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Discussions

Integrated assessment of the impact of climate and land use changes on groundwater quantity and quality in Mancha Oriental (Spain)

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Abstract

Climate and land use change (global change) impacts on groundwater systems cannot be studied in isolation, as various and complex interactions in the hydrological cycle take part. Land-use and land-cover (LULC) changes have a great impact on the water cycle and contaminant production and transport. Groundwater flow and storage are changing in response not only to climatic changes but also to human impacts on land uses and demands (global change). Changes in future climate and land uses will alter the hydrologic cycles and subsequently impact the quantity and quality of regional water systems. Predicting the behavior of recharge and discharge conditions under future climatic and land use changes is essential for integrated water management and adaptation. In the Mancha Oriental system in Spain, in the last decades the transformation from dry to irrigated lands has led to a significant drop of the groundwater table in one of the largest groundwater bodies in Spain, with the consequent effect on stream-aquifer interaction in the connected Jucar River. Streamflow depletion is compromising the related ecosystems and the supply to the downstream demands, provoking a complex management issue. The intense use of fertilizer in agriculture is also leading to locally high groundwater nitrate concentrations. Understanding the spatial and temporal distribution of water availability and water quality is essential for a proper management of the system. In this paper we analyze the potential impact of climate and land use change in the system by using an integrated modelling framework consisting of the sequentially coupling of a watershed agriculturally-based hydrological model (SWAT) with the ground-water model MODFLOW and mass-transport model MT3D. SWAT model outputs (mainly groundwater recharge and pumping, considering new irrigation needs under changing ET and precipitation) are used as MODFLOW inputs to simulate changes in groundwater flow and storage and impacts on stream-aquifer interaction. SWAT and MODFLOW outputs (nitrate loads from SWAT, groundwater velocity field from MODFLOW) are used as MT3D inputs for assessing the fate and transport of nitrate leached from the topsoil. Results on river discharge, crop yields, groundwater levels and groundwater nitrate concentrations obtained from simulation fit well to the observed values. Three climate change scenarios have been considered, corresponding to 3 different GCMs for emission scenario A1B, covering the control period, and short, medium and long-term future periods. A multi-temporal analysis of LULC change was carried out, helped by the study of historical trends by remote sensing images and key driving forces to explain LULC transitions. Markov chains and European scenarios and projections have been used to quantify trends in the future. The cellular automata technique was applied for stochastic modeling future LULC maps. The results show the sensitivity of groundwater quantity and quality (nitrate pollution) to climate and land use changes, and the need to implement adaptation measures in order to prevent further groundwater level declines and increasing nitrate concentrations. The sequential modelling chain has been proved to be a valuable assessment and management tool for supporting the development of sustainable management strategies.

1 Introduction

Future climate and land use changes will modify the current hydrological processes in the Mediterranean Europe and consequently impact its groundwater systems quantity and quality. While climate change will alter hydrological conditions due to changes in the major climate variables (air temperature, precipitation, and evapotranspiration), groundwater resources will be impacted by climate change through their interaction with surface water bodies (e.g., lakes and rivers), but also indirectly through the recharge process (Jyrkama and Sykes, 2007). Therefore, quantifying the climate change impacts on groundwater requires the assessment of climate change impacts in the hydrological variables that interact with groundwater systems (groundwater recharge, pumping, pollutant leaching, etc.). However, adequate assessments regarding those variables are difficult to obtain, as they depend on

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multiple physical factors subject to high heterogeneity. Expected consequences of climate change in Mediterranean regions will include lower water tables and decreased groundwater discharge, which may reduce stream baseflow and impact water supply and groundwater dependent ecosystems (Klove et al., 2013). These effects will be higher in heavily committed groundwater bodies. Predicting the behavior of recharge and discharge conditions under future climatic and land use changes (LUC) is essential for integrated water management and adaptation.

Numerical simulation models provide the most adequate way to estimate the impacts of climate and land use changes on groundwater systems. Numerical hydrological models have been used to estimate climate and land use change impacts on the surface processes of a watershed (Mango et al., 2011; Shrestha et al., 2013; Ma et al., 2014). Those models are also useful tools to deal with the uncertainties associated to hydrological processes (Kingston and Taylor, 2010; Xu et al., 2011). However, in order to assess the impacts of the estimated future conditions (climate, land use, water demands, adaptation, etc.) on groundwater systems, some forms of coupling between hydrological and hydrogeological processes must be used (Holman et al., 2012; Pulido-Velazquez et al., 2014). However, the full coupling of numerical sub-models to groundwater models remains a challenge, as sometimes requires assumptions that hinder detailed assessments about certain variables. For that, conceptual models or frameworks, whose combination is also known as sequential coupling, can be used as an alternative to adequately assess climate and global change impacts in both hydrological and hydrogeological processes.

The main goal of this study is the assessment of climate and land use change impacts in the Mancha Oriental system (Spain). The approach used consists on the sequential coupling of the hydrological model SWAT, the groundwater flow model MODFLOW, and the groundwater transport model MT3DMS. Section 2 presents the case study, describes the methodology used and provides information about the calibration and validation processes followed. Section 3 analyses the results obtained under climate change scenarios, discussing the main findings and the novelty features found in the results. Section 4 summarizes the conclusions that can be drawn from the case study and the methodology used, and clearly states the contribution of this work to the climate and land use change impact assessment.

2 Materials and methods

2.1 Case study: the Mancha Oriental system in Spain

The Mancha Oriental system (MOS) is located in an area of semiarid climate in the southwestern part of the Jucar River Basin, mainly within the Albacete province, Spain (Fig. 1). The study area covers about 8400 km^2 consisting on plains surrounded by ranges that delimitate the borders between the Jucar, the Tajo (Tagus), the Guadiana and the Segura river basins. The northern area is dominated by three main rivers: the perennial Jucar river and the seasonal Valdemembra and Ledaña rivers. The southern portion is a former endorheic plain which was artificially connected to the Jucar river in the XIX century by the Maria Cristina Channel. The main land use of the area is agriculture, being especially characteristic the circular-shaped groundwater-irrigated crop areas, devoted mainly to corn, wheat and barley. A detailed geological description can be found in Sanz (2003) and Sanz et al. (2009, 2011).

In the last 25 years, an important transformation from dry to irrigated lands has taken place in La Mancha, in central Spain, with the development of an intensive agriculture that represents one of the main factors in the current economic development of the region. More than 80 000 ha of lands equipped with modern technologies are currently irrigated, regarded as one of the most important in Spain, with most of these lands depending on groundwater. The main crops are wheat, corn, barley and alfalfa, with a significant share of the crop production still dependent of CAP subsidies, and with some growing areas of vegetables and vineyard. The aquifer has been subject to intensive groundwater pumping during the last decades (since the 70's), which has resulted in a continued drop of groundwater levels, especially in its southern zone where irrigated crops concentrate (Sanz et al., 2011). In 2009 the groundwater body was declared in bad status by the Jucar River Basin Authority (Confederacion Hidrografica del Jucar, CHJ) due to the unbalance between groundwater renewable resources and abstractions. The water table decline has caused the extinction of wetlands and lagoons formerly located in the zones close to the city of Albacete, such as the Acequion or Salobral lagoons. The stream-aquifer interaction with the Jucar river has been also substantially affected: formerly the aquifer discharge was added to the Jucar river flow, while today the river recharges the Mancha Oriental aquifer (Sanz et al., 2011). This has led to a significant depletion of streamflow in the Jucar river with important environmental consequences (such as the drying of a significant reach of the Jucar River in the summers of 1994 and 1995), provoking conflicts with downstream uses. The Mancha Oriental quantitative status of the groundwater body is in risk, but it is failing in meeting the EU Water Framework Directive requirement of a good chemical status, because of the increasing groundwater nitrate pollution due to the intensive use of fertilizers in agriculture. Nitrate concentrations in the aquifer system have locally reached values up to 125 $\mathrm{mg\,L^{-1}}$ (Moratalla et al., 2009), far away of the standard of 50 $\mathrm{mg\,L^{-1}}$. Different strategies for controlling groundwater nitrate pollution in the area have been proposed, including fertilizer quotas and fertilizer taxes (Peña-Haro et al., 2010).

In order to deal with these issues, the Jucar River Basin Authority (CHJ) is proposing, in the framework of the new Jucar River Basin Management Plan (PHJ), actions for a more sustainable management of Mancha Oriental aquifer including demand reduction (mainly by irrigation efficiency improvement), some substitution of water source from groundwater to Jucar inflow, and an intense research on the aquifer behavior (CHJ, 2009b). The control of groundwater abstractions and water use by remote sensing and personal inspections (Castaño et al., 2010), and collective actions through groundwater user associations (Lopez-Gunn, 2003) are helping to stabilize groundwater abstractions. In this context climate change is likely to exacerbate the groundwater management issues, as decreasing groundwater recharge is likely to increase the pressure on the quantity and quality status of the Mancha Oriental aquifer.

2.2 Climate change scenarios

The climate change scenarios rely on the SRES A1B emission scenario for Europe. Climate data predicted were obtained from three different GCM drivers: CNRM (National Centre of Meteorological Research), ECHAM5-r3 (European Centre for Medium-Term Weather Forecast), and HADCM3-Q0 (Hadley Centre). These scenarios have been downscaled using the SMHIRCA 3.0 RCM (Regional Climate Model) of the Swedish Meteorological and Hydrological Institute (SMHI). This study is one of the 16 case studies in the GENESIS Project, which deals with climate and land use impacts on groundwater and dependent ecosystems. For all case studies, the same dynamic downscaling method was applied by the GENESIS Project partner SMHI, which provided the meteorological forcing time series for the climate change scenarios (Kjellstrom et al., 2011; Nikulin et al., 2011). Daily time series of the relevant meteorological variables were provided for the 1961–2100 period, corresponding to a control period (1961–1990), and the short-term (2010–2040), medium-term (2040–2070), and long-term (2070–2100) scenarios.

A comparison was made for the control period (1961–1990) between the climate scenarios and the historical time series, in order to check if they were reproducing the observed patterns in the main statistics of temperature and precipitation. Historical data was obtained from the Spanish Meteorological Agency (AEMET). The comparison of monthly averaged means and standard deviations for maximum temperature and precipitation can be seen in Fig. 2. With regard to maximum temperatures, the ECHAM5 scenario is the one whose monthly means better resemble the historical pattern, being the CNRM scenario the one located further from the observations. Regarding standard deviations of monthly temperature, all scenarios showed lower values, especially during summer, with no remarkable differences between them. Figure 2 also shows differences on the mean precipitation monthly pattern, especially in

April and September. No climate change model was adequately reproducing the winter observed precipitation. CNRM and HADCM3 scenarios seemed to be more close to the observed data from January to August, but the ECHAM5 scenario appeared to be more adequate after August. The same situation was found regarding the standard deviation comparison between scenarios and observed data.

The temperature and precipitation series for the three climate scenarios are shown in Fig. 3, which depicts the 10 year moving average values. There is a steady increase in temperature, with a decreasing trend in precipitation, more accused in the long-term. The other meteorological variables provided (relative humidity, solar radiation and wind speed) did not show any clear trend. Finally, CO_2 concentrations were obtained from the carbon cycle models ISAM and BERN, both used in the IPCC Fourth Assessment Report climate projections. A concentration value of 421.67 ppmv was considered for the short-term period, while concentrations of 531.67 and 665.50 ppmv were considered for the mid and long-term respectively.

2.3 Land use change projections

Land use change is a complex process dominated by a large number of variables. In order to adequately assess the effects of the global change, land use change must be added to the changes related to climatic variables, coupling the climate change scenarios with the projected land use changes, whose driving forces belong to different categories of social, economic, political, human and natural factors. Four land use change scenarios (LUCS) have been considered in this case study, each one with regard to different time periods

- LUCS-1: short-term scenario based on a multi-temporal analysis of historical LUC changes and their key drivers, future EU scenarios and a combination of LUC allocation techniques.

- LUCS-2: medium-large term scenario considering persistence of the main LUC evolution trend observed in the last 20 years, being characterized by a change from non-irrigated crops to irrigated areas, partially supported by the subsidies coming from the EU Common Agricultural Policy (CAP). LUCS-1 results are used as the basis for the projection.

- LUCS-3: medium-large term scenario considering the policies recently set up by the Mancha Oriental Farmers' User Association (JCRMO), and potential energy and water price increases, the latest coming from the application of the pricing policies required by the EU Water Framework Directive (WFD). These driving forces would force LUC causing a decrease in the irrigated area, which would return to be operated without irrigation. LUCS-1 and LUCS-2 results are used as the basis for the projection.
- LUCS-4: no land use change. This scenario has been formulated to be compared with the previous ones, making possible the identification of synergic effects between climate and land use changes. It has been defined by all the three time periods, and its land use pattern corresponds to the current one.

For the short-term LUC scenario, a multi-temporal analysis of LULC change (Oñate-Valdivieso and Bosque Sendra, 2010) is carried out, studying historical trends (using remote sensing images; Calera et al., 1999) and key driving forces for explaining LULC transitions. A spatially explicit model was use for that purpose, the Land Change Modeler Module (Eastman, 2006). This model provides a set of tools to perform historical analysis, trends and future scenario projections based on GIS techniques.

Data sets include series of remote sensing images, driving forces and scenarios from regional projects. LULC images from CORINE Land Cover Project were used as baseline (1990, 2000 and 2006; Fig. 4).

Corine Land Cover (CLC) images have 100 m resolution and provide a LULC classification scheme widely used in all Europe (Feranec et al., 2010). Based on these images, historical analysis was performed to identify, evaluate and select the most significant LULC transitions. To develop LULC future scenarios all transitions need to be modeled according to the most likely driving forces. Driving forces were chosen from the available literature and statistical data with spatial representativeness (INE, 2011) from a wide range of biophysical, social, economic and political factors. A set of 20 driving forces were finally selected and spatially represented in GIS format (raster), using a Cramer's V test to select relevance of each driving force in every transition with a threshold value of 0.15 (Eastman, 2006). Table 1 shows the driving forces selected.

Markov chains and European scenarios and projections (Eururalis 2.0 and Image 2.2) have been used to quantify trends in the future. The EU project Eururalis 2.0 (Klijn et al., 2005) was chosen because its focus on rural areas. Eururalis developed Europe's future land-use scenarios for 2010, 2020 and 2030 (Westhoek et al., 2006; Rienks, 2007); all available on-line to assist decision makers on the most likely scenarios of the Common Agricultural Policy (CAP). Predictions of LULC future scenarios are obtained through a combination of suitability maps and transition probability matrices extracted from all data sets described. Multicriteria Evaluation (MCE) method using Artificial Neural Networks (ANN) was performed to obtain suitability maps (Oñate-Valdivieso and Bosque Sendra, 2010) where change could happen for each transition selected. Multilayer Perceptron (MLP) with three layers, backpropagation of error algorithm and the sigmoid transformation function were used to train every ANN. Transition probability matrices (TPM), based on Markov's chain theory, express the probability of one LULC to change to another in a determined period of time. TPM were obtained from historical data and from Eururalis land-use scenarios. Applying the Markov process theory to the historical data (2000–2006), transition matrices for the 2000–2010 period were derived. For 2000–2020 period, transition matrices were obtained from the tendencies showed by the Eururalis scenario. Finally, cellular automata algorithm fed with suitability maps of every transition and transition probability matrices produced the final suitability maps and land-use scenarios. A detailed explanation of the methodology can be found in Henriquez-Dole (2012).

2.4 Modelling framework

Numerical simulation models provide the most effective way to estimate the impacts of climate and land use changes on water quantity and quality of groundwater systems. In order to assess the impacts of the assumed future conditions (climate, land use, water demands, adaptation, etc.) on groundwater systems, some forms of coupling need to be assumed between those forcings and hydrogeology. This requires the practical integration of operational models that not only represent all of the relevant processes in the hydrologic system in a physically meaningful way, but are also simple enough to allow large-scale basin-wide applications (Sophocleous and Perkins, 2000).

Different processes of the hydrologic cycle need to be modeled and integrated. The characterization of the land phase of the hydrological cycle is essential for assessing the impacts of climate and land use changes on the temporal and spatial distribution of groundwater recharge and contaminant loadings. Moreover, in basins in which irrigated agriculture is a dominant land use, as in our case study, we also need to involve calculations of plant growth and crop yields, crop ETs, irrigation applications and groundwater pumping changes. Another additional requirement in this case was to include simulation of nitrate leaching from the crop fertilization, in order to assess impacts of future scenarios on groundwater nitrate pollution. The tool selected for this purpose was SWAT. The Soil and Water Assessment Tool (SWAT) is one of the most widely used watershed model worldwide, applied extensively to a broad range of scales and environmental conditions (Gassman et al., 2007, 2014).

While the distributed SWAT model is capable of properly reproduce the spatio-temporal distribution of groundwater recharge rates (at the spatial resolution given by their hydrologic response units), its groundwater module is lumped; therefore, distributed parameters (such as hydraulic conductivity and storage coefficient) cannot be represented, and the approach and is very limited for expressing the spatial distribution of groundwater levels and groundwater flow dynamics (Kim et al., 2008).

Different SWAT-MODFLOW integration and coupling approaches have been proposed to deal with that issue (Sophocleous and Perkins, 2000; Kim et al., 2008).

The proposed modelling framework sequentially couples the SWAT watershed model with the fully-distributed groundwater model MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), and finally the multispecies transport model MT3D model (Zheng and Wang, 1999) for simulating the fate of the nitrate leached into the aquifer system. In this approach, SWAT model outputs are used as MODFLOW inputs, and SWAT and MODFLOW outputs are used as MT3D inputs. Figure 5 shows the links among the models.

2.5 Watershed modelling

SWAT is a physically-based basin-scale continuous time hydrological model that operates focused on predicting land use management impacts on hydrology, sediments, agricultural production and chemical yields (Arnold et al., 1998; Neitschet al., 2005; Gassman et al., 2007). Calculations are done on a daily basis, offering results at both daily and monthly time scales.

The SWAT interface tool in ArcGIS (ArcSWAT), is used to develop the model input datasets. The SWAT model requires a wide range of data depending on the modeled processes. It firstly divides the study area into different sub-basins regarding the river network. The sub-basins are further discretized into Hydrologic Response Units (HRUs) consisting of homogenous soil, slope, and land use combinations (equal combinations associated to different sub-basins remain as separated HRU's). At the HRU scale, SWAT simulates the processes specified by the user, being able to perform calculations related to hydrological processes, sediment transport, nutrient cycle, soil temperature, crop growth, and pesticides management (Arnold et al., 1999).

Water balance is the driving force behind all the processes in SWAT because it impacts plant growth and the movement of sediments, nutrients, pesticides, and pathogens (Arnold et al., 2012). SWAT calculates the hydrology at each HRU by means the water balance equation, which includes daily precipitation, evapotranspiration, percolation, runoff, and return flow components. Every process included in the model can be solved using different methodologies. In our case, the surface runoff derived from daily rainfall is estimated with a modification of Soil Conservation Service (SCS) curve number method (included in the model). The percolation through each soil layer is predicted using storage routing techniques combined with crack-flow model (Arnold et al., 1995). The evapotranspiration was estimated using Hargreaves formula. Finally, the flow routing in the river channels is computed using the variable storage coefficient method (Williams, 1969).

SWAT uses a single plant growth model to simulate all types of land cover and differentiates between annual and perennial plants. The plant growth model is used to assess removal of water and nutrients from the root zone, transpiration, and biomass/yield production (Arnold et al., 2012). Planting, harvesting, tillage passes, nutrient and pesticide applications can be simulated for each cropping system with specific dates or with a heat unit scheduling approach. The irrigation applications can be simulated for specific dates or with an autoirrigation routine, which triggers irrigation events according to a water stress threshold.

The nitrogen (N) processes and soil pools simulated by SWAT are described in Neitsch et al. (2002). SWAT monitors five different pools of N in the soil. Two of them are inorganic forms of N: NO_3 and NH_4^+. The other three are organic forms of N: fresh organic N associated with crop residue and microbial biomass, and the active and stable organic pools associated with the soil humus. SWAT is capable to simulate N fixation by legumes, fertilizer inputs and nitrogen in the rainfall as well.

The SWAT model for the Mancha Oriental system (MOS) has been fed with the following inputs, divided into four categories: DEM, climate data, soil data and land use data.

The Digital Elevation Model (DEM) used in SWAT has a 670 m × 670 m cell size, being used to delimitate a total amount of 35 sub-basins (using the ArcSWAT watershed delineator tool) and to derive the slope map.

Daily-scale historical climate data records have been obtained from the Climatic Research Unit (CRU) website (available at: http://badc.nerc.ac.uk/data/cru/); the Spanish Meteorological Agency (AEMET) raster database (available at: http://escenarios.aemet.es/); and data records obtained in several stations within the case study area from the AEMET and the Integrated Service of Irrigation Advising (SIAR). Air relative humidity, wind speed and solar radiation were only completely provided in the Albacete – Los Llanos weather station. In order to complete these data records, a spatial correlation analysis has been carried out, using the available data to obtain correlation coefficients between cells and obtaining the unrecorded variable's values as function of the recorded ones by the application of regression analysis.

The soil type data has been obtained using the FAO's Digital Soil Map of the World. In the case study area Glegyc Cambisol (Bg), Chromic Luvisol (Lc), and Calcic Cambisol (Bk) soil types have been found. The appearance of these soil types in the SWAT soil database has been checked and, if any soil type has been not found, it has been added to the database.

Land use data has been obtained from the CORINE Land Cover (CLC) project, corresponding to the year 2000. CLC data was obtained at 1 : 100000 scale, with a 100 m × 100 m resolution mesh and a minimum land use unit area about 25 ha. The CLC-obtained data has been compared with the ERMOT project (Henriquez-Dole, 2012) land images, in order to check its availability.

DEM, soil and land use data have been used to establish the model's HRU's. These HRU's have been obtained as combination of 12 land use categories, 7 soil type categories and 1 slope category. In a preliminary SWAT HRU definition, an excessive amount of HRU's has been found. In order to reduce them, a surface filter has been applied not considering, within one specific sub-basin, each land use and soil type whose surface is below the 10 % of the total sub-basin area (except irrigated areas). Moreover, the agriculture land use surface has been divided in each sub-basin between wheat (23.6 %), onion (4.5 %), corn (40.4 %), sugarbeet (4.5 %), barley (18.0 %) and alfalfa (9.0 %). After these operations, a final amount of 445 HRU's has been obtained.

Once the model's HRUs have been created, the crop management (quantity of applied fertilizer, the seedtime, irrigation and harvest timetable; the water source, hydric stress threshold, etc.) must be introduced in the SWAT model, due to its influence in the hydrologic process. Crop management parameters were based on normal practice of farmers in the watershed.

2.6 Groundwater flow model

MODFLOW is a fully distributed model that solves the three-dimensional groundwater flow equation using finite-difference (FD) approximations. The model calculates the hydraulic head at each cell of the FD grid (for which the aquifer properties are assumed to be uniform), and from there, the flow between cells, stream-aquifer or lake-groundwater interaction, flows through drains etc. The model requires geological and hydrogeological aquifer information such as top and bottom layer elevations, hydraulic parameters at the grid (hydraulic conductivity, storage coefficient), as well as the boundary and initial conditions and stresses.

The MOS groundwater model consists of 7 hydrogeological units (HU), three of them are considered as aquifers (HU2, HU3 and HU7) and the other as aquitards (Sanz et al., 2011, 2009). The hydrogeological unit 7 is present throughout the MOS and is composed of limestone and fractured dolostone. The HU3 is only present in the northeast part of the study area and is composed of fractured limestone and dolostone. The upper aquifer, the HU2, which is located in the central part is composed of an alternate sequence of marl-lime and marl. Six hydrogeological domains can be identified in the MOS: Northern (ND), Central (CD), El Salobral-Los Llanos (SLD), Moro-Nevazos (MND), PozoCañada (PCD) and Montearagón-Carcelén (MCD) domains. According to Sanz (2009, 2011) there is hydraulic connection between the ND, CD and SLD domains, but not between MND, PCD and MCD or among these three and ND, CD and SLD. The Jucar River is the most important surface body and it is hydraulically connected to the aquifer, mainly to the HU2.

The groundwater flow was simulated using MODFLOW 2005 (Harbaugh, 2005). The model was discretized into 114 columns, 129 rows and 6 layers. The cell size is 1 km^2. The main aquifers are represented by layers 2, 4 and 6 (HU7/HU6/HU5, HU3 and HU2), while the other layers are semipermeable units (HU4, lower HU1 and upper HU1). Layers 2 and 6 allocate the majority of wells. To the west of the studied area it is located the Western Mancha System, which it is assumed that it has a groundwater discharge into the MOS. This was simulated by a constant head boundary condition. The initial heads were taken from Sanz (2005). The hydraulic conductivity and storage coefficients were initially obtained from Sanz (2005), although these values were further modified during the calibration process. The hydraulic conductivity varies between 0.05–500 m day^{-1} and the storage coefficient, between 1×10^{-4} and 1×10^{-5}. Recharge and pumping values for calibration and validation were obtained from the SWAT model outputs for the historical climatic conditions and crop distributions.

2.7 Groundwater nitrate transport model

MT3DMS (Zheng and Wang, 1999) is a three-dimensional groundwater solute transport model that solves the groundwater transport equation using a FD approximation, discretizing the spatial domain into cells in which equal characteristics and solute concentrations are assumed. The model simulates the transport problem considering advection, dispersion, diffusion, sorption and chemical reactions. MT3DMS is designed for use with any block-centered FD flow model; therefore it is common to use it in combination with MODFLOW, under the assumption of constant fluid density and full saturation. The model obtains the pollutant concentration evolution over time. To achieve this, the model requires as inputs, along with all the information previously mentioned for the MODFLOW model, the mechanical and chemical pollutant properties, such as advection or diffusion coefficients, decay and sorption coefficients.

For the MOS mode, initial concentration values were interpolated from data reported in Moratalla et al. (2009). Nitrate leaching loads entering the aquifer were obtained as

SWAT outputs. Only agricultural sources were considered. Since only few scattered measured values of nitrate concentrations were available for calibration, the calibration mainly consisted in matching the maximum nitrate concentrations simulated with the ones reported in Moratalla et al. (2009).

3 Model calibration and validation

In the proposed modelling framework, given the sequential use of models, the SWAT, MODFLOW and MT3D models were calibrated independently; the modelling chain was then tested with the observed values.

3.1 SWAT calibration

The SWAT calibration procedure has followed four sub-processes, consisting on river flow, groundwater recharge, crop yield and nitrate leaching calibrations. A preliminary sensitivity analysis was run using the SWAT-CUP software (Abbaspour, 2012), obtaining that the most sensitive parameters of the model were the SCS Curve Number (CN2), the groundwater discharge coefficient (α), the travel time coefficient from soil to shallow aquifer, the inverted flow coefficient that is finally lost due to evaporation, and the two primary evapotranspiration parameters. That sensitivity analysis also showed that the CN2 and α parameters were, by far, the most sensitive ones. The fact that the CN2 parameter was the most sensitive enhances the importance of combined climate and land use change analyses in the Mancha Oriental aquifer.

Two river gauging stations have been selected to calibrate the SWAT model's hydrology. The first one, Los Frailes (08036 station), is located at the very center of the case study zone, close to the Jucar and Valdemembra rivers confluence. The second one, Alcala del Jucar station (08144), is placed downstream of the confluence between Jucar and Ledaña rivers, and therefore, downstream the reach of stream-aquifer connection within the Mancha Oriental aquifer. Figure 1 shows the location of both gauging stations. Daily flow data from 1994 to 2004 have been used to calibrate the SWAT model, with data from 1991 to 1993 as warm-up period. Figure 6 shows the comparison between the simulated and observed values. It shows an adequate performance of the SWAT model, which adequately reproduces the Jucar river discharge. For the 08036 station, we obtained a correlation coefficient of 0.92 and a Nash–Sutcliffe efficiency (NSE) coefficient equal to 0.84, while for station 08144 those values were 0.83 and 0.68 respectively.

Groundwater recharge values obtained from SWAT have been compared with the ones reported in previous studies in the same case study. Sanz et al. (2010) estimate a mean recharge of 320 $\mathrm{Mm^3\,year^{-1}}$; while the Jucar River Basin Management Authority (CHJ, 2013) establishes a recharge between 238 and 334 $\mathrm{Mm^3\,year^{-1}}$. The SWAT model results offer a mean annual groundwater recharge of 310 $\mathrm{Mm^3}$.

The net values obtained for stream-aquifer interaction were also compared to those reported in the literature and modelling reports for the area. The values previously reported expressed a range from 40 to 60 $\mathrm{Mm^3\,year^{-1}}$, where SWAT reported 45 $\mathrm{Mm^3\,year^{-1}}$.

Unlike other previous studies using SWAT (e.g. Narula and Gossain, 2013), SWAT calibration has been also based on the crop simulation component. The simulated irrigation volumes and crop yields have been compared with the ones reported from crop surveys and experimental data in the zone. These data have been obtained from deliverables of the agronomic technical institute of the province (Instituto Técnico Agronómico Provincial, ITAP). As seen in Table 2, the SWAT model performance is consistent with the expected values.

With regard to nitrate leaching, there is no possible comparison with historical observed data, as there are no historical records. The calibration of nitrate leaching is carried out after calibrating the hydrological component of the watershed model (since the land phase of the hydrological cycle influences the transport and transformation of NO_3 in the topsoil) and the crop growth component. Nitrate leaching calculations uses SWAT-predefined functions, information on fertilizer types and application, soil characteristic (including initial NO_3 concentration), and other factors such as the percolation factor affecting NO_3 transport.

In order to find out if the SWAT model performance is adequate, its nitrate leaching values have been compared with ones provided in previous studies about nitrate leaching from agriculture in the region (Martin-Benlloch, 2012) (Table 2). In addition, nitrogen leaching estimates were also tested through comparison of the resulting simulated groundwater nitrate concentration from MT3D with the observed values. Given the usual absent of data, the calibration and valudation of nitrate loads is often based on observed nitrate concentrations in surface gauging stations and observed groundwater nitrate concentrations (e.g. Mariela et al., 2011; Amon-Armah et al., 2013; Laurent and Ruelland, 2011; Narula and Gossain, 2013).

3.2 MODFLOW

MODFLOW calibration has been carried for the same period as the SWAT model (1994–2004 period), using 24 piezometers. Figure 7 graphs the calibration results obtained in 8 piezometers located in different parts of the Mancha Oriental aquifer. The model performance closely resembles the historical records at the observation wells and, therefore, the MODFLOW model has been adequately calibrated.

3.3 MT3DMS

The MT3D model calibration was hindered by the lack of data, especially by the lack of a continuous time series with at least one record per month. The initial concentration values were interpolated from data reported in the literature (Moratalla et al., 2009). The nitrates entering the aquifer were calculated using the SWAT model, whose leaching calibration process has been showed. Since only few scattered measured values of nitrate concentrations are available for calibration, the calibration consisted in matching the maximum nitrate concentrations simulated and their spatial distribution pattern with the ones reported in the literature (Moratalla et al., 2009).

4 Scenario results

Each scenario run refers to a single combination of climate change, period and land use scenario, up to a total number of 24 (Table 3).

4.1 Impacts on hydrology

The most relevant hydrological impact in terms of effect on groundwater dynamics is the variation on groundwater recharge. Figure 8 depicts the mean annual groundwater recharge values associated to each scenario run in SWAT.

All the climate change scenarios agree in a reduction of the mean recharge. Using averaged results across scenarios, the recharge would be reduced 7 % in short-term, 16 % in medium-term and 30 % in long-term. The obtained decreased recharge can be justified with the decrease of the precipitation in all the studied climate change scenarios (Table 4). In both cases the average reduction is higher with longer periods of time. It can be observed the opposite pattern with the temperature, which increases over the time horizon (see Fig. 3).

Furthermore, it is observed that the runs with land-use scenario 2 (GC02, GC10, GC18, GC3, GC11 and GC19) show the highest recharge, independently of the climate change scenario simulated. This pattern is associated with the increase of irrigation area in this scenario (the irrigated area reaches a maximum of 1000 km^2 in LUCS-2). Greater irrigated areas lead to higher percolation rates. Irrigation prevents the soil water deficiency in semiarid regions during the dry periods, enabling deep percolation in the early rainfall and, when applied in excess, irrigation water may also provide an additional percolation flux (Seiler and Gatt, 2007), although in this case the irrigation efficiencies are high (the most common irrigation system is drip center pivots).

Climate change seems to be the main driver of change, given that the differences between different climate scenarios with equal land use ones are larger than the differences found when the climate scenarios remain the same and the land use scenario is changed. The differences found between different land use scenarios are as much 5 % of the total recharge, noticeable but low when compared with the maximum 30 % reported earlier.

Climate and land use change impacts on crop yield have been also studied. All the ECHAM5 scenario shows a slight increase in crop yields between the short and the mid term, followed by a reduction between the mid and long-term. On the other hand, the results for the CNRM and HADCM3 scenarios show a general decreased crop yield for all the future periods. As SWAT provides the crops with enough water to satisfy their irrigations needs, either by rain or groundwater, the crop yield diferences between scenarios cannot be asigned to precipitation changes by rather to the effect of temperature variations, which are lower for the ECHAM5 scenario.

4.2 Impacts on groundwater quantity

Figure 9 shows the evolution of the groundwater levels associated to the aquifer layers 2 and 6, which hold the largest amount of pumping wells, covering the scenarios GC01 to CG05 and CG09 to GC13 that correspond to all the possible combinations between the ECHAM5, CNRM, LUCS-2 and LUCS-3 scenarios. These runs have been combined in four evolution patterns: the GC01-02-03, the GC01-04-05, the GC09-10-11 and the GC09-12-13.

The results show a decrease–increase cycle, without a generalized descending trend, influenced by the Jucar river relationship with the aquifer, the recharge distribution and the crop areas evolution assessed by the land use change scenarios. The groundwater tables decline noticed in the historical records continues until the year 2020, in which the levels start to oscillate without showing a clear decreasing trend. In the layer 6, the LUCS-3 scenarios show higher levels than the corresponding LUCS-2, being the land use change the major driving force, as scenarios with the same LUCS but with different climate change scenarios are very similar. On the other hand, scenarios with different LUCS but the same climate change scenario show higher differences. For layer 2, the groundwater levels showed by the LUCS-3 scenarios are higher than the LUCS-2 ones, but the oscillations between scenarios are more relevant and, during some periods, the groundwater tables offered by the LUCS-3 scenarios are located below the LUCS-2 ones. To sum up, the land use change scenarios effect on groundwater levels is higher than the climate change one. The lower amount of pumping associated to the LUCS-3 scenarios leads to higher groundwater levels. However, general declines can be noticed for the whole scenarios. The oscillations noticed in the series evolution are associated to climate variability, adding an important source of uncertainty to the results.

4.3 Impacts on groundwater quality

Groundwater quality impacts of climate and land use changes have been analyzed in terms of groundwater nitrate concentrations using the MT3DMS model.

Nitrate leaching results from SWAT runs are showed in Fig. 10. Higher values of nitrate leaching are obtained for the scenarios based on the CNRM model (GC09 to GC16), associated to higher precipitations that originate higher groundwater recharge. The scenarios associated with the LUC-2 land use change scenario (the largest irrigated areas) are generally the ones with higher nitrate leaching values, while the LUCS-4 offer the lower bound of nitrate leaching values, indicating a synergic effect between climate and land use change. Differences between land use change scenarios become significant in the medium and long term. The decreasing precipitation and recharge plays a beneficial effect in the nitrate leaching, being reduced in all the future scenarios.

MT3DMS results are showed in Fig. 11. Nitrate concentrations in the Mancha Oriental aquifer increase in nearly all the observation points. Nitrate change concentration trends match with the expected behavior, showing an increase over the century, with the highest concentrations for the LUCS-2 scenario. There is no agreement between the points in the time period that shows higher concentration increases, but the majority of them show the steepest increases at the end of the XXI century, driven by the recharge reduction previously noticed. All the climate change and land use change scenarios show the same evolution trend for a particular point.

Regarding climate change, the CNRM-driven scenarios appear as the ones with higher concentrations in the majority of the case study area. On the other hand, land use change scenarios do not show a significant effect, with the exception of several points and time periods, being the LUCS-2 the one that offers higher nitrate concentrations, as expected. However, there are control locations and time periods that do not follow the general trend, caused by specificities regarding their locations.

5 Discussion and conclusions

Global (climate and land use) change impacts on water quantity and quality in the Mancha Oriental aquifer system (MOS) have been assessed through the sequential coupling of 3 models: a watershed hydrological model (SWAT), a groundwater flow model (MODFLOW) and a groundwater transport model (MT3D). The models have been successfully calibrated and validated using a large array of diverse observations: gauged streamflow time series, crop yields and irrigation reference values (essential for ensuring adequate modeling of crop responses in an essentially agricultural basin), and records of groundwater heads and nitrate concentrations. The spatial and temporal evolution of water quantity and quality has been obtained then for three climate change scenarios (corresponding to different GCMs) and three land use change scenarios for nearly all the XXI century. In this way, the study has shown that the integrated sequential use of the 3 models offers a valuable tool for assessing the impacts of land use and climate change pressures, getting an essential insight into the system vulnerability and potential adaption options for a more sustainable management.

The modelling results point out at the same situation: a future drier and hotter climate would produce further groundwater level declines (caused by a reduced recharge, and in some scenarios, and increased in groundwater pumping for irrigation), which can be significant in certain areas of the aquifer, and increasing streamflow depletions in the connected river. Although further studies at basinwide level would be needed, it must be concluded that global change could be a great threaten and challenge to Mancha

Oriental aquifer and to the whole Jucar River Basin, as this aquifer plays an important role in the Jucar middle-basin streamflows, especially regarding the fact that the aquifer status is not good at this moment. Despite the recent stabilization of groundwater abstractions, the expected reduced recharge from climate change projections will add additional pressure on the sustainability of the groundwater system. Increasing streamflow depletion in the Jucar river would decrease the amount of water available downstream, increasing conflicts for meeting downstream demands and environmental requirements. In order to avoid these and other potential future threatens, the new Jucar River Basin Management Plan include a program of measures to prevent further groundwater level depletion and enhance groundwater heads recovery, in order to achieve a good quantitative and chemical status in the Mancha Oriental aquifer as required by the EU Water Framework Directive. Global change poses an additional hurdle to this intended program of measures, as changing patterns would decrease the aquifer's natural recharge and would force to further develop a robust of adaption of to ensure sustainable groundwater use.

Regarding these premises, several conclusions of this case study should be made:

- Global change must be taken into account in the planning and assessment of the management policies for a sustainable development of the Mancha Oriental system, as the results obtained without considering global change impacts are likely to be too optimistic
- The currently intended program of measures regarding the MOS must be re-assessed in order to:
  - Check the effectiveness of this program of measures under climate global conditions
  - Redefine the program of measures to adapt to global change conditions

Participatory processes engaging the relevant stakeholders are essential in the successful definition and implementation of sustainable adaptation measures for groundwater management, and techniques as the Multi Attribute Value Theory, already applied to the case study (Apperl et al., 2014) can be very useful for ranking measures based on the stakeholder preferences and values and for anticipating potential conflicts among competing uses.

Finally, climate and land use changes impact not only groundwater levels and groundwater discharge to the river, but also groundwater quality. Increasing groundwater nitrate concentrations can be anticipated due to the continuous intense use of fertilizers in agriculture over time. Economic instruments might have an essential role in enhancing a sustainable management of diffuse pollution for the future (Peña-Haro et al., 2014).

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Table 1. Selected driving forces for the Mancha Oriental land use change.

Biophysical factors	Distance to rivers Distance to lakes Mean annual precipitation (Thiessen) Mean annual temperature (Thiessen) Slope Digital Elevation Model (DEM) Orientation Soil type (organic matter proportion) Proximity to flooding zones
Social Factors	Distance to urban agglomerations Distance to towns Population density in 2003 (municipal level) Population growth rate (1996–2003) at municipal level
Economic and Political factors	Distance to local roads Distance to regional roads Distance to national roads Distance to pumping extraction plants Location of agriculture zones Belonging to a specific province Belonging to the Mancha Oriental Aquifer

Table 2. Crop irrigation, crop and nitrate leaching management calibration.

Crop type	Irrigation (mm)		Yield (Tn ha^{-1})		Leaching (kg NO$_3$ ha^{-1})	
	SWAT	ITAP	SWAT	ITAP	SWAT	GEPIC
Wheat	363	350–420	7.2	7–8	53	45–85
Onion	572	550–620	5.1	4.5–5.5	114	100–120
Corn	552	500–600	12.2	12–13	100	90–115
Sugarbeet	827	800–900	12.8	12.5–13.5	74	65–90
Barley	282	250–350	8.6	8–9	34	30–45
Alfalfa	782	750–850	12.1	11.5–12.5	12	10–30

Table 3. Analysis scenarios.

Scenario	Climate Change scenario	Land use scenario	Period
GC01	ECHAM5	LUCS-1	Short-term
GC02	ECHAM5	LUCS-2	Mid-term
GC03	ECHAM5	LUCS-2	Long-term
GC04	ECHAM5	LUCS-3	Mid-term
GC05	ECHAM5	LUCS-3	Long-term
GC06	ECHAM5	LUCS-4	Short-term
GC07	ECHAM5	LUCS-4	Mid-term
GC08	ECHAM5	LUCS-4	Long-term
GC09	CNRM	LUCS-1	Short-term
GC10	CNRM	LUCS-2	Mid-term
GC11	CNRM	LUCS-2	Long-term
GC12	CNRM	LUCS-3	Mid-term
GC13	CNRM	LUCS-3	Long-term
GC14	CNRM	LUCS-4	Short-term
GC15	CNRM	LUCS-4	Mid-term
GC16	CNRM	LUCS-4	Long-term
GC17	HADCM3	LUCS-1	Short-term
GC18	HADCM3	LUCS-2	Mid-term
GC19	HADCM3	LUCS-2	Long-term
GC20	HADCM3	LUCS-3	Mid-term
GC21	HADCM3	LUCS-3	Long-term
GC22	HADCM3	LUCS-4	Short-term
GC23	HADCM3	LUCS-4	Mid-term
GC24	HADCM3	LUCS-4	Long-term

Table 4. Monthly average temperature and precipitation over the short, medium and long term.

Period	Average temperature (˚C)			Average precipitation (mm)		
	ECHAM5	CNRM	HADCM3	ECHAM5	CNRM	HADCM3
Historical	18.0	19.3	17.6	417.6	412.2	408.5
Short term	18.9	20.2	19.1	375.8	408.1	367.6
Medium term	20.4	21.4	20.8	338.2	379.2	339.1
Long term	22.0	22.4	21.8	279.8	346.3	347.2

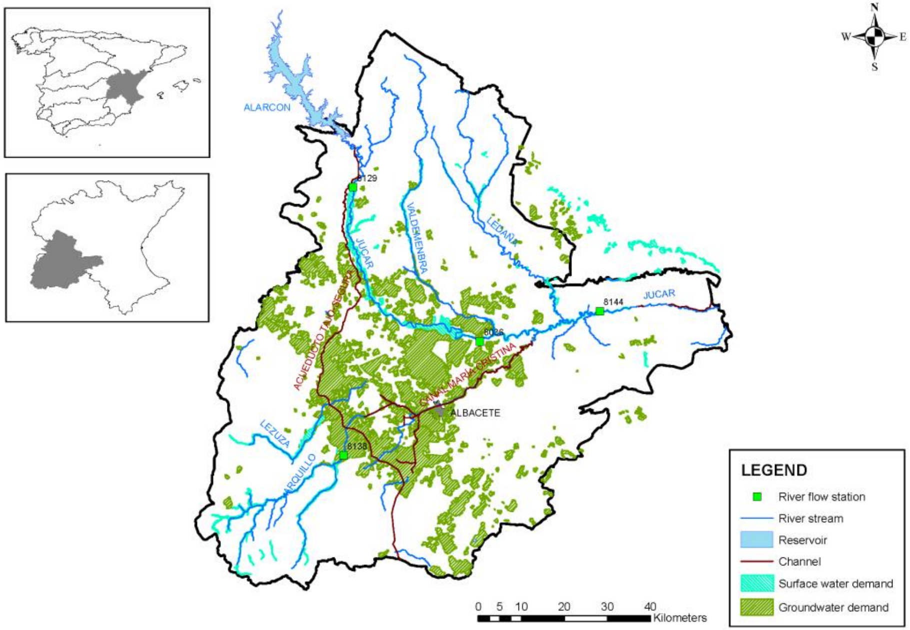
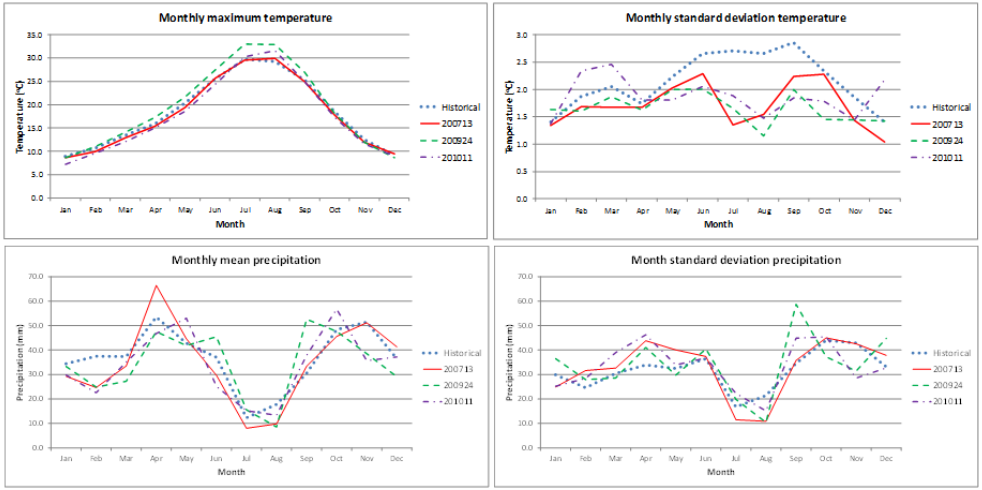


Figure 1. Mancha Oriental Aquifer location map.


Monthly maximum temperature

Monthly standard deviation temperature

Monthly mean precipitation

Month standard deviation precipitation

Figure 2. Monthly mean and standard deviation comparison on temperature and precipitation.

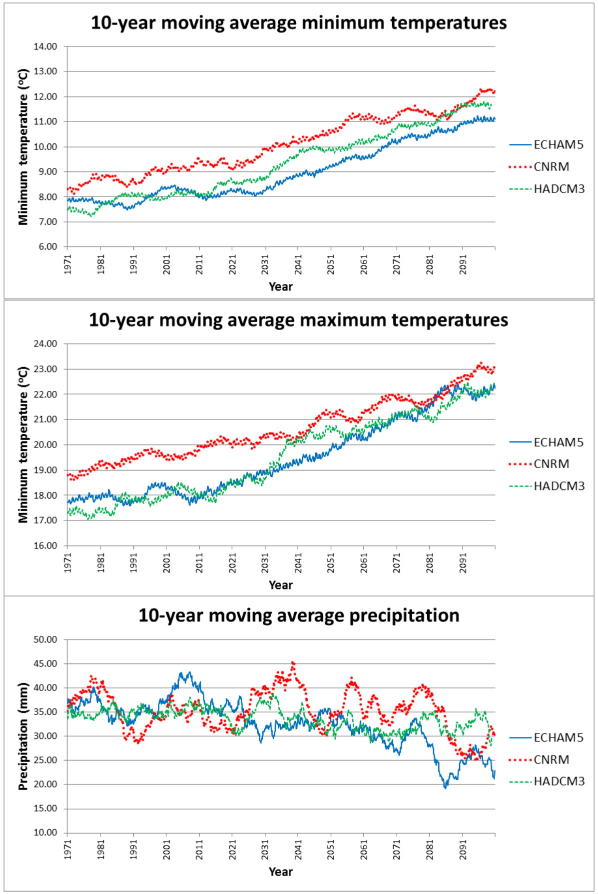


Figure 3. Temperature and precipitation 10 year moving average values for the climate change scenarios.

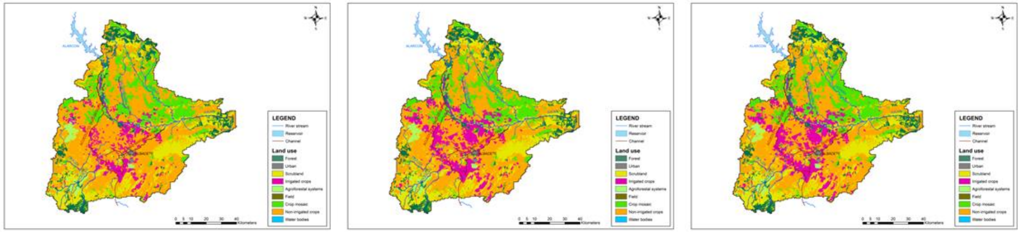


Figure 4. CORINE Land Cover images for years 1990, 2000 and 2006 in the Mancha Oriental Aquifer.

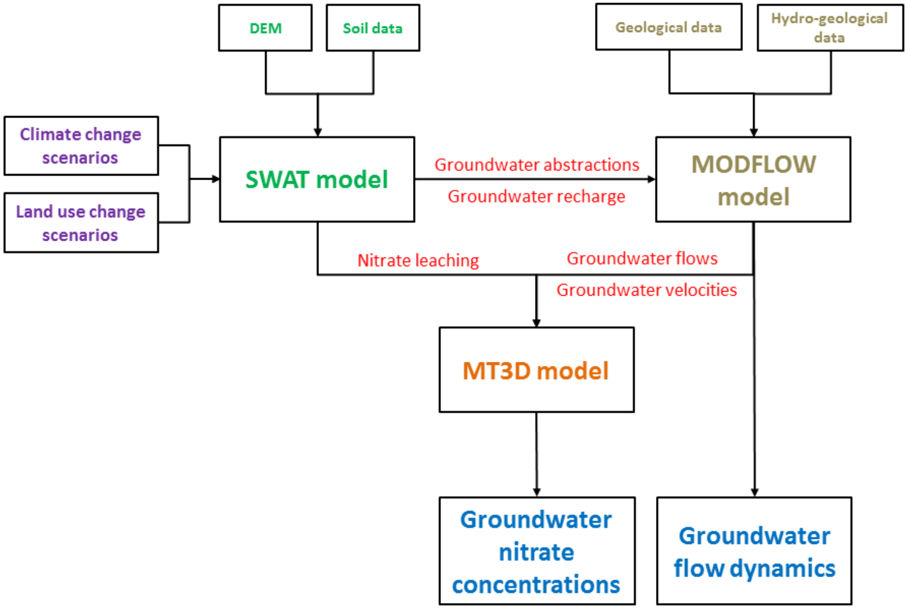


Figure 5. Modeling framework adopted.

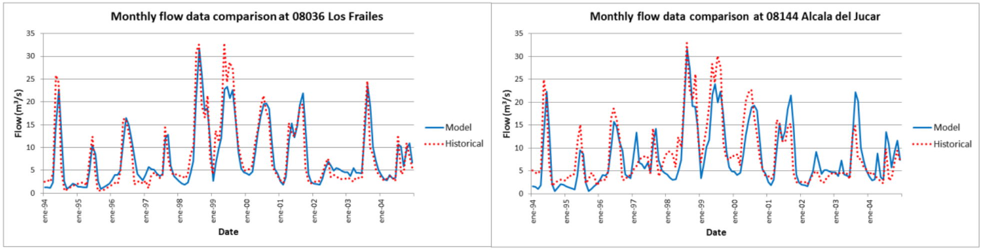


Figure 6. SWAT model calibration at 08036 station (left) and 08144 station (right).

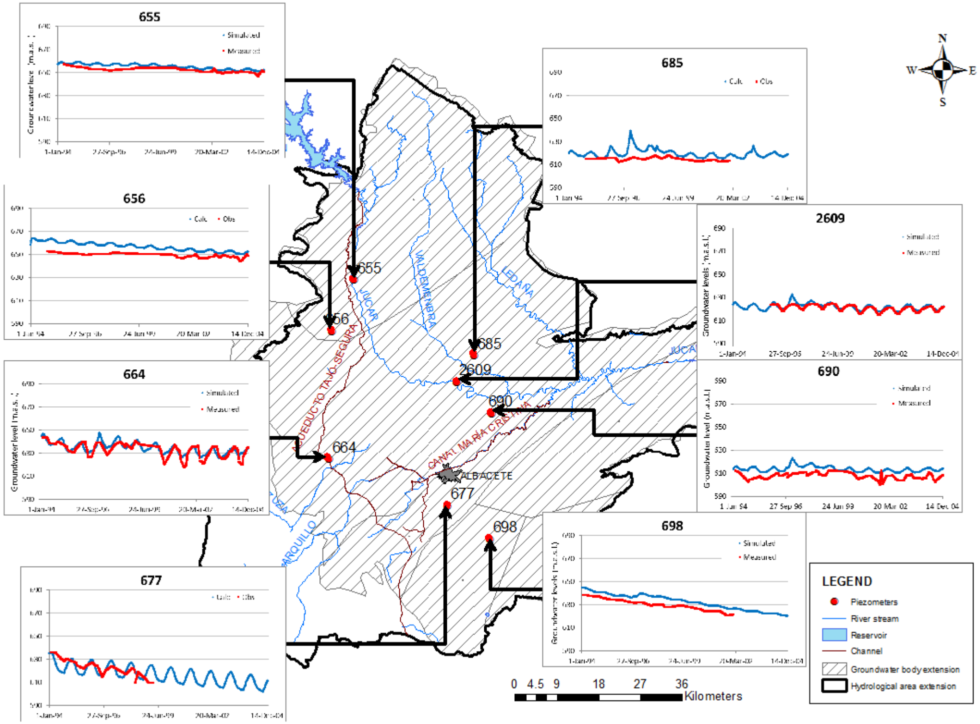


Figure 7. MODFLOW model calibration.

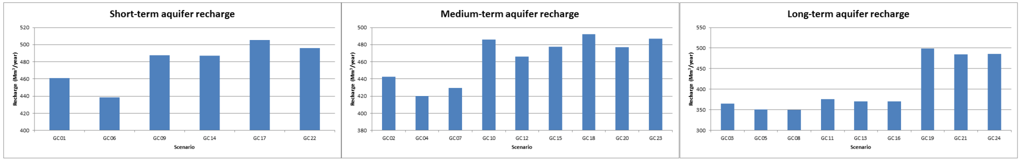


Figure 8. Groundwater recharge results obtained with SWAT for the short-term (left), medium-term (middle) and long-term (right).

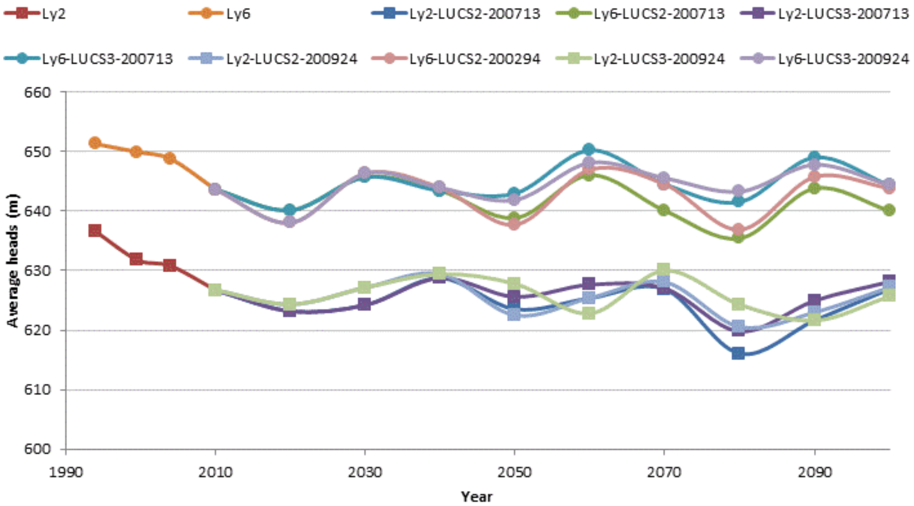


Figure 9. Groundwater level evolution during the XXI century of layers 2 and 6 of the Mancha Oriental Aquifer.

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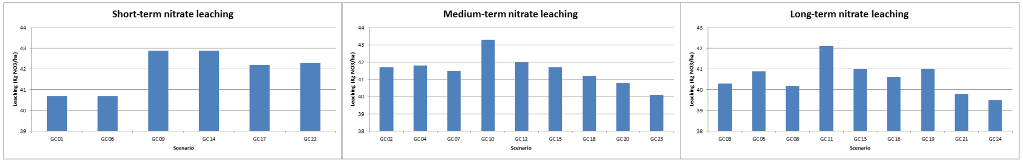

Figure 10. Nitrate leaching results obtained with SWAT for the short-term (left), medium-term (middle) and long-term (right).

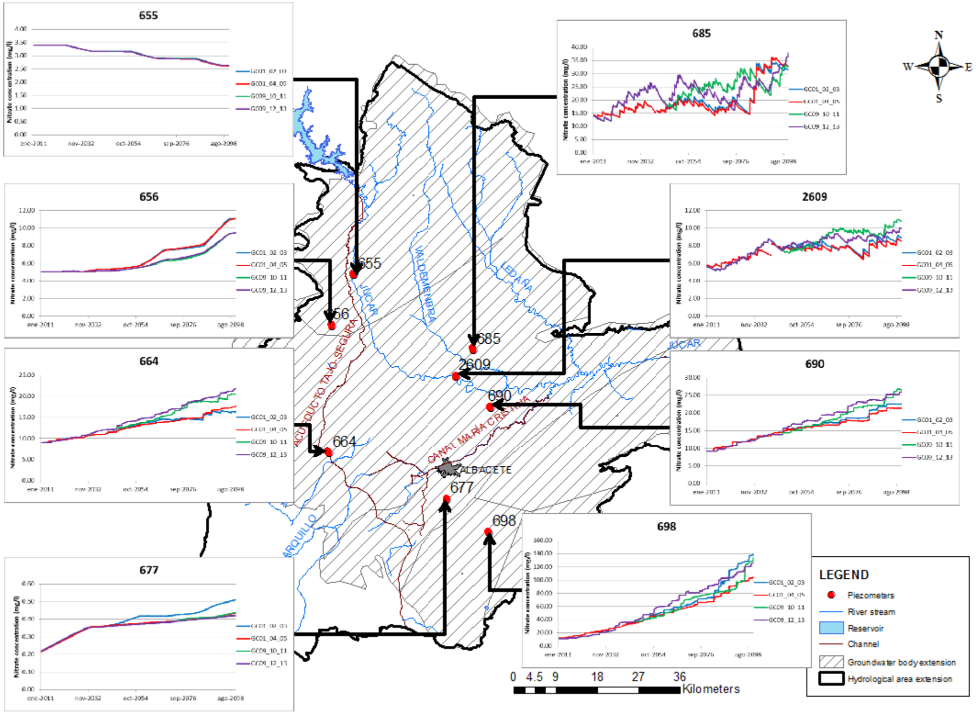

Figure 11. Nitrate concentration evolution in the Mancha Oriental aquifer obtained with MT3DMS.