fact that there is a strong correlation between shallow groundwater and surface water balance processes (Maxwell et al., 2007; Kollet and Maxwell, 2008) such as evapotranspiration, soil moisture and surface runoff (Guevara et al., 2019c). According to Healy and Cook (2002), climatic factors are expected to substantially affect to shallow and unconfined aquifers due to the short transit time in the unsaturated zone. Accurate estimation of recharge is vital to properly manage an aquifer. Projections of groundwater recharge are closely related to the projected changes in precipitation and land use. According to Taylor et al. (2013) there are many uncertainties and little research that analyze the direct impacts of climate change on groundwater systems. This type of analysis is essential to know the spatio-temporal distribution of future recharge and to analyze aquifer's vulnerability with climate change.

To quantify future water vulnerabilities, it is necessary to consider the interactions between climate change, climate variability, land use, soil type, topography, geology, surface and groundwater hydrology (Thót 1999; Sophocleous, 2002; Krause et al., 2009; Taylor et al., 2013). This will allow to evaluate and understand the long-term climate variability and productivity of shallow groundwater ecosystems in order to plan and manage properly the water resources in plains, taking into account the increasing tensions with these resources as a consequence of industrial, agricultural and ecological needs (Green et al. 2011).

Climate models are the most reliable tool available today to predict future climate prospects as a result of anthropic actions and natural changes due to external forcing of the climate system (Barros et al., 2013). According to Gleick (1989), one of the most important consequences of climate change will be the alteration of regional hydrological cycles because the projected impacts of climate change vary significantly according to the scale, location and timing of the analysis.

To determine the future impacts of the water balance in a basin, the outputs of the Regional Climate Models (RCM) are currently used, which have a horizontal resolution of around 25 km and are more suitable than the General Circulation Models (GCMs) to capture the geographic variability of precipitation and temperature as input to hydrological models (Gutowski et al., 2003; Olesen et al., 2007; Christensen et al., 2007; Gao et al., 2008). This allows a better understanding of the interactions between the numerous processes involved in the water balance (Brulebois et al., 2018) in order to improve monitoring systems and to take measures to develop adaptive capacity and ecosystem resilience (Alley et al., 2003).

The outputs of the climatic variables of the RCMs are used as input data to execute hydrological models allowing flow simulations to be carried out. The inability of these RCMs to adequately simulate current climatic conditions (mainly the precipitation) must be taken into account (Christensen et al., 2008), because they have systematic errors or biases that generate overestimation or underestimation of the observed variables (Teutschbein and Seibert, 2012). To correct these biases different polarization correction methods are used, being one of the most reliable the Bias Correction by Spatial Disaggregation (BCSD), method which compares the results of the RCM with the corresponding climatic observations during a common period and it uses the derived information to adjust future climate projections so that they are consistent with historical climate records (Wood et al., 2004).

In plains, classic hydrological models do not represent adequately the spatio-temporal variation of the water table, nor the GW-SW interactions because they do not take into account the distributed parameters such as hydraulic conductivity (K), storage coefficient (Sy) in the aquifer and the permeability of the stream bed (Guevara-Ochoa et al., 2019c). In addition, if we want to evaluate a water problem (e.g., droughts, floods, pollution, water quality, etc.) these types of models represent with great uncertainty the movement of water in this type of systems (Guevara-Ochoa et al., 2019b), and often they do not capture the low flows satisfactorily. Therefore, new approaches of integrated modeling at regional scale coupling hydrological-hydrogeological models (Barthel and Banzhaf, 2016), are essential for the integrated management of water resources in plains (Sophocleous, 2002). These models allow to analyze the exchange of local, intermediate and regional groundwater flow systems, which are essentially important for the study of interactions between groundwater and surface water in plain areas (Tóth, 1963).

Several numerical coupling approaches have been developed for the study of GW-SW interactions. The differences stand in the way the coupling is treated:

There are completely coupled approaches: where surface and groundwater flow equations are solved simultaneously. As an example of this type of models we have the HydroGeoSphere (Brunner and Simmons, 2012), and ParFlow (Maxwell et al., 2009).

On the other hand, there are loosely coupled approaches: when two or more individual models are coupled through the exchange of model results. As an example of this type of models we have the GSFLOW (Markstrom et al., 2008), SWAT-MODFLOW (Bailey et al., 2016), among others.

According to Flipo et al. (2014), Pryet et al. (2014), the first approach is limited for small areas due to its high computational cost. For this reason, its use to regional studies is limited. Furthermore, according to Semenova and Beven (2015) and Barthel and Banzhaf (2016), the use of completely coupled approaches for integrated modeling at regional scale is generally not advantageous because in most cases the input data is limited. On the other hand, the loosely coupled approaches, have been most used for the evaluation of GW-SW interactions at regional scale, they have a license and codes freely available and allow to take into account crop rotation, management practices, water demand, contamination by agricultural waste, reservoirs, etc. These variables are critical in the context of the analysis of the water balance in basins where extensive agriculture is implemented (Guevara et al., 2019c).

There is a large amount of literature that covers the use of classical hydrological models (uncoupled), under climate change scenarios. Some of the most cited examples are the study of Bae et al. (2011) which applies thirteen GCMs outputs with three greenhouse gas emission scenarios in Korea to analyze the effects of three semi-distributed hydrological models and potential evapotranspiration (PET) computation methods to analyze climate change impact in the water resources. Teng et al. (2011) assess the relative uncertainties of climate change on the runoff across southeast Australia from fifteen GCMs and five hydrological models. Thompson et al. (2013) evaluate the uncertainty in the projections of the Mekong river flow using seven GCMs and the MIKE-SHE hydrological model. Teklesadik et al. (2019) performs a comparison between six hydrological models and four GCMs to assess the impacts of climate change on the Upper Blue Nile basin.

The coupled hydrological-hydrogeological modeling under climate change scenarios has been very poorly evaluated and mainly these studies have focused on the future temporal variation of streamflow, recharge and variation of groundwater heads. Some examples are those described Goderniaux et al. (2009) that applied the HydroGeoSphere model in a basin in Belgium to analyze climate change impacts on groundwater reserves. Later Gamvroudis et al. (2017), applies the integrated Soil and Water Assessment Tool (SWAT) model with the three-dimensional model groundwater flow Princeton Transport Code (PTC) model in Greece in order to evaluated the impacts of surface and groundwater variability response to future climate change in the Evrotas River Basin. The impact of climate chance on temporal dynamics of GW-SW interaction, has been evaluated mainly in Canadian watersheds, through loosely coupled schemes and using outputs derived of GCMs. Scibek et al (2007) uses the integrated BRANCH and MODFLOW models for estimating future impacts of climate change on groundwater and surface water interactions and groundwater levels within the unconfined Grand Forks aquifer in British Columbia. Then Saha et al. (2017) applied the Gridded Surface-Subsurface Hydrologic Analysis model (GSSHA) in the Kiskatinaw River, located in British Columbia, to analyze temporal dynamics of GW-SW interaction under climate change scenarios. Currently, there is a large uncertainty about how climate change could affect the spatio-temporal patterns of the GW-SW interaction (Saha et al., 2017), making it difficult to use modeling results for water resources management. In addition, there is also the inability of GCMs to adequately represent the variability of precipitation and temperature in a basin. The combined use of an integrated hydrological-hydrogeological modeling approach, under advanced climate change scenarios through corrected regional climate models, will allow a better spatial representation of both surface and groundwater flows and should greatly improve the robustness of projections of the impact of climate change on the GW-SW interaction. The new approaches of integrated modeling at regional scale obtained by coupling hydrological-hydrogeological models (Barthel and Banzhaf, 2016) under climate change scenarios, are essential for the integrated management of water resources in plains (Sophocleous, 2002). GW-SW interaction in plains is important to maintain streamflow and support aquatic ecosystems that are highly dependent on groundwater (Kløve et al., 2014). Coupled modeling under climate change scenarios emerges as a response to understand the spatio-temporal dynamics between surface and groundwater both current and future, since these two components interconnect with each other in the same resource (Winter et al., 1998; Fleckenstein et al., 2010).

GW-SW coupled modeling on a daily scale is necessary as it considers daily rainfall distributions so as not to underestimate future recharge (Taylor et al., 2013). Due to the large amount of information needed to simulate this type of process with coupled models (Kløve et al., 2014; Barthel and Banzhaf, 2016), the mechanisms that cause hydrological changes under climate change scenarios with respect to GW-SW interactions are poorly studied or unknown (Huntington and Niswonger, 2012; Hassan et al., 2014). In addition, there is a great uncertainty in the residence times of groundwater, including local and regional groundwater flows that discharge towards the surface.

The objectives of this study are: (1) to analyze and reproduce on a daily scale the spatio-temporal patterns of the water balance and the GW-SW interactions for the period 2020-2050 under climate change scenarios (one of mitigation and one of non-mitigation of greenhouse gases) for an area of the Pampas plain. The analysis was performed based on a baseline scenario calibrated and validated for the period 2003-2015 (Guevara-Ochoa et al., 2019c) and contrasted with two scenarios of the regional climate model CCSM4 RCP (4.5 and 8.5) for the period 2020-2050; (2) To integrate the annual water balance calculated by SWAT-MODFLOW model with the standardized precipitation index to define and monitor the drought and flood effects on the study area under two climate change scenarios. This study was applied in the upper creek basin of Del Azul with the SWAT-MODFLOW coupled model of Bailey et al. (2016), for the water balance quantification and GW-SW interactions.

## 2. METHODOLOGY

First we describe the study region, and the conceptual flow model in the basin. Then the CMIP5 regional climate model used to quantify future climate projections is detailed, followed by the description of the coupled hydrological-hydrogeological model to reproduce the spatio-temporal patterns of the water balance and the GW-SW interactions for both, the baseline (2006-2015 ) and the RCP (4.5 and 8.5) scenarios of the CCSM4 regional climate model for the period (2020-2050). Finally, the method for the detection of water extremes is described, how the water extremes are analyzed both for the baseline and for future scenarios. Figure 1 shows a flowchart that summarises the applied methodology to evaluate spatio-temporal dynamics of water balance and GW-SW interactions under climate change scenarios.

### 2.1 Study area

The study is applied in the upper creek basin of Del Azul (Figure 2.a). This basin is located at the center of the province of Buenos Aires, Argentina, between 59 ° 46' and

60 ° 08' west longitude and 36 ° 49' and 37 ° 21' south latitude, with an area of 1024 km$^2$. This basin disaggregates in three sub-basins: Azul superior (764 km$^2$), Videla (120 km$^2$) and Santa catalina (140 km$^2$).

The basin has an altitudinal variation of 366 to 142 meters above sea level (see Fig. 2.a). In its upper part it has a hills area that belongs to the Tandilia system (Silva and Amato, 2012), in the middle part of the basin there is an area with undulations and the lower part becomes a plain in transition (Guevara-Ochoa et al., 2019a). According to Guevara-Ochoa et al. (2017) the distribution of the average monthly rainfall in the basin has an isohygro regime with a general tendency of more abundant rains in the north and south, while the intermediate zone of the basin presents a lower rainfall.

81.5% of the land use in the basin is rainfed agriculture (Guevara-Ochoa et al., 2018) with a predominance of the wheat-soybean double crop system (39.4%), soybean 37.2% and corn 5% of the study area.

## 2.2 Conceptual flow model of the upper creek basin of Del Azul

The conceptual flow model of the upper basin of the Del Azul stream is presented in Figure 2.b. To the southeast of the basin, the basement outcrop, which deepens to the north is composed of metamorphic rocks and loess sediments of eolo-volcanic origin of variable granulometry have been accumulated on it. These sediments are part of the Pampeano aquifer and in the northern part of the basin they reach a thickness of about 120 m. These sediments have mantiform calcareous intercalations, known as pedogenic calcretes that confer low permeability to the aquifer.

Groundwater flow in the basin moves from southeast where the Tandilia system is located to the northeast. In the upper part of the basin there is a local groundwater flow that converges to the Azul stream. In the northern zone, the water table changes and a regional groundwater flow of low hydraulic gradients is formed parallel to the stream as shown in Figure 2.b.

In periods of water excess, the surface water flow is characterized by the movement of large water volumes, covering large surface areas with less than one meter depth and with very low energy. In these periods, large flooded areas are generated for long periods of time ranging from a few days to months, which is due to: the low slope of the terrain, a poorly defined drainage network with low hydraulic capacity and the increase in the groundwater table that can reach the surface with an undefined periodicity. The concentrated action of wind deflation in these areas is capable of excavating closed depressions, known as deflation hollows, which play a significant role in water storage and movement, because a flow by connection of surface water storage is generated (Kovacs, 1983; Guevara-Ochoa et al., 2019b). The surface runoff in the basin is not only generated by soil saturation when there is a storm "Hortonian runoff", but is also generated by processes of excess saturation in variable source areas "Dunnean runoff", where the increase in the groundwater level up to the surface of the terrain saturates the soil (Dunne and Black, 1970; Easton et al., 2008; Kumar et al., 2016; Ares et al., 2018).

## 2.3 Regional Climate Model

The data from the Community Climate System Model fourth version (CCSM4) (Gent et al., 2011) were used. According to studies by Yin et al. (2013), Barros et al. (2013), Maenza et al. (2017) and Lovino et al. (2018), the CCSM4 obtained the best performance for the simulation of precipitation and the temperature of the regional climate for both South America and Argentina, so it's expected that this climate model presents less uncertainty for the long-term simulation of both water balance and GW-SW interactions than other models.

The regional climate model CCSM4 data was obtained from the NASA Earth Exchange (NEX) Global Daily Downscaled Projections (GDDP) project. This data set has only two scenarios: one of mitigation (stabilization) of greenhouse gases RCP 4.5 (538 ppm $CO_2$) and one without mitigation of RCP 8.5 gases (936 ppm $CO_2$). Each one of the climatic projections includes the maximum temperature, minimum temperature and rainfall at a daily scale for the 1950-2100 period. The regional climatic data of the NEX-GDDP was based on a statistical scale reduction of global climate models (Tang et al.,

2016) and it has a spatial resolution of 0.25 °. This data set is corrected by Bias Correction using the Spatial Disaggregation (BCSD) method (Wood et al., 2002; Wood et al., 2004; Teutschbein and Seibert, 2012; Thrasher et al., 2012). The purpose of this project is to provide a small-scale data set to assess the impact of climate change at regional and local scales. The data generated with the NEX-GDDP have been used in several studies such as in India (Sahany et al., 2018; Mortuza et al., 2018), Europe (Conceição et al., 2018), China (Yu et al., 2018; Zhang et al., 2018; Huang et al., 2018) and Latin America (Castillo et al., 2018).

### 2.4 Description of the coupled SWAT-MODFLOW model

The SWAT-MODFLOW model is a single executable code developed by the University of Colorado (Bailey et al., 2016; Bailey and Guevara-Ochoa, 2016; Bailey et al., 2017). It consists of a coupling module made in FORTRAN programming language, that uses the code of the Soil and Water Assessment Tool (SWAT 2012; revision 591) which is a continuous semi-distributed hydrological model (Neitsch et al., 2011; Arnold et al., 2012) and the MODFLOW-NWT model, which is a distributed model that solves the three-dimensional groundwater flow equation using finite differences and Newton's method when the flow equation is non linear, in a confined-unconfined aquifer (Harbaugh et al., 2000;McDonald and Harbaugh, 2003). The SWAT model is particularly limited in terms of dealing with groundwater flow, due to its semi-distributed internal nature, while MODFLOW needs net recharge in a distributed form, which is a basic information to model groundwater flow. Therefore, the coupling or integration of these two models allows both groundwater and surface water hydrological components to be reasonably quantified in a single modeling framework, as supported by common model evaluation statistics (see, e.g., Bailey et al., 2016; Wei et al., 2018; Molina-Navarro et al., 2019; Aliyari et al., 2019; Liu et al., 2019; Guevara-Ochoa et al., 2019c).

### 2.5 Standardized Precipitation Index (SPI)

The SPI is an index used mainly to characterize the risk of water extremes such as droughts (Guttman, 1998; Hayes et al, 1999; Penalba and Rivera, 2013) and floods

(Seiler et al., 2002; Du et al 2013). This method has been validated in different places worldwide since only the observed monthly precipitation is needed. The monthly precipitation record is adjusted to a probability distribution and then transformed into a normal distribution (McKee et al., 1993). Since the SPI is normalized, wet and dry periods can be represented in the same way. The SPI can be calculated for different time scales. As we are interested in the spatio-temporal patterns of GW-SW interactions, we employed the 12-month SPI because with this time scale the analysis can be linked to the stream levels, reservoir levels and groundwater head.

### 2.6 Integration of the annual water balance with the SPI

For the current and future evaluation of droughts and floods in plains standardized indices are used but these indices cannot quantify the deficit/excess volume characteristic in a system, which makes them difficult to use in water management. Therefore, these indices have to be used together with the analysis of surface and groundwater volumes, which are obtained through the GW-SW coupled modeling. In this way thresholds can be established in the system to adequately predict water extremes in plains.

## 3. RESULTS

The spatio-temporal comparison between the results of the water balance and the interactions between groundwater and surface water in the upper creek basin of Del Azul is presented below. A baseline scenario is studied for the period (2003-2015) and is contrasted with two futures scenarios of the CCSM4 regional climate model RCP 4.5 and RCP 8.5 for the period (2020-2050). First, the calibration and validation of both surface and groundwater flow of the SWAT-MODFLOW model is presented, then the effect of climate change on precipitation and temperature is analyzed. Next, the surface and groundwater discharge are compared, together with the variation of the water table and the groundwater reserves. Following the anomalies of the GW-SW interactions are analyzed and finally the water extremes (droughts and floods) are evaluated, through the integration of the SPI with the annual water balance calculated by SWAT-MODFLOW for the three scenarios.

### 3.1 Input data, calibration and validation of the coupled SWAT-MODFLOW model

The input data, spatial configuration and calibrated parameters of SWAT, MODFLOW and SWAT-MODFLOW models for upper creek basin of Del Azul are presented in the work by Guevara-Ochoa et al. (2019c).

The model simulation for the base line scenario in the upper creek basin of Del Azul was carried out for the period (2003-2015) using daily time steps. Model calibration was performed for the period 2006-2010 and model validation for 2011-2015. A warm-up period of 3 years (2003-2005) was applied. Three stations with hydrometric information and 9 groundwater monitoring wells were used for model calibration. To adequately model the hydrological processes in plains, it is necessary to consider both the surface flow and the groundwater heads. The hydrograph calculated at the hydrometric stations of: Seminario, Videla and Santa Catalina and groundwater heads calculated with SWAT-MODFLOW at the locations of the 9 observation boreholes are shown in Figure 3. To assess the fit of the SWAT-MODFLOW model, statistical indices were used, such as the NS (Nash and Sutcliffe, 1970), the coefficient of determination ($R^2$). As shown in Table 1, the coupled model satisfactorily represents the processes of daily flow in the basin, since an NS ≥ 0.5 was obtained (Moriasi et al., 2007). Table 2 presents the root mean square error (RMSE) between the observed and calculated values of the groundwater levels. The SWAT-MODFLOW model adequately reproduces the temporal trends and fluctuations observed in both surface and groundwater flows and for both dry and wet periods.

Full details on the spatial coupling, calibration, validation and representation of the water balance and GW-SW interactions of the SWAT-MODFLOW model for the base line scenario in the upper creek basin of Del Azul is presented in Guevara-Ochoa et al. (2019c)

### 3.2 Effect of climate change on precipitation and temperature

Positive trends in precipitation (PCP) and average temperature (TMP) are expected for the upper basin of the Del Azul stream. An increase in average annual rainfall is expected under both future scenarios. RCP 4.5 shows an average annual rainfall increase of 16% (about 160 mm), while RCP 8.5 shows an increment around 20% (about 190 mm). The average annual temperature in the basin shows an increase with the RCP 4.5 of 5.3% (around 0.79 ° C) and with the RCP 8.5 an increment of 6.5% (around 0.97 ° C).

As for the monthly average anomalies of precipitation and temperature positive and negative trends in precipitation are observed for both future scenarios. With RCP 4.5 there are changes between -25.5% to +146% representing absolute variations between -13 to +44 mm. With RCP 8.5, changes between -12% to +124% are expected, i.e. absolute variations from -9 to +74 mm. Positive trends are expected in the summer-autumn periods, mainly in the months of March and June for both future scenarios. In these two months, RCP 4.5 shows increases around 60%, while RCP 8.5 shows increases about 81%. Negative precipitation trends are expected in the winter-spring periods. RCP 4.5 shows decreases of 13%, in August and September, while RCP 8.5 shows reductions larger than 9.6% in the months of August and October.

The monthly average temperature anomaly with RCP 4.5, changes between -4.5% to +25.4%, representing variations between -0.98 to +3.47 °C. With respect to RCP 8.5, changes between -2.6% to +27.4%, representing variations between -0.57 to +3.13 °C are expected. Positive trends are expected for the summer, fall and winter periods that show increases over 18%. In the spring season, negative temperature trends are predicted in which the months of November and December stand out with decreases exceeding 1.6%.

### 3.3 Effect of climate change on the water balance

The comparison of the annual average water balance calculated by the SWAT-MODFLOW for the three scenarios is presented in Figure 4. In the annual average, the evapotranspiration (ET), RCP 4.5 presents an increment of 21% that represent an average increase of 140 mm with respect to the baseline, while RCP 8.5 presents an increment of 23% representing an increase of 160 mm.

The annual average recharge (RCH) presents positive anomalies for both scenarios, with RCP 4.5 it displays increases of 36% representing an average of 18 mm, while for RCP 8.5 it shows a raise of 64% that represents an average of 32 mm. The annual average surface runoff (SURQ) with RCP 4.5 shows an increase of 13%, which represents 6 mm with respect to the baseline, while with RCP 8.5 there is an increment of 31% representing an increase of 14 mm.

The annual average soil moisture (SW) presents negative anomalies for the two RCPs with respect to the baseline scenario. The RCP 4.5 exhibits an average reduction of 8% representing a decrease of 8 mm, while with RCP 8.5 it decreases by 2%.

The anomalies in the monthly average water balance with respect to the baseline scenario are presented in Table 3. When analyzing each component of the water balance, it was found that the actual evapotranspiration for the two RCPs shows an increase for all months of the year. There is only a small negative anomaly for RCP 4.5 in February. Regarding surface runoff and net recharge, positive anomalies occur mainly in late summer and early winter, which is consistent with the increase in rainfall for these periods. As for soil moisture, decreases were found mainly for the spring-summer periods and positive anomalies in the autumn-winter months.

Figure 5 shows the spatio-temporal anomalies of the annual average water balance for the upper creek basin of Del Azul calculated by means of SWAT-MODFLOW model. ET anomalies show positive trends throughout the basin with higher increases in the Azul superior under the two future scenarios. The lowest increases for the two RCPs occur in the Videla and Santa catalina sub-basins. The SURQ presents positive trends mainly in the sub-basins of Azul superior and Santa catalina, while in the Videla sub-basin, negative anomalies occur in some areas.

The soil moisture presents positive anomalies for the two future scenarios mainly in the Santa catalina sub-basin, while in the Azul superior and Videla sub-basins it displays significant reductions in soil moisture, mainly for the RCP 4.5 scenario. The recharge in the basin presents positive anomalies, the larger increases are in the upper part of the basin for RCP 4.5, while RCP 8.5 increases northward where a flatter relief occurs.

### 3.4 Effect of climate change on groundwater discharge and streamflow

The anomaly in the groundwater discharge and streamflow was analyzed at the Seminario station. Figure 6.a shows the comparison of the annual average groundwater discharge for the three scenarios, while the monthly average anomalies are presented in Figure 6.b. Positive anomalies of the groundwater discharge are predicted for the two analyzed future scenarios. RCP 4.5 shows an increment of 20% that represents an average increase of 7 mm with respect to the baseline, while RCP 8.5 shows an increment of 36% that means an increase of 12.6 mm. These positive changes will occur mainly in the autumn-winter period due to the fact that during these times there is a lower actual evapotranspiration in the basin as shown in Table 3.

The comparison of the average annual streamflow is presented in Figure 7.a. According to the two analyzed RCPs, increasing trends of streamflow in the Del Azul stream are predicted. With the baseline, the resulting annual average streamflow rate varies from 1.1 to 6.1 $m^3/s$, with an annual average for the 2006-2015 period of 3.1 $m^3/s$. The RCP 4.5 presents a variation in the annual average streamflow of 1.7 to 6.8 $m^3/s$, with an annual average for the 2020-2050 period of 3.6 $m^3/s$. The RCP 8.5 shows a variation of 1.7 to 6.9 $m^3/s$, with an annual average for the 2020-2050 period of 4 $m^3/s$.

The anomalies in the average monthly streamflow are presented in Figure 7.b. Streamflow increasing trends appear mainly in summer, autumn and beginning of winter for the two RCP, while a decreasing trend is observed in the months of May, August and September. With RCP 4.5 there are variations in the average monthly streamflow between -1.8 and +2.2 $m^3/s$, while with RCP 8.5 differences of -1.3 and +4.3 $m^3/s$ are expected. Figure 7.c shows an analysis of the streamflow return periods calculated using the Gumbel methodology (1941) for the three scenarios at the watershed outlet point. The probability of flooding events will increase with respect to the baseline for both RCPs.

### 3.5 Effect of climate change on the variation of the water table and groundwater reserves

Figure 8 shows the spatio-temporal anomaly of the annual average water table for the two future analyzed scenarios with respect to the baseline. There are increases in groundwater heads mainly to the southeast and northwest of the basin under the two RCPs. In the southwest of the basin there are decreases in the groundwater level, that are much more pronounced for the RCP 4.5 scenario (Figure 8.a). Towards the Videla sub-basin there are also decreases in the water table but they are more prominent with RCP 8.5 as seen in Figure 8.b.

Figure 9 shows the variation of groundwater reserves for the three scenarios. There is a clear increasing trend in reserves for the two RCPs. In Figure 9.a the baseline shows a maximum groundwater reserve of 13.9 $Hm^3$, the RCP 4.5 of 14.1 $Hm^3$ and with the RCP 8.5 of 14.3 $Hm^3$. The anomaly of the monthly average groundwater reserve in the upper creek basin of Del Azul is presented in Figure 9.b. There are increments in the reserves throughout the year. With the RCP 4.5 it increases by 1.2%, while with the RCP 8.5 there are increases of 1.4%. The largest increases occur in the summer, autumn and early winter periods with RCP 4.5 while for RCP 8.5 this happens in autumn and winter.

### 3.6 Effect of climate change on spatio-temporal interactions GW-SW

The annual average anomaly of the GW-SW interaction in the Azul superior sub-basin is as follows: the discharge from the aquifer to the stream will increase by 5% with RCP 4.5, while with RCP 8.5 the increment will be as much as 24%. On the opposite side, the recharge from the stream to the aquifer, is expected to increment with by 12% with RCP 4.5, while it decreases by 5% with RCP 8.5. In the Videla sub-basin, the discharge of the aquifer to the stream will increment by 66% with RCP 4.5, while it will increase by 57% with RCP 8.5. On the other hand, the recharge from the stream to the aquifer is predicted to increase by 36% with RCP 4.5, while with RCP 8.5 the increment will be 14%. In the Santa catalina sub-basin, the discharge from the aquifer to the stream will increase by 12% with RCP 4.5, while it will decrease by 5% with RCP 8.5. On the opposite side, the recharge from the stream to the aquifer is expected to decrease in the two future scenarios, by 84% with RCP 4.5 and by 87% with RCP 8.5.

Figure 10 shows the average monthly comparison of the GW-SW interaction for the three scenarios in each sub-basin. In Figure 10.a the comparison of the GW-SW interaction in the Azul superior sub-basin is presented, in Figure 10.b the Videla sub-basin and finally in Figure 10.c shows the interaction in the Santa catalina sub-basin. Negative values represent discharge from the aquifer towards the stream, positive values represent recharge of the stream towards the aquifer. For the 3 sub-basins there are increases in the discharge of the aquifer to the stream for the two RCPs. The recharge of the stream to the aquifer will increase in the sub-basins Azul superior and Videla with the exception of the month of May. In contrast, the Santa catalina sub-basin shows a considerable reduction, with both future scenarios.

Figure 11 shows the average spatial patterns of the GW-SW interaction for the 1655 river cells of the SWAT-MODFLOW model for the three scenarios. The baseline scenario has a tendency to discharge groundwater to the streams in the upper and middle part of the basin. While towards the upper part of the Santa catalina sub-basin where the bedrock outcropping is located, the opposite occurs, i.e. the stream tends to recharge the aquifer due to the small thickness of the aquifer. The increase in groundwater levels with RCP 4.5 and RCP 8.5 will cause GW-SW exchanges to be reversed in some sectors of the stream by increasing the number of cells that discharge groundwater into the stream as shown in red cells (Figure 11). These anomalies occur mostly in the Santa catalina sub-basin, in the upper part of the Videla sub-basin and in the lower part of the Azul superior sub-basin. The average daily variation of the GW-SW interaction in the river cells for the three scenarios in the summer, autumn, winter and spring periods is shown in Figures 12, 13, 14 and 15 respectively. The discharge from the aquifer to the stream for the baseline scenario presents higher values in the summer-winter season and lower values in autumn, while for the two future scenarios, higher discharges are observed for the autumn-winter season and lower in summer. With respect to the recharge from the stream to the aquifer for the three analyzed scenarios, higher values in the autumn season are reached, while in spring the lowest recharge values are found.

### 3.7 Effect of climate change on water extremes

One of the main problems in the Pampas region is the alternation of wet and dry periods over time. To analyze the variability of the water extremes (droughts and floods) for the three scenarios, the calculation of the annual water balance by SWAT-MODFLOW model and the SPI is made (Figure 16). For the baseline scenario (Figure 16.a) we can highlight the extreme drought that occurred in 2008 during this period, the storage of water in the soil is very low, due to the high evapotranspiration and the rainfall deficit. From the annual rainfall of 574 mm of water, 568 mm were evapotranspired, about 99% of the total precipitation. This extreme drought affected the province of Buenos Aires, because the rainfall decreased by around 40%. A number of head cattle died, the soybean crop was reduced by 30%, the wheat crop was reduced by 20% and losses exceeding USD $ 700 million were estimated for what the government declared the “Agricultural Disaster” (Scarpati and Capriolo, 2013). The year 2012 is also highlighted as an extremely wet period. According to the analysis of the water balance, the precipitation was 1314 mm, of which 160 mm were surface runoff (12% of this year total precipitation). 45% of the province of Buenos Aires area was flooded, there were large agricultural losses exceeding USD $ 500 million due to the fact that precipitation increased by around 60% this year (Guevara-Ochoa et al., 2019b).

Figure 16.b shows the annual water balance and the SPI calculated for the RCP 4.5 scenario. Extreme droughts could occur during the years (2024-2025, 2038-2039, 2041-2042 and 2049), and floods the years (2027, 2029, 2031-2033 and 2047-2048).

With RCP 8.5 (Figure 16.c), extreme droughts may happen in the years (2020, 2024, 2036-2039 and 2048-2050) and floods in the years (2021-2022, 2032-2034, and 2044-2046). In the periods with extreme droughts, a decrease in precipitation down to values below 725 mm is observed in the annual water balance. This precipitation is not enough to satisfy evapotranspiration, which is why water deficit situations are generated. Regarding the situations of water excess, an increase in rainfall above 1100 mm is observed in the annual water balance, which generates an average surface runoff of 110 mm, representing from 10 to 14% of the total precipitation of the year.

According to the SPI analysis with RCP 4.5 scenario, there will be a higher frequency of droughts, but they will be short-term, compared to RCP 8.5, which has a lower frequency of droughts, but they are more extensive over time. In contrast, the wet periods showed lower frequency, but more extension over time with RCP 4.5 and they occur with greater severity in the period 2020-2033, unlike RCP 8.5 scenario, which presents wet periods with high frequency and lower extension in the time, but from 2033 the severity of the wet periods increases.

## 4. DISCUSSION

The coupled GW-SW modeling under climate change scenarios allows to understand the temporal dynamics of both current and future between groundwater and surface water, especially in plains, because in these systems there are low hydraulic gradients and the GW-SW exchange mechanisms depend largely on the groundwater flow. It should be pointed out that in plain landscapes, vertical water movements predominate and according to Guevara-Ochoa et al. (2019b) there is a strong correlation between shallow groundwater with the water balance processes on the surface, since the water table can rise on the surface with an undefined periodicity. All the aforementioned factors make hydrological-hydrogeological coupled models essential to generate useful alternatives to guide water planning and management practices in plains.

However, the hydrological modeling under climate change scenarios is subject to uncertainties from many sources such as the predictions of General Circulation

Models: structure, type, initial conditions, methods of downscaling, etc. (Kienzle et al., 2012). Not only the uncertainty associated with climate models can lead to large differences in future climate scenarios, but also the selection of different hydrological modeling approaches, input data, model structure, and parameters (Lespinas et al., 2014). These uncertainties can significantly affect the accuracy of a model to predict the response to climate change and, consequently, the effectiveness of joint strategies for water management. To amend this situation, it is important to quantify the uncertainties of both surface and groundwater flows to have an idea of their magnitude. The combined use of an integrated hydrological-hydrogeological modeling approach with the SWAT-MODFLOW model and an appropriate calibration approach, under advanced climate change scenarios through a corrected regional climate model, will allow a better spatial representation of surface and groundwater flows and should greatly improve the robustness of projections of the impact of climate change on the GW-SW interaction. To reduce uncertainties in the face of climate change, future studies require to assess the robustness of SWAT-MODFLOW model in plains when it is subjected to a wider range of natural climate variability, including the addition of more climate change scenarios. In addition, future studies should contemplate the use and comparison with fully coupled approaches for surface water and groundwater simulation because, as stated before, surface water processes are highly influenced by groundwater in plains.

To calibrate GW-SW coupled models, it is essential to consider both the surface flow and the groundwater head simultaneously. Until now, most applications with these kinds of models only calibrate surface flows (Goderniaux et al., 2009; Guevara-Ochoa et al. 2019c). In addition, it is important to validate the GW-SW interactions calculated by this type of models to reduce uncertainties in modeling with the aid of new orientations or technologies through the use of distributed fiber-optic temperature sensing (Sebok et al., 2013; Hare et al., 2015), electromagnetic filtration meters (Rosenberry et al., 2013), geophysical characterization (McLachlan et al., 2017 ), conservative tracers (Bertrand et al., 2014), tracers with stable isotopes (Ala-aho et al., 2015) and tracers with radioactive isotopes (Ortega et al., 2015). These approaches allow identification of dynamics such as the exchange of flow patterns, residence time, seasonal variability of the GW-SW interaction, groundwater discharge and recharge zones, but in a local scale.

At present, the SWAT-MODFLOW model has only been applied under climate change scenarios in the Little Smoky watershed located in Alberta, Canada (Chung et al., 2019). This study does not apply a joint calibration technique of the SWAT-MODFLOW model in transitory state, thus the uncertainty for the evaluation of the impact of climate change on GW-SW interactions can be large. In this sense, the study by Guevara-Ochoa et al. (2019c) gives some guidelines about the calibration of these models. In previous studies, procedures for the calibration and validation of this type of models are not described. This is very important because the methodology can be applied to other sites.

Based on the results of this study and the few applications that have been made with coupled models to analyze the impact of climate change on GW-SW interactions (Sibeck et al., 2007; Saha et al., 2017; Chung et al., 2019), it is acknowledged that future climate induces changes in the groundwater head, modifying in turn the groundwater discharge towards to stream and vice versa.

In addition, we use the water balance results of the coupled model together with the standardized precipitation index to define and monitor the drought and flood effects on the study area under two climate change scenarios. The monitoring and risk assessment of droughts and floods in plains requires the use of coupled models because the impact of the water extremes depends largely of the variation on groundwater levels.

For the period 2020-2050 in the upper creek basin of Del Azul, there are trends in rainfall increase between 16% to 20% and a temperature increase between 5% to 7%. These results are similar to those reported by Maenza et al. (2017). Future water balance shows an increase in most of the components. Increments trends are expected in the actual evapotranspiration between 21% to 23%, runoff between 13% to 31%, recharge between 36% to 64%, however soil moisture decreases is expected to be between 2% to 8%. With respect to streamflow, increment are expected between 20% to 36%, in agreement with Saurral et al. (2013) and Camilloni et al. (2013) for the period 2020–2050. The increase is expected for both mean streamflows and peak flows. Regarding the interactions of the GW-SW fluxes, the average annual discharge of the aquifer to the stream is expected to increment between 5% to 24%, while recharge from the stream to increase between 5% to 12%. Concerning the SPI related to the water balance for the period 2020-2050, alternations of both the time and the length of dry and wet periods are expected for the two scenarios. With RCP 4.5 low frequency of wet episodes, but with a greater severity and permanence in time in contrast to RCP 8.5 that presents less frequency in dry periods, but with higher permanence and severity.

From an ecological point of view, the impact of climate change will depend on the scale of the groundwater system and the interaction of GW-SW (Tóth, 1963). In the upper part of the basin a larger impact is expected for the two RCPs in vegetation, benthic fauna and nutrient concentration, since the discharge of this area depends on changes in the seasonality of the recharge, because the flow transit times are smaller. In contrast, the lower part of the basin will be less affected by changes in the seasonality of the recharge because the flow transit times are longer (Waibel et al., 2013; Kløve et al., 2014).

The results of this study could not be compared with other similar studies in Latin America nor in plains due to the fact that the GW-SW coupled modeling under climate change scenarios has not been applied in these regions; Therefore, this study can provide some hints to modelers, as well as decision makers.

## 5. CONCLUSIONS

The coupled modeling between the SWAT and MODFLOW models under climate change scenarios has led us to analyze the future spatio-temporal dynamics of surface runoff, actual evapotranspiration, recharge, water table variation, groundwater reserves, aquifer discharge, GW-SW interactions, as well as the variation of wet and dry periods for the upper creek basin of Del Azul.

This study advises that the use of GW-SW coupled models under climate change scenarios for the integral management of water resources in plains is essential, since there is a strong interaction between groundwater and surface waters, where the variation in groundwater level plays very role in the response to droughts and floods.

The results showed that climate change has important effects on the spatio-temporal patterns of groundwater showing monthly, seasonal, and annual changes. This study gives evidence that groundwater in the upper creek basin of Del Azul contributes significantly to streamflow for both the baseline scenario and the two considered climate change scenarios.

This study proposes a novel approach for the evaluation of water extremes in plains, since through coupled modeling under climate change scenarios integrated with climate indices such as SPI, the droughts and floods in plains can be predicted and monitored. From this study, it becomes evident, that in the future the same problem that the region currently faces, which is the alternation of floods and droughts over time, will be present. However, according to the analysis, when periods of drought occur the ecosystem may be more resilient due to increases in the level, reserves and discharge of groundwater.

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**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

**Figure 1**. Flow chart of the applied methodology.

**Figure 2.** a. Upper creek basin of Del Azul, b. Conceptual flow model of the upper creek basin of Del Azul.

**Figure 3.** Transient calibration of streamflows in three stations and groundwater levels nine monitoring boreholes. Calculated values (red) and observed (blue).

**Figure 4.** Annual average comparison of the water balance. Baseline (red color), RCP 4.5 (green color) and RCP 8.5 (blue color). Actual evapotranspiration (ET), recharge (RCH), surface runoff (SURQ), soil moisture (SW).

**Figure 5**. Spatio-temporal annual average anomaly of the water balance. Actual evapotranspiration (ET), surface runoff (SURQ), soil moisture (SW), recharge (RCH).

**Figure 6**. Groundwater discharge in the upper creek basin of Del Azul. **a.** Annual average groundwater discharge comparison, **b.** Monthly average anomaly of the groundwater discharge with respect to the baseline. Baseline (red color), RCP 4.5 (green color) and RCP 8.5 (blue color).

**Figure 7**. Streamflow at the watershed outlet point of the upper creek basin of Del Azul, **a.** Annual average streamflow comparison, **b.** Monthly average anomaly of the streamflow with respect to the baseline, **c.** Comparison of the return periods for the three scenarios. Baseline (red color), RCP 4.5 (green color) and RCP 8.5 (blue color).

**Figure 8**. Spatio-temporal annual average anomaly of the groundwater level. **a.** RCP 4.5 y **b.** RCP 8.5.

**Figure 9.** Variation of the groundwater reserve in the upper creek basin of Del Azul. **a.** Annual average. **b.** Monthly average anomaly of the groundwater reserve with respect to the baseline. Baseline (red color), RCP 4.5 (green color) and RCP 8.5 (blue color).

**Figure 10.** Monthly average comparison of exchange between groundwater and surface water for sub-basin. Negative values represent discharge of the aquifer towards the stream, positive values represent recharge of the stream towards the aquifer.

**Figure 11.** Spatial variation of the GW-SW interactions in the river cells for the three scenarios proposed.

**Figure 12.** Spatio-temporal average monthly of the GW-SW interaction in the river cells for the summer period for the three scenarios.

**Figure 13.** Spatio-temporal average monthly of the GW-SW interaction in the river cells for the autumn period for the three scenarios.

**Figure 14.** Spatio-temporal average monthly of the GW-SW interaction in the river cells for the winter period for the three scenarios.

**Figure 15**. Spatio-temporal average monthly of the GW-SW interaction in the river cells for the spring period for the three scenarios.

**Figure 16.** Alternation of wet and dry periods in the upper creek basin of Del Azul, **a.** baseline, **b.** RCP 4.5 and **c.** RCP 8.5. In the Figures located on the left margin: PCP (blue bars), ET (green line), RCH (red line), SURQ (orange line) and SW (yellow line).

**Table 1.** Statistical analysis between the observed and calculated daily flows in three control points, for SWAT-MODFLOW model.

| Station | Statistical | Statistical comparison for the whole (2006-2015) | Statistical comparison of calibration period (2006-2010) | Statistical comparison of validation period (2011-2015) |
|---|---|---|---|---|
| Seminario | NS | 0.6 | 0.67 | 0.59 |
| | $R^2$ | 0.6 | 0.68 | 0.59 |
| Videla | NS | 0.46 | 0.42 | 0.46 |
| | $R^2$ | 0.46 | 0.43 | 0.47 |
| Santa Catalina | NS | 0.35 | 0.37 | 0.31 |
| | $R^2$ | 0.5 | 0.43 | 0.5 |

**Table 2**. Root mean square error between the groundwater levels observed and calculated by the SWAT-MODFLOW model.

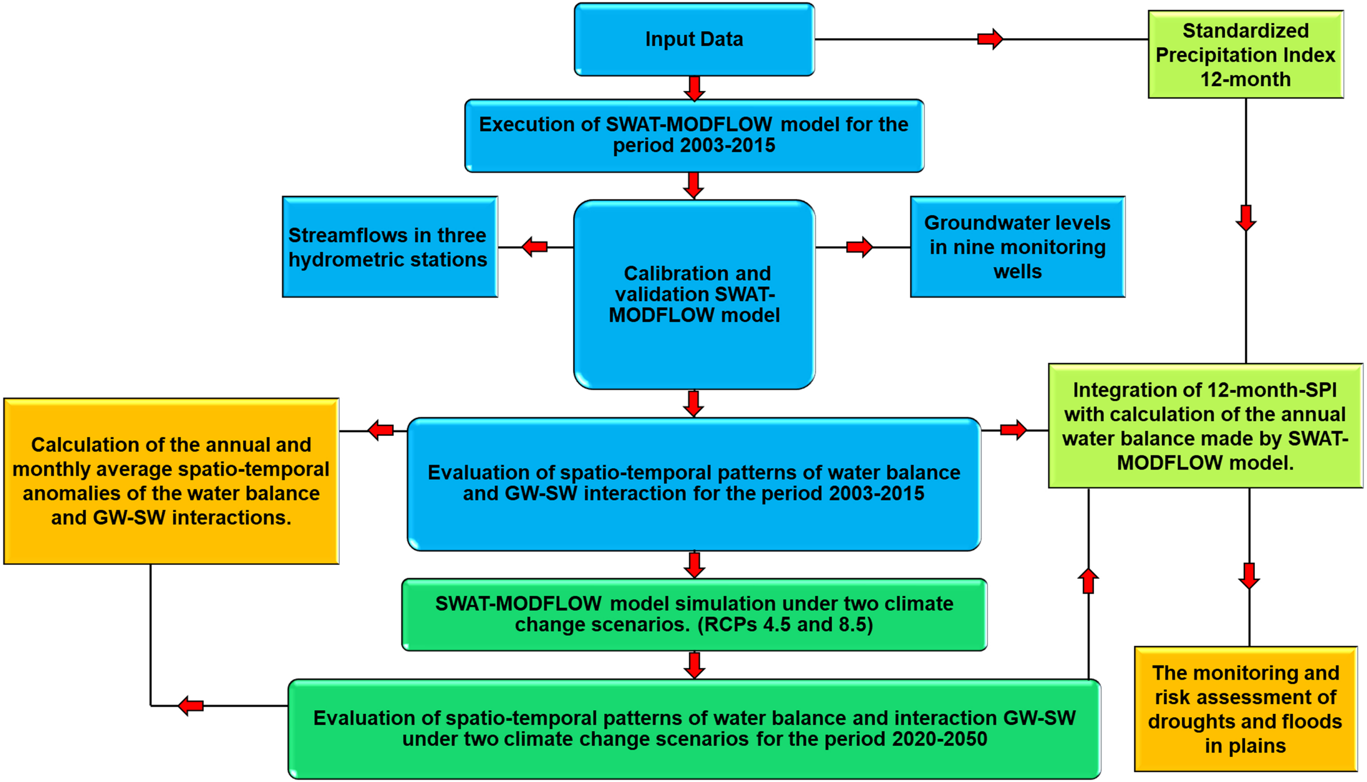
| Wells | RMSE (m) |
|---|---|
| Loma pampa | 0.87 |
| La firmeza | 1.02 |
| El cortijo | 2.17 |
| El cerrito | 1.49 |
| Candentey | 1.24 |
| Santa Maria | 1.54 |
| La nutria | 0.82 |
| Vivarelli | 0.75 |
| Chillar | 1.13 |

**Table 3.** Annual average anomaly of the water balance (RCP-baseline). Precipitation (PCP), Temperature (TMP), Actual evapotranspiration (ET), recharge (RCH), surface runoff (SURQ), soil moisture (SW).

| **Variable** | | **PCP (mm)** | | **TMP (°C)** | | **ET (mm)** | | **SURQ (mm)** | | **RCH (mm)** | | **SW (mm)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RCP** | | **4.5** | **8.5** | **4.5** | **8.5** | **4.5** | **8.5** | **4.5** | **8.5** | **4.5** | **8.5** | **4.5** | **8.5** |
| **Summer** | **January** | 1.39 | -2.83 | 1.12 | 1.26 | 4.88 | 1.05 | -1.19 | -0.88 | -1.35 | -1.45 | -9.81 | -12.97 |
| | **February** | 12.77 | 17.75 | 2.35 | 2.50 | -1.79 | 0.76 | 3.63 | 2.42 | 4.00 | 1.47 | -4.13 | -2.54 |
| | **March** | 40.10 | 74.37 | 3.47 | 3.13 | 9.70 | 14.69 | 7.00 | 12.93 | 7.92 | 15.13 | -7.20 | 4.32 |
| **Autumn** | **April** | 0.14 | 25.21 | 2.16 | 2.26 | 18.83 | 24.05 | -0.78 | 4.27 | -1.33 | 6.09 | 0.85 | 28.87 |
| | **May** | 1.37 | 1.43 | 2.31 | 2.58 | 18.27 | 20.43 | -5.69 | -4.44 | 0.70 | 2.64 | -7.64 | 15.50 |
| | **June** | 44.09 | 37.55 | 1.92 | 2.10 | 7.57 | 8.32 | 2.90 | 5.96 | 11.01 | 11.23 | 1.42 | 11.52 |
| **Winter** | **July** | 20.00 | 8.02 | 0.97 | 1.68 | 9.16 | 10.09 | 5.48 | 0.96 | 2.34 | 1.26 | 11.17 | 18.15 |
| | **August** | -13.98 | -5.26 | 0.94 | 1.31 | 13.85 | 14.40 | -5.59 | -4.99 | -2.27 | 0.64 | 9.38 | 14.76 |
| | **September** | -7.86 | -1.40 | -0.18 | 0.10 | 13.29 | 15.83 | -0.59 | -1.17 | -1.60 | -1.65 | -5.03 | 5.29 |
| **Spring** | **October** | 11.74 | -9.34 | -0.26 | -0.18 | 21.31 | 19.94 | 1.23 | -0.42 | 0.11 | -1.76 | -16.39 | -15.79 |
| | **November** | 4.48 | -4.61 | -0.30 | -0.49 | 14.46 | 8.65 | -0.06 | -0.37 | 0.13 | -0.36 | -31.55 | -37.69 |
| | **December** | 22.26 | 28.13 | -0.98 | -0.57 | 11.55 | 9.73 | -1.35 | -0.90 | -1.65 | -1.37 | -29.49 | -33.06 |

**Highlights**

- GW-SW coupled modelling is essential to water management in plains
- The climate change alters the spatio-temporal patterns of the GW-SW interaction
- Groundwater level plays a very important role in the maintenance of ecosystems



Input Data
Standardized Precipitation Index 12-month
Execution of SWAT-MODFLOW model for the period 2003-2015
Streamflows in three hydrometric stations
Calibration and validation SWAT-MODFLOW model
Groundwater levels in nine monitoring wells
Integration of 12-month-SPI with calculation of the annual water balance made by SWAT-MODFLOW model.
Calculation of the annual and monthly average spatio-temporal anomalies of the water balance and GW-SW interactions.
Evaluation of spatio-temporal patterns of water balance and GW-SW interaction for the period 2003-2015
SWAT-MODFLOW model simulation under two climate change scenarios. (RCPs 4.5 and 8.5)
Evaluation of spatio-temporal patterns of water balance and interaction GW-SW under two climate change scenarios for the period 2020-2050
The monitoring and risk assessment of droughts and floods in plains

Figure 1

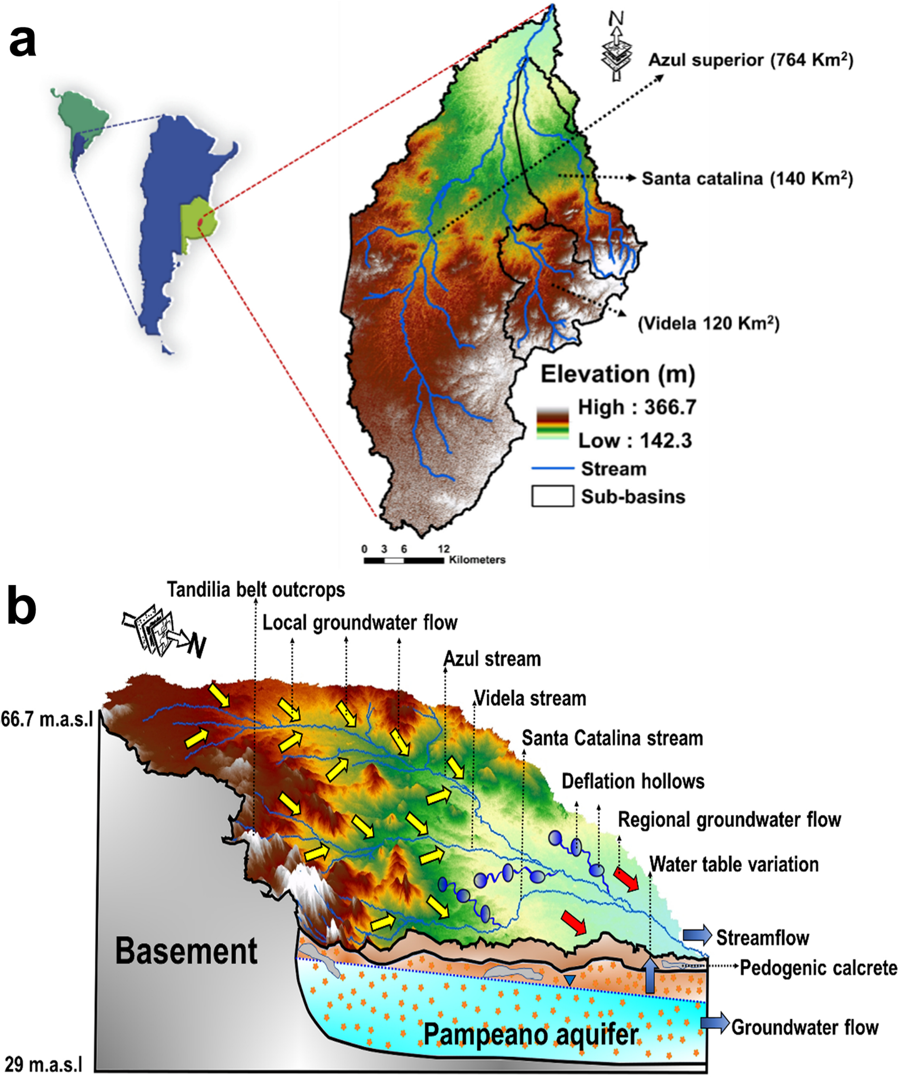

a
N
Azul superior (764 Km²)
Santa catalina (140 Km²)
(Videla 120 Km²)
Elevation (m)
High : 366.7
Low : 142.3
Stream
Sub-basins
0 3 6 12
Kilometers
b
N
Tandilia belt outcrops
Local groundwater flow
Azul stream
Videla stream
Santa Catalina stream
Deflation hollows
Regional groundwater flow
Water table variation
366.7 m.a.s.l
Streamflow
Pedogenic calcrete
Basement
Groundwater flow
Pampeano aquifer
29 m.a.s.l

Figure 2

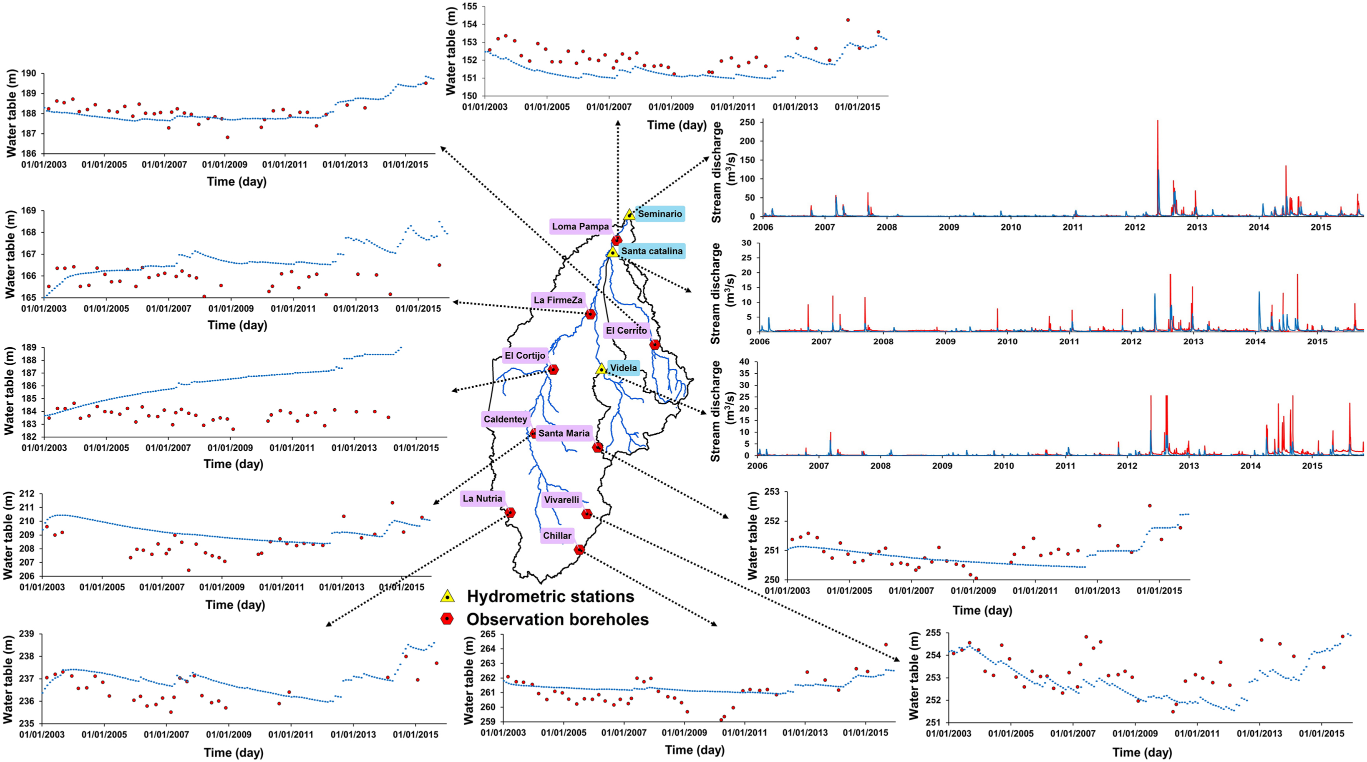

Loma Pampa
Seminario
Santa catalina
La FirmeZa
El Cerrito
El Cortijo
Videla
Caldentey
Santa Maria
La Nutria
Vivarelli
Chillar
Hydrometric stations
Observation boreholes
Water table (m)
Time (day)
Stream discharge (m³/s)
01/01/2003
01/01/2005
01/01/2007
01/01/2009
01/01/2011
01/01/2013
01/01/2015
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015

Figure 3

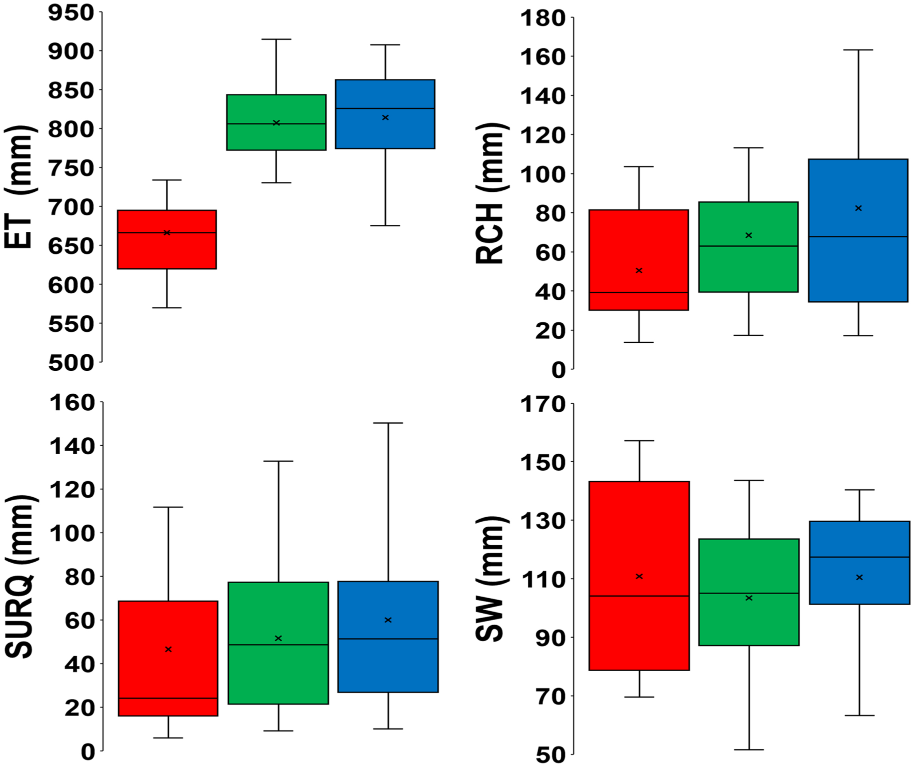

950
900
850
800
750
700
650
600
550
500
ET (mm)
180
160
140
120
100
80
60
40
20
0
RCH (mm)
160
140
120
100
80
60
40
20
0
SURQ (mm)
170
150
130
110
90
70
50
SW (mm)

Figure 4

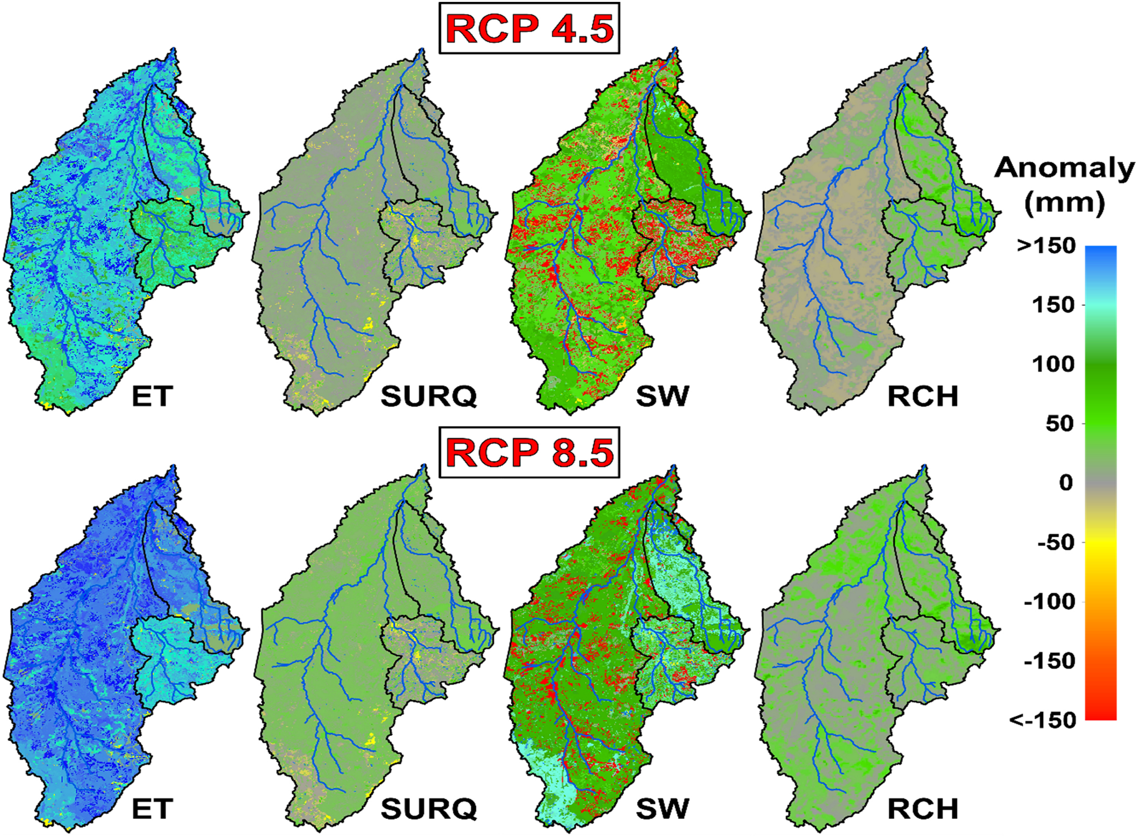

RCP 4.5
ET
SURQ
SW
RCH
RCP 8.5
ET
SURQ
SW
RCH
Anomaly (mm)
>150
150
100
50
0
-50
-100
-150
<-150

Figure 5

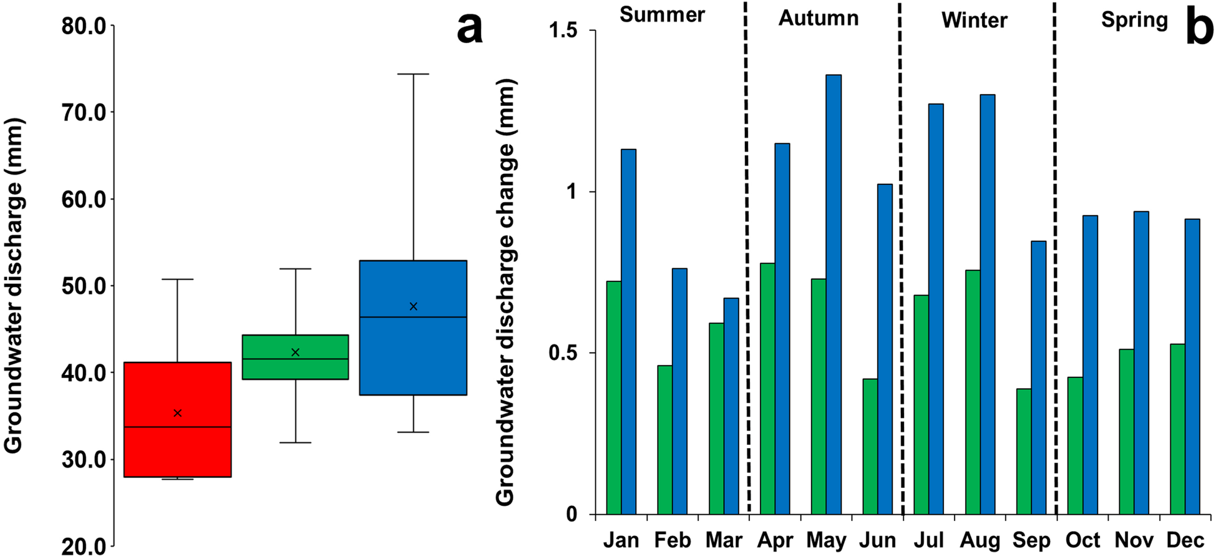

a
Groundwater discharge (mm)
80.0
70.0
60.0
50.0
40.0
30.0
20.0
b
Summer
Autumn
Winter
Spring
Groundwater discharge change (mm)
1.5
1
0.5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 6

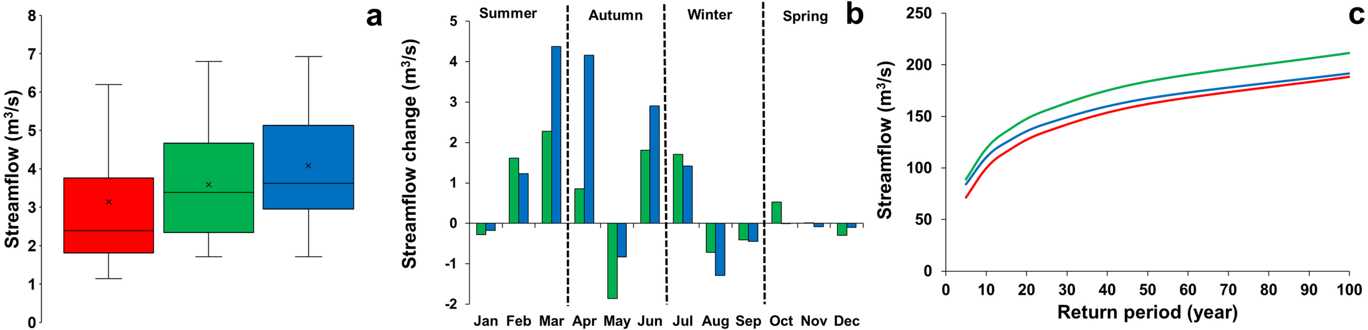

a
Streamflow (m³/s)
0
1
2
3
4
5
6
7
8
b
Summer
Autumn
Winter
Spring
Streamflow change (m³/s)
-2
-1
0
1
2
3
4
5
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
c
Streamflow (m³/s)
0
50
100
150
200
250
0
10
20
30
40
50
60
70
80
90
100
Return period (year)

Figure 7

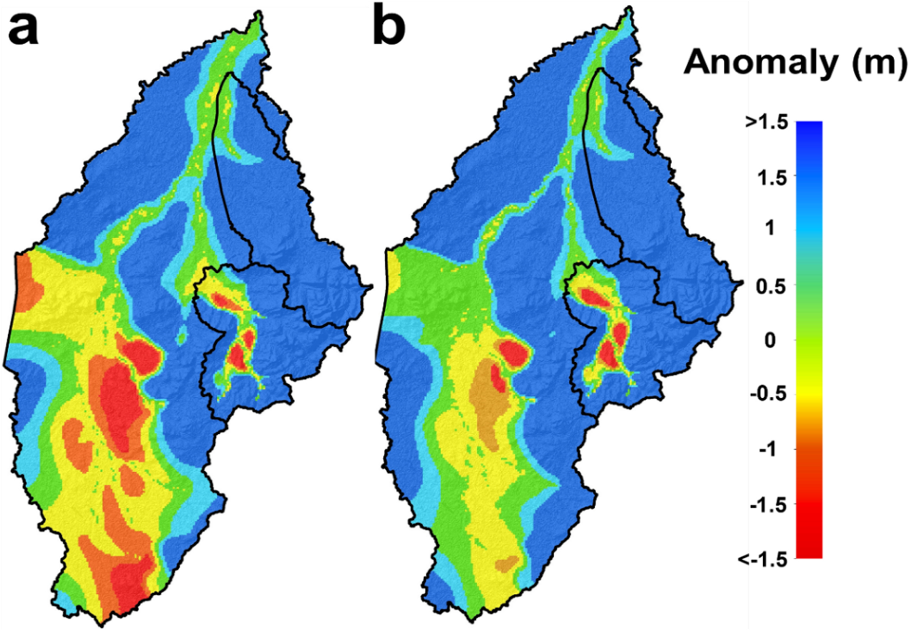


Figure 8

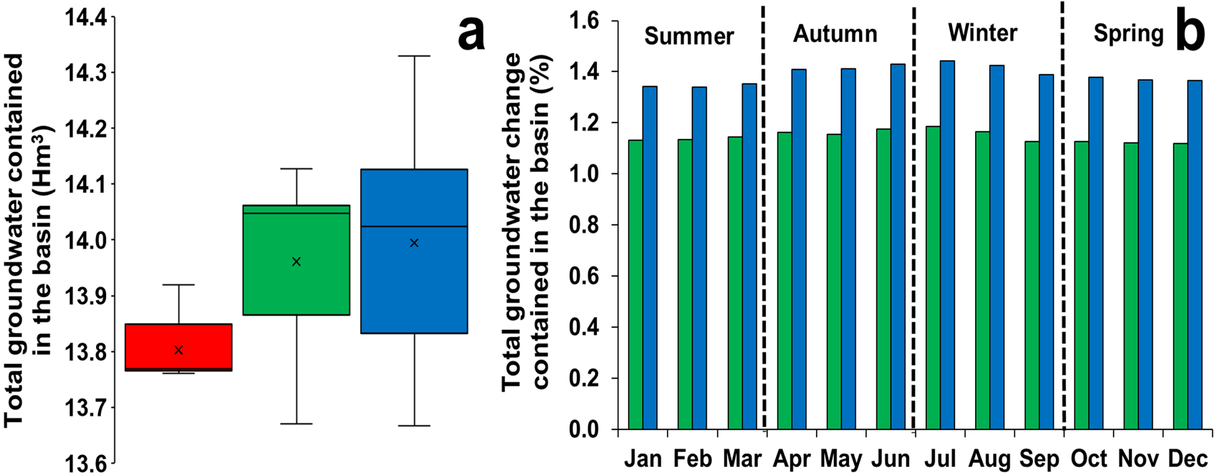

a
Total groundwater contained in the basin (Hm³)
14.4
14.3
14.2
14.1
14.0
13.9
13.8
13.7
13.6
b
Total groundwater change contained in the basin (%)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Summer
Autumn
Winter
Spring
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 9

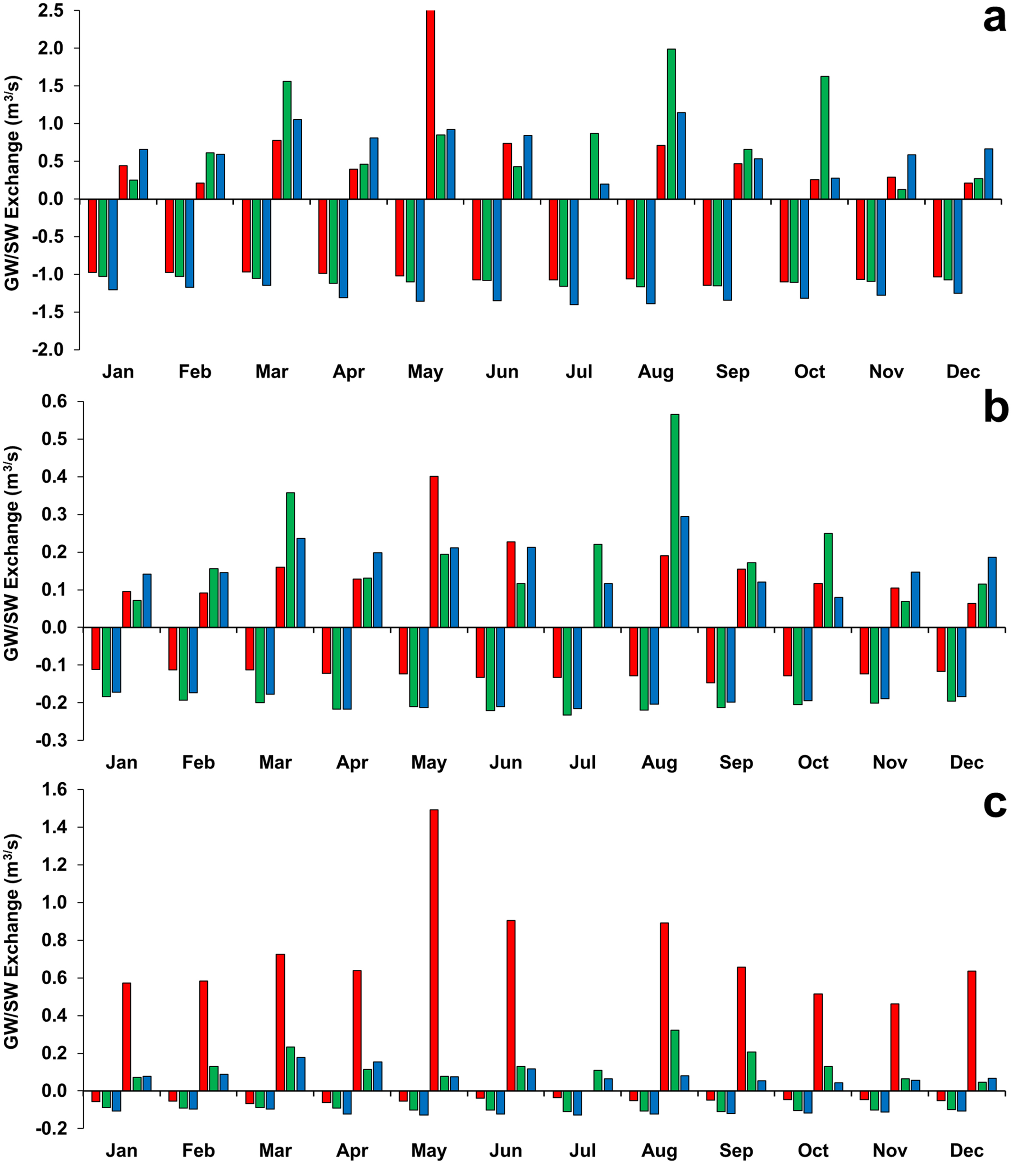

a
b
c
GW/SW Exchange (m³/s)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 10

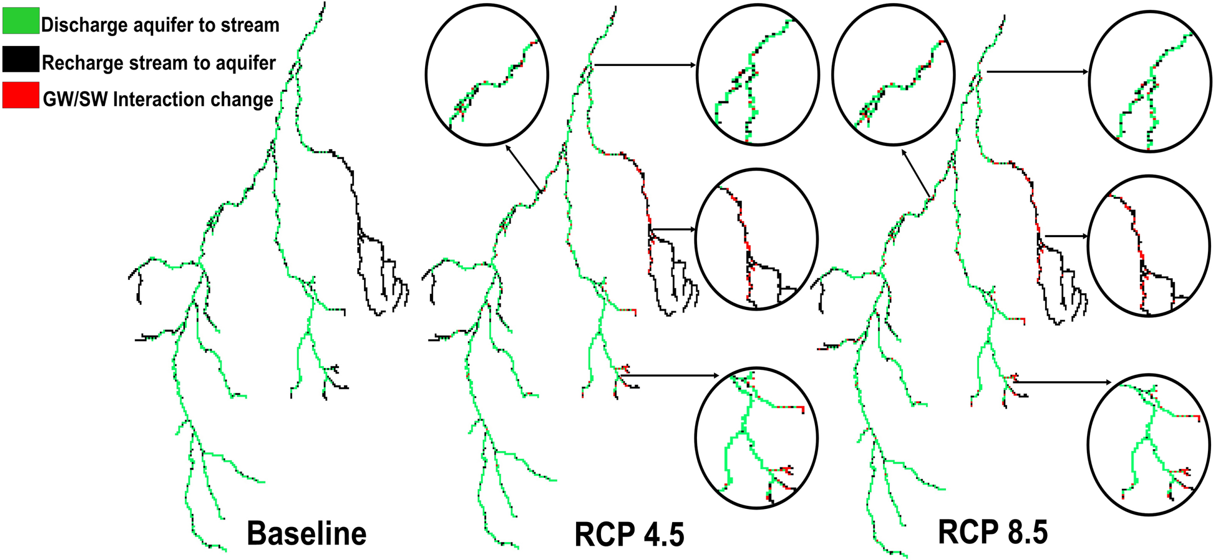

Discharge aquifer to stream
Recharge stream to aquifer
GW/SW Interaction change
Baseline
RCP 4.5
RCP 8.5

Figure 11

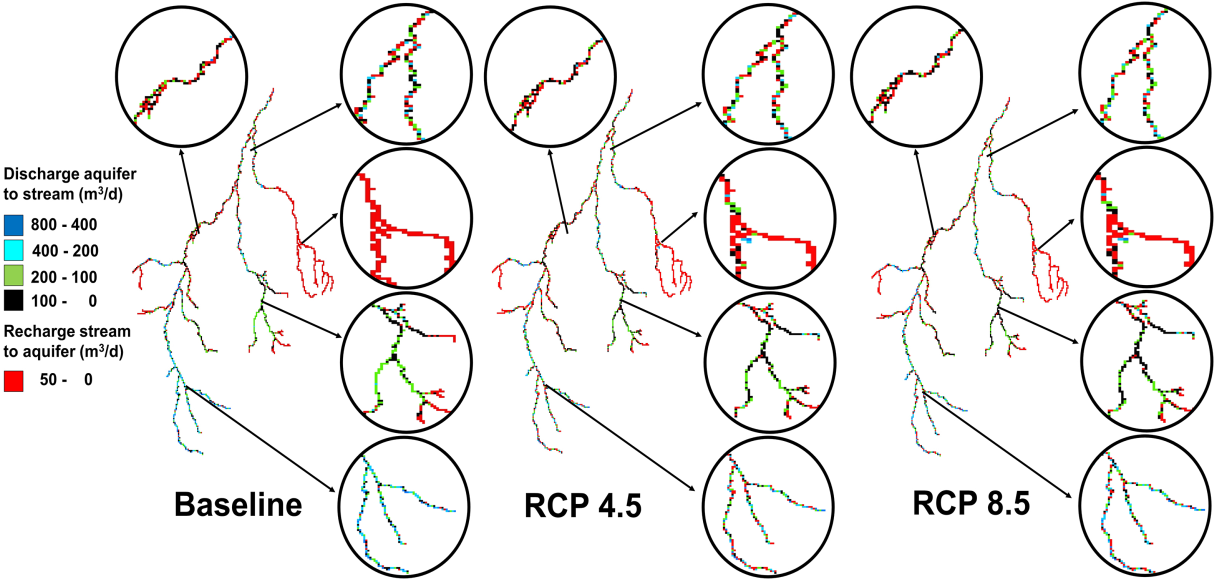

Discharge aquifer to stream ($m^3/d$)
800 - 400
400 - 200
200 - 100
100 - 0
Recharge stream to aquifer ($m^3/d$)
50 - 0
Baseline
RCP 4.5
RCP 8.5

Figure 12

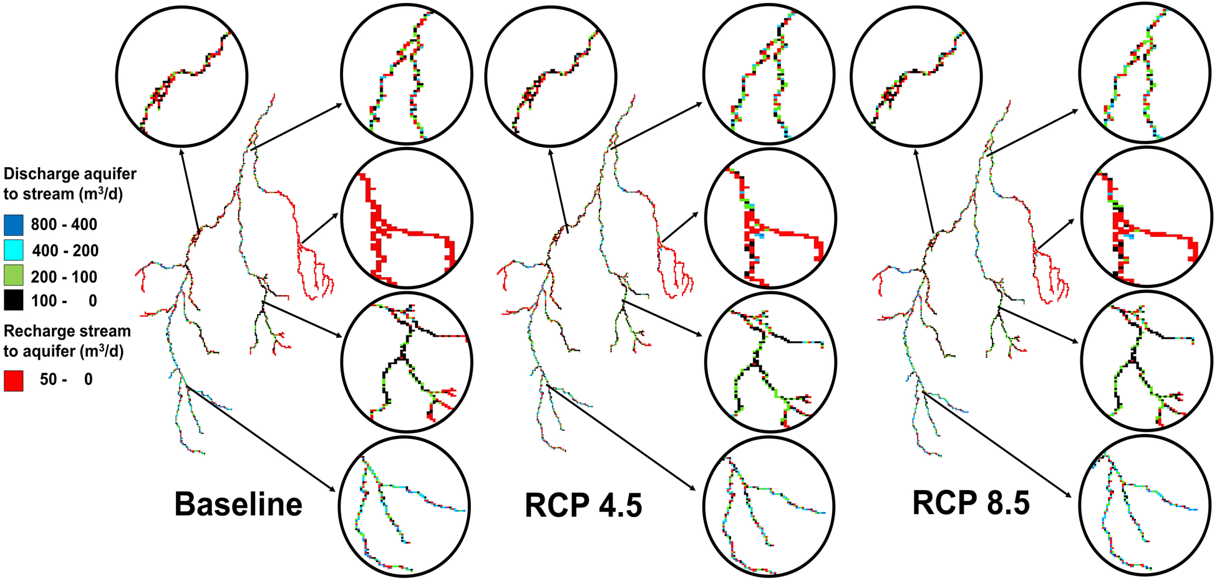

Discharge aquifer to stream (m³/d)
800 - 400
400 - 200
200 - 100
100 - 0
Recharge stream to aquifer (m³/d)
50 - 0
Baseline
RCP 4.5
RCP 8.5

Figure 13

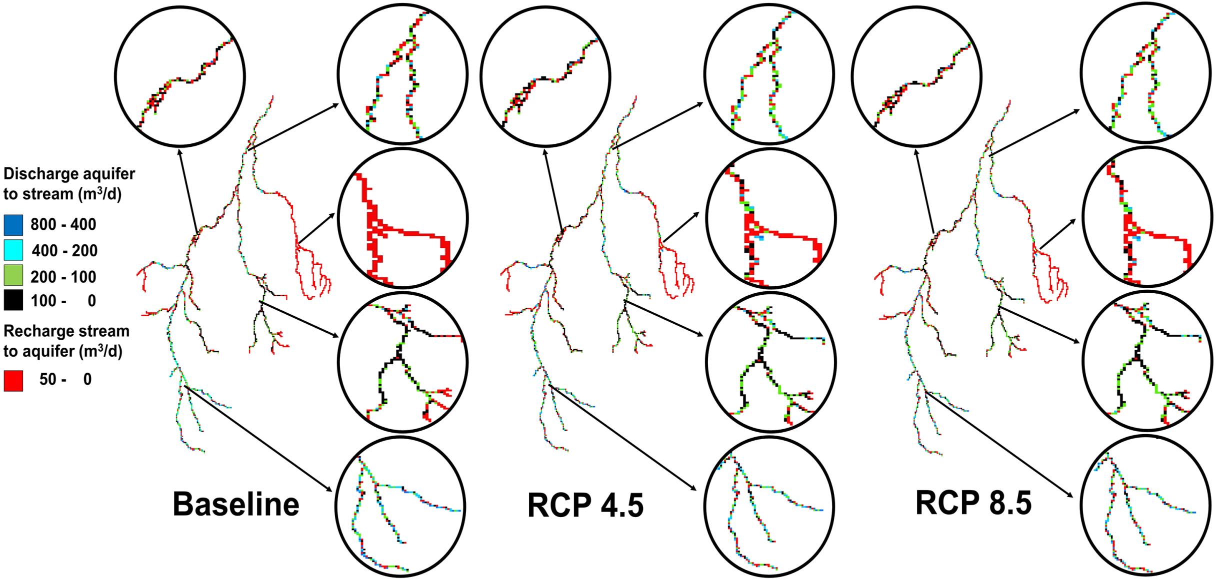

Discharge aquifer to stream (m³/d)
800 - 400
400 - 200
200 - 100
100 - 0
Recharge stream to aquifer (m³/d)
50 - 0
Baseline
RCP 4.5
RCP 8.5

Figure 14

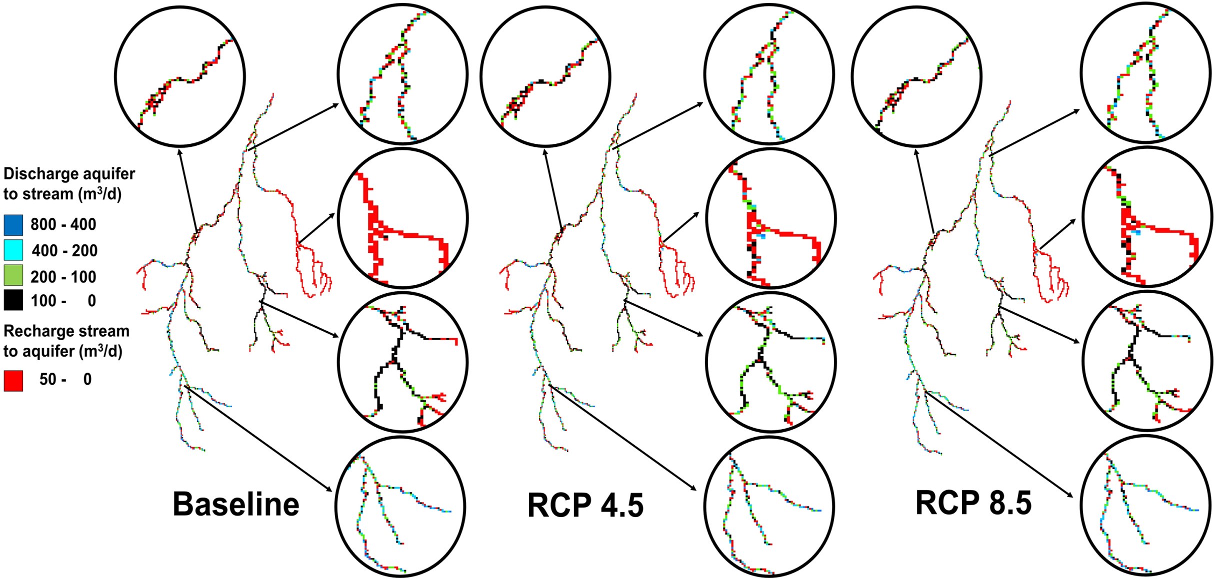

Discharge aquifer to stream ($m^3$/d)
🟦 800 - 400
🟦 400 - 200
🟩 200 - 100
⬛ 100 - 0
Recharge stream to aquifer ($m^3$/d)
🟥 50 - 0
Baseline
RCP 4.5
RCP 8.5

Figure 15

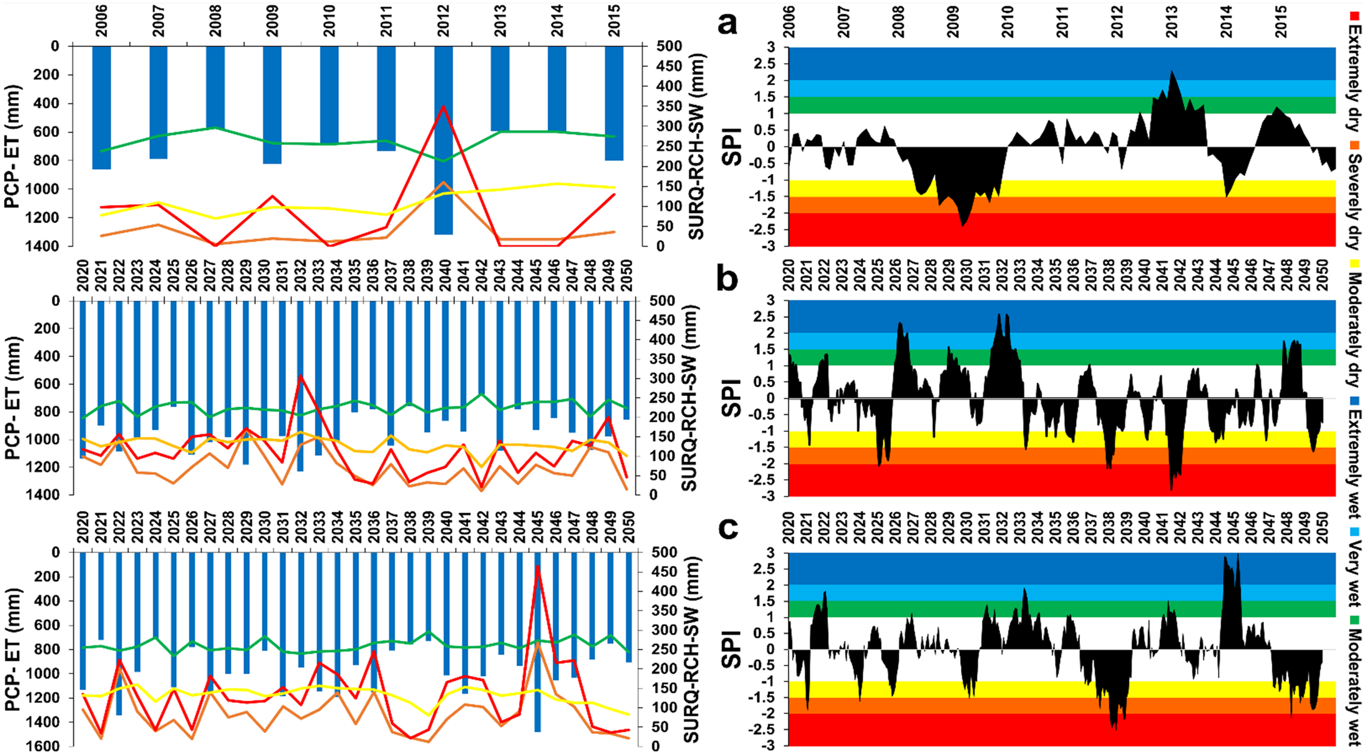

a
b
c
PCP- ET (mm)
SURQ-RCH-SW (mm)
SPI
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2020
2030
2040
2050
■ Extremely dry
■ Severely dry
■ Moderately dry
■ Extremely wet
■ Very wet
■ Moderately wet

Figure 16