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PILOT DESCRIPTION AND ASSESSMENT

Lorca
(Spain)

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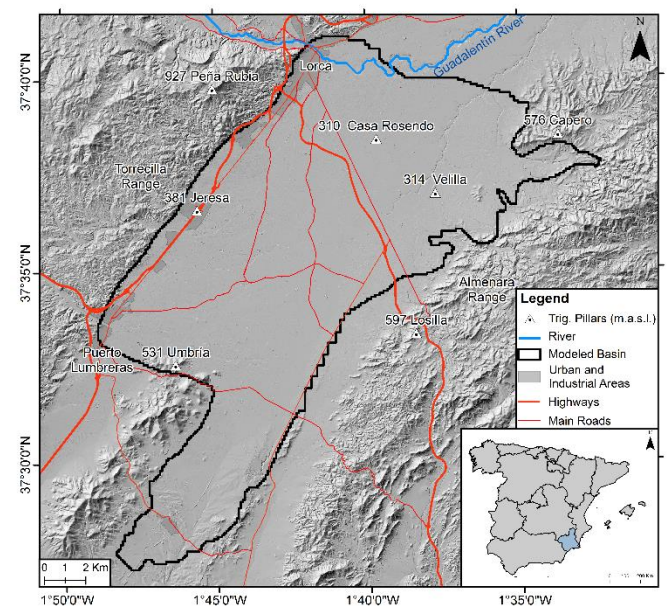
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LIST OF ABBREVIATIONS & ACRONYMS

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1 EXECUTIVE SUMMARY

Pilot name	UPPER GUADALENTÍN BASIN	
Country	Spain	
EU-region	Mediterranean region	
Area (km ²)	250 km ²	
Aquifer geology and type classification	Detrital. Sedimentary	
Primary water usage	Irrigation / Drinking water	
Main climate change issues	The Spanish Mediterranean arc is a drought vulnerable area that experienced three important dry periods between 1990 and 2012, where 68 aquifer systems have been declared partially overexploited and 10 as completely overexploited by national authorities. Agriculture, traditionally the most important economic activity in the area, is being progressively replaced by urban and touristic activities. These both activities still have an important impact over groundwater resources. Piezometric data from the Alto Guadalentín basin show a continuously descending piezometric level over the last 60 years; from a few meters below land surface in the 60's to approximately 200 m below land surface nowadays. This piezometric level drop has generated of the highest subsidence rates induced by groundwater extraction measured in Europe (>10 cm/yr).	
Models and methods used	Groundwater mathematical model that reproduces groundwater evolution during 52 years is developed. The geometry of the model was improved introducing data derived from InSAR deformation ad borehole data. The resulting aquifer system history of the piezometric level is compared with ENVISAT deformation data to calculate a first-order relationship between groundwater changes, soft soil thickness and surface deformation. This deformation is validated with displacement data from ERS and ComoSkyMed satellites. Future climate changes scenarios are used to generate recharge series, which are introduced in the model to evaluate future groundwater and deformations in the aquifer.	
Key stakeholders	Segura River Basin Authority, farmers associations (farmers are a highly heterogeneous group, whose interests often cannot be generalised; this implies a wide range between those associations working at institutional level and those working at political scale representation), water supply companies,	



	Environmental Conservation Groups.
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Lorca pilot site is located over the Alto Guadalentín aquifer, which is situated in Murcia Region, Southeast Spain. The Guadalentín hydrographic system responds to a structural control: the main watercourses fit in the geological fracture system, partially controlled by the faults activity in the Guadalentín area. The hydrographic system provokes multiple deposits and geological features (gullies, badlands, alluvial fans, debris cones, glacis, alluvial terraces, ravines, etc. (Cerón and Pulido-Bosch, 1996). The main watercourse in the area is the Guadalentín River with very low flow non- permanent rates that only increase due to extreme flood events (Ezquerro et al., 2017), reaching up to 3000 m³/s (Cerón, 1995). Mediterranean areas such as the Southeast of Spain are affected by convective storms (commonly developed in Autumn) with very quick development, short duration and very high intensity constituting a permanent potential threat. For Guadalentín basin, these events resulted in numerous catastrophic floods (Ezquerro et al., 2017). The area presents a dry climate following the Koppen-Geiger Classification modified (AEMET-IM, 2011). This matches with severe drought periods, and consequently, water stress in the area has historically appeared with temporal effect causing water shortages. Agricultural development has led to the overexploitation of the aquifer system (CHS, 2007). This fact is reflected in a global descendent groundwater level trend until 2009. The aquifer has been also declared to not achieve a good quality status.

In order to increase the knowledge about the aquifer system behavior and ultimately improve its management, a numerical groundwater model was developed. This model simulates changes in groundwater flow, from the original steady state conditions in the aquifer system back in 1960 to 2012 conditions. The conceptual model was rigorously set up using available geological, geophysical and groundwater flow data, and included the delineation of the model geometry and the boundaries conditions. Earth Observation (EO) techniques, more precisely A-DInSAR, were also used to improve the conceptual and physical groundwater flow models. This method provides surface displacements time series caused by terrain motion such as land subsidence, and corroborated an important relationship between subsidence, piezometric levels changes and compressible thickness variations in the studied area. An empirical deformation model based on the groundwater numerical model results was adjusted.

Most of the work presented here was developed in the study by Ezquerro et al. (2017). Shortages in the TACTIC budget have not allowed further development of this methodology or its application in other pilot sites. For future works or projects, two are the main recommendations: (i) from the stakeholder perspective, the real use of the numerical groundwater model for water management purposes, and (ii) from a research view, further work should be done to numerically coupled flow and geomechanical models, that will allow a realistic estimation of water storage variations in the aquifer.

2 INTRODUCTION

Climate change (CC) already have widespread and significant impacts in Europe, which is expected to increase in the future. Groundwater plays a vital role for the land phase of the freshwater cycle and has the capability of buffering or enhancing the impact from extreme climate events causing droughts or floods, depending on the subsurface properties and the status of the system (dry/wet) prior to the climate event. Understanding and taking the hydrogeology into account is therefore essential in the assessment of climate change impacts. Providing harmonised results and products across Europe is further vital for supporting stakeholders, decision makers and EU policies makers.

The Geological Survey Organisations (GSOs) in Europe compile the necessary data and knowledge of the groundwater systems across Europe. In order to enhance the utilisation of these data and knowledge of the subsurface system in CC impact assessments the GSOs, in the framework of GeoERA, has established the project “Tools for Assessment of Climate change Impact on Groundwater and Adaptation Strategies – TACTIC”. By collaboration among the involved partners, TACTIC aims to enhance and harmonise CC impact assessments and identification and analyses of potential adaptation strategies.

TACTIC is centred around 40 pilot studies covering a variety of CC challenges as well as different hydrogeological settings and different management systems found in Europe. Knowledge and experiences from the pilots will be synthesised and provide a basis for the development of an infra structure on CC impact assessments and adaptation strategies. The final projects results will be made available through the common GeoERA Information Platform (<http://www.europe-geology.eu>).

The present document reports the TACTIC activities in the pilot site of Lorca, in Spain. More specifically, the results related with Task 4.5. of WP4. This task aims to assess subsidence in aquifer systems using DInSAR satellite data. Numerical groundwater flow models and synthetic aperture radar differential interferometry (DInSAR) that detects surface movements were used to understand subsidence related with groundwater withdrawal and calibrate hydrogeological and geomechanical models. SAR-derived deformation series were compared with piezometric change data and soft soils thickness data in order to evaluate a first relationship between them and improve the conceptual and physical hydrogeological model. The historical analysis of satellite SAR images since 1992 permitted to implement robust numerical models that can be used to understand the impact of global change into aquifer systems. The task is focus on Lorca pilot in Spain, but the same methodology could be applied elsewhere (aquifer having subsidence problems, enough piezometric data, and good response of InSAR).

3 PILOT AREA

The Guadalentín Basin, SE Spain, is one the driest regions of Europe. It is located in Murcia Province (Southeastern of Spain), where the Guadalentín River, tributary of the Segura River, flows. This fertile depression was drilled in 1960 in order to improve the area's productivity by exploiting the important underlying aquifer. Increasing groundwater extractions revitalized Guadalentín agriculture in the 1980s, but led to the declaration that the aquifer-system was temporally overexploited in 1987 (CHS, 2006). New regulations and water transferred from Tajo's basin produced a reduction of pumping and abandonment of some wells from 1988. Piezometric levels began to slowly stabilize in major areas but continued declining in areas close to the still numerous active wells.

Site description and data

Location and extension of the pilot area

The Alto Guadalentín basin (Figure 1) is an intramontane sedimentary NE-SW-oriented basin containing an aquifer system hydraulically connected to the Bajo Guadalentín aquifer-system. Altitudes in the basin range from 300 to 400 m a.s.l. while the surrounding mountains range from 500 to 950 m a.s.l. This basin is an alpine orogenic tectonic depression with a Paleozoic pre-orogenic metamorphic basement covering an area of approximately 250 km². Basement shows a horst and graben pattern with maximum depths of 1000 m below land surface (Cerón and Pulido-Bosch, 1996). The Guadalentín depression is bounded to the north by the active Alhama de Murcia fault (Martínez-Díaz et al., 2012).

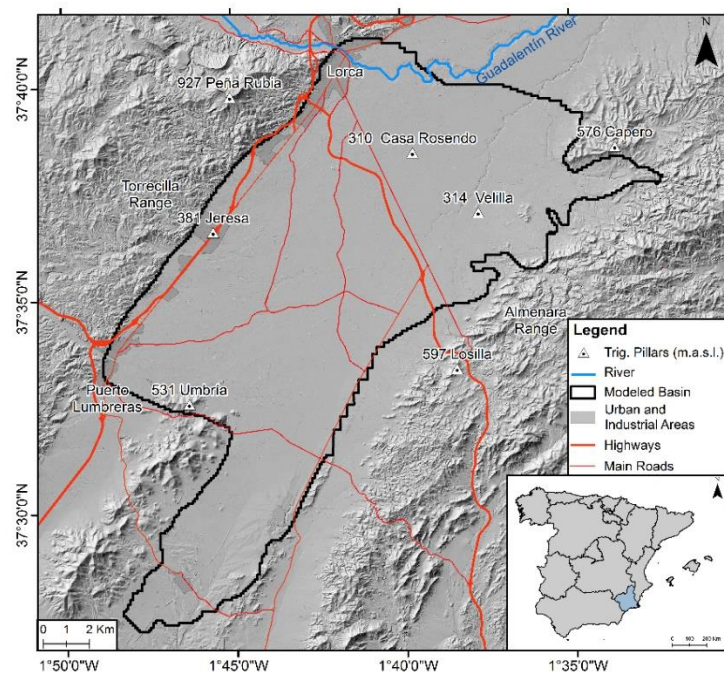


Figure 1. Location of the pilot area



The Segura Hydrographic Demarcation is the organism that manages both surface and ground water bodies in the area. Land uses in the study area comprise artificial (4.5%), agricultural (91.0%) and forest areas (4.5%). Among the agricultural areas (248 km²), 85% corresponds to irrigated surfaces. Related to the artificial land use, Lorca and Puerto Lumbreras (Figure 1) constitute the two principal urban areas. The population in the basin area reached 107,000 inhabitants in 2012, with a slow decreasing trend since then. The main population centre is Lorca city (nearly 94,500 inhabitants in 2019), which constitutes the third most populated urban area in the Murcia Region. The economy is based mainly on irrigated agriculture, although farming and industrial activities are also weakly developed.

Geology/Aquifer type

The aquifer system developed over the metamorphic basement is constituted by sedimentary materials accumulated during the basin formation (IGME, 1981). Taking into account the horst and graben pattern of the basement, its thickness has a remarkable variability oscillating from 300 to 900 m depending on the location (Cerón, 1995; IGME, 1985). The geometry of the aquifer is defined by limits in NW (permian-triassic materials), SE (triassic-miocene materials) and N. The northern limit is defined by the contact with the multilayer aquifer system of Bajo Guadalentín. The transition zone between the two aquifers is characterized by thick clay layers that lose lateral continuity towards the Alto Guadalentín. The southern border (open) is defined by the contact with the Sierra de Enmedio triassic loamy materials (CHS, 2015). The plio-quaternary sediments (gravels and sands) define the upper unconfined aquifer layer followed by a layer composed of miocene detrital materials with conglomerate and sand deposits. This layer constitutes a low permeable semiconfined level. The triassic materials represent the deepest impermeable limit.

Plio-Quaternary sediments compose the main and most productive layer of the aquifer system (Figure 2). This layer comprises sediments from near ranges alluvial fans generating sand and gravel lenses embedded in a clay and silt matrix. The upper part of the aquifer is unconfined, while deeper areas have a semiconfined behavior.

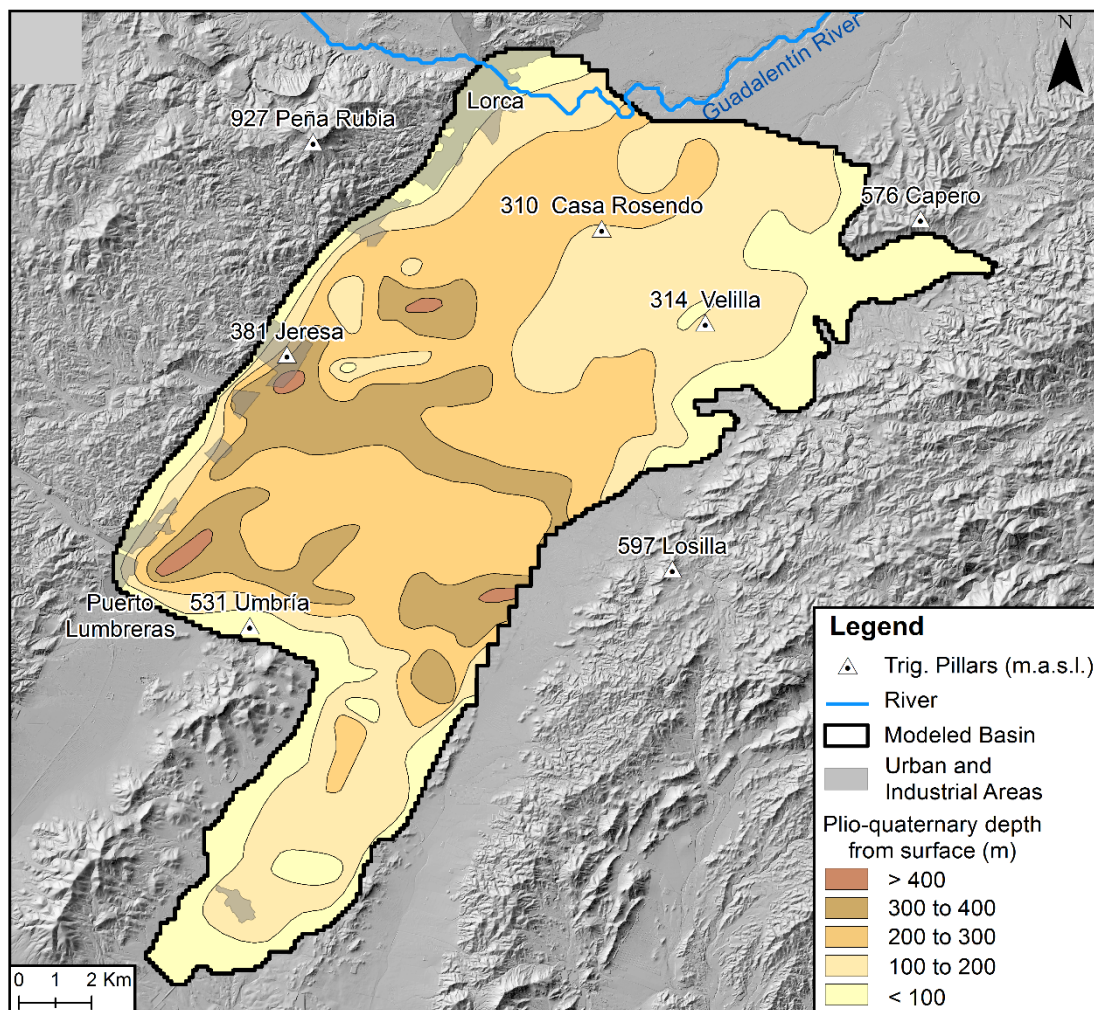


Figure 2. Main aquifer layer depth

Inflows

Table 1 resumes yearly water inflows estimated for the period 1960-2012 by Ezquerro et al. (2017). Aquifer-system recharge strongly depends on rainfall ($8.80 \text{ hm}^3/\text{year}$, CHS, 2005). There is an area in the northern part of the basin of 30 km^2 with low permeability materials outcropping at the surface which can be considered impervious and not susceptible to surface recharge. According to the rainfall series provided by the Spanish National Meteorological Agency (AEMET) average rainfall is around 250 mm/yr , usually concentrated in storm events from August to October (Figure 3). During the 52 studied years a rainfall declining trend can be observed with two severe droughts from 1994 to 1996 and from 2001 to 2003.

There are also inflows to the aquifer system infiltration and stream infiltration through Guadalentín River, Nogalte Rambla and other minor water courses along the eastern and western margins (Figure 4). Another important source of recharge is infiltration from the irrigation return flow ($2.70 \text{ hm}^3/\text{year}$, CHS, 2005).



Table 1. Yearly water inflows to the Alto Guadalentín River, estimated for the period 1960-2012 by Ezquerro et al. (2017)

Inflows	Average (hm ³)	Max (hm ³)	Min (hm ³)
Guadalentín River	1.04	2.60	0.20
Nogalte Rambla	1.04	2.60	0.20
W rambla	0.70	1.73	0.13
E rambla	1.39	3.47	0.27
Rainfall infiltration	7.0	26.74	2.23
Irrigation returns Lorca Irrigators Association	2.09	2.83	1.65
Irrigation returns Puerto Lumbreras Irrigators Association	1.55	3.09	0.12

Agricultural importance of this area is linked with water availability, supplied by different sources (Figure 4). This agricultural water demand is being met by water supplied from nearby reservoirs, groundwater extractions and, more recently, transference of water from other major basins (Tajo-Segura water transference, 1979). Agricultural development has affected the aquifer because of the extractions and the recharge from irrigation returns.

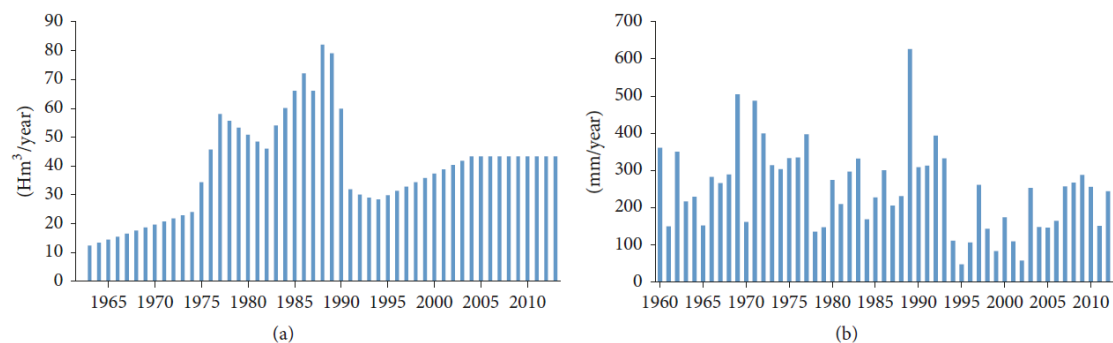


Figure 3. (a) Wells extraction rate. Maximum extractions of 80 hm³ reached in 1987 were drastically reduced after 1989 restrictions. (b) Rainfall series from Spanish Meteorological Survey. Two dry periods are clearly represented from 1994 to 2003

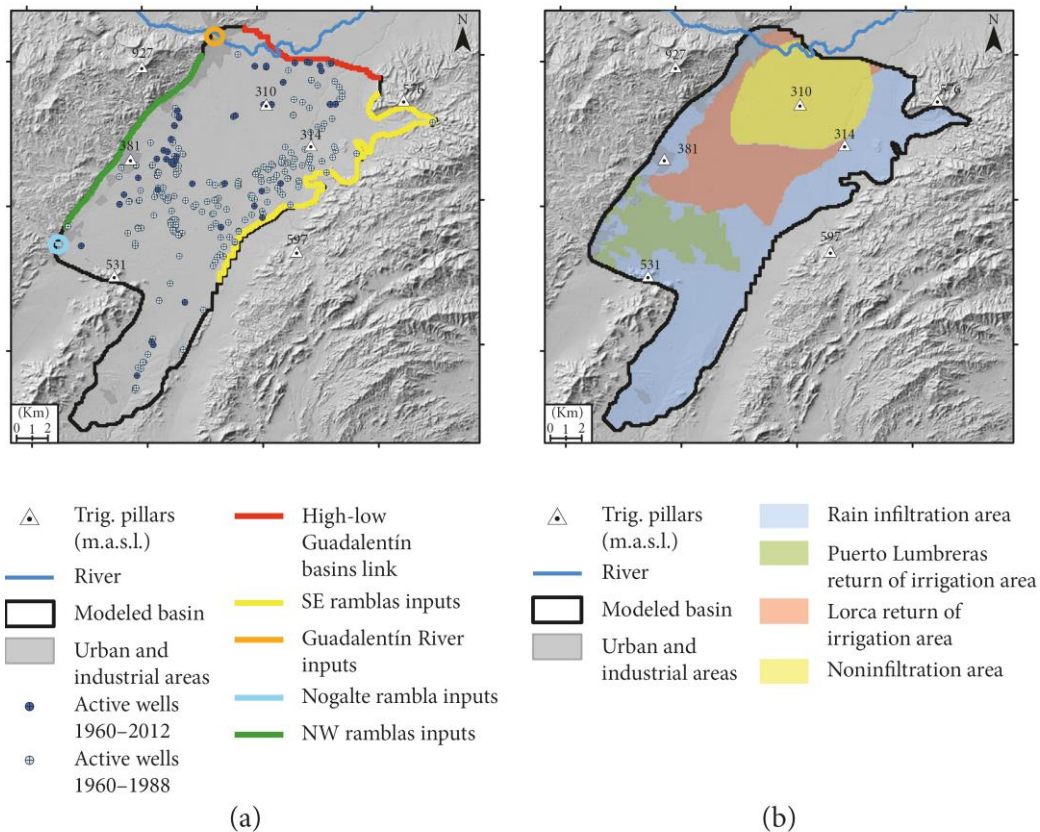


Figure 4. Basin inflows and outflows

Hydraulic head evolution

As previously commented, an intensive groundwater withdrawal has been depleting the aquifer-system since 1960 from a few meters below land surface to approximately 200 m below land surface nowadays (Ezquerro et al., 2017). The declaration of the aquifer as temporally overexploited in 1987 reduced the pressure of the aquifer-system produced a slight stabilization of the general piezometric level but continued declining near the still active wells.

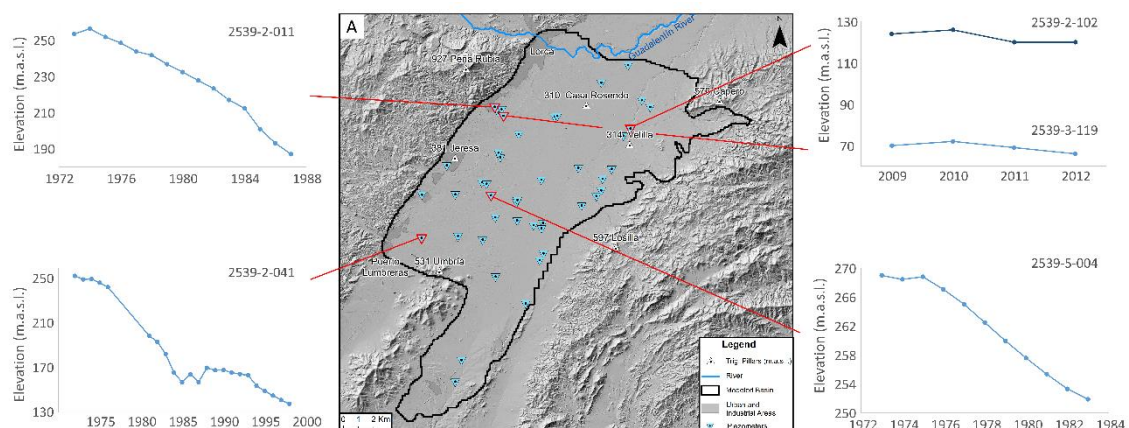


Figure 5. Location of hydraulic head observation points and piezometric evolution



Outflows

Discharge from the Alto Guadalentín aquifer occurs through the connection with the Bajo Guadalentín aquifer-system (Figure 4) and the numerous wells pumping its resources, which in occasions, take water from nearly 400 m depth. Extraction rates were governed by the increasing irrigation water demand and annual rainfall (Figure 3), reaching its maximum at the end of 1980s when 80 hm³/yr were pumped. After restrictions on groundwater pumping were imposed in 1989, the extraction rate dropped to less than 30 hm³/yr in the early 1990s. During the mid-to late 1990s, extractions increased slightly to compensate for a series of dry years. From 1960 to 1989 312 wells were registered and distributed throughout the basin. Two areas near the basin center (eastern center and western center) showed denser concentrations of wells. Since 1989 the number of wells has been reduced. Of the remaining 50 wells, the deepest and most productive are mainly concentrated in the western area. Nowadays, average value of pumping rates is quantified in around 34 hm³/year. Groundwater discharge to streams was not considered because the Guadalentín stream has a losing-disconnected relation with the Alto Guadalentín aquifer-system.

4 METHODOLOGY

In this section the different methods used to set up and adjust the aquifer groundwater mathematical model are described

A-DinSAR processing

A-DInSAR technique

Advanced Differential synthetic aperture radar interferometry (A-DInSAR) is a remote sensing technique for monitoring large-coverage deformation episodes of the earth surface. It uses Synthetic Aperture Radar (SAR) images that are collected by Earth-orbiting satellites. These spaceborne sensors acquire data regardless of the weather and operate day and night in a quasi-polar orbit, either ascending (south - north) or descending (north - south).

SAR sensors

Since the early 90s, several SAR satellites with ever-improving imaging characteristics have been launched by an international community of satellite providers, collectively ensuring continuous coverage of the Earth with SAR data (Flores-Anderson et al., 2019). The characteristic bands at which SAR satellites operates are L-band, C-band and X-band (Figure 6), with wavelengths of 23.6, 5.6 and 3.1 cm, respectively. With moderate to high-resolution capabilities and increased vegetation penetration, C-band data can be seen as a good compromise between X-band and the longer wavelength L-band sensor classes to monitor areas with low to moderate vegetation.

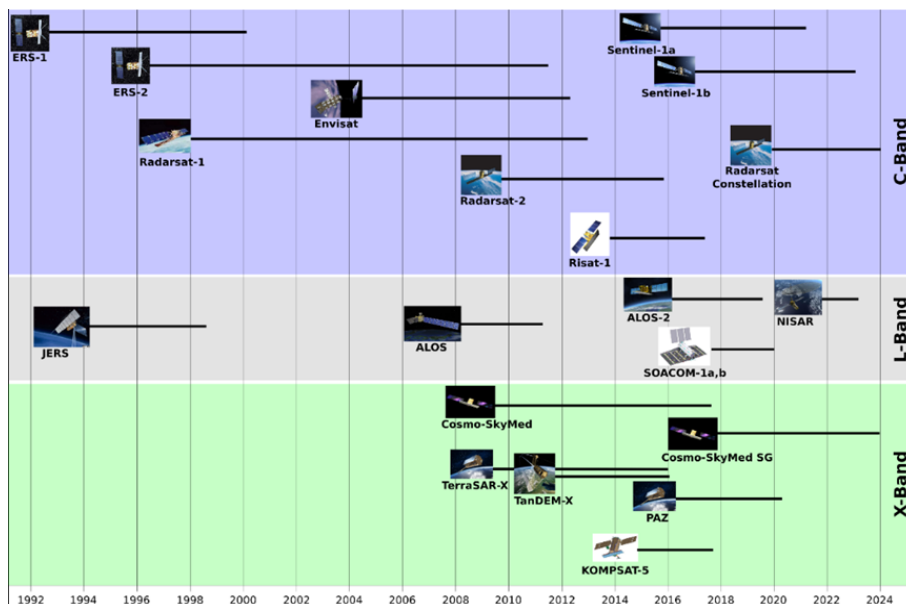


Figure 6. Chart of past, present and upcoming SAR satellite missions operating at L-band, C-band and X-band (UNAVCO, web).



The Alto Guadalentin aquifer groundwater model has been adjusted using various SAR satellite datasets, covering different time periods from 1992 to 2012. These are C-band ERS (1992–2000), ENVISAT (2003–2010), and X-band Cosmo-SkyMed (CSK) (2011–2012). Later studies of the basin have also used Sentinel 1 data, but this satellite was launched in 2014, so its out of the modelled period. The details of each sensor are summarized in Table 2 (Flores-Anderson et al., 2019).

Table 2 Properties of the spaceborne SAR sensor used to adjust the aquifer numerical model.

SENSOR	ERS-1	ERS-2	ENVISAT	CSK
LIFETIME	1991-2001	1995-2011	2002-2012	2007-
WAVELENGTH/ FREQUENCY	C-band $\lambda = 05.6\text{cm}$	C-band $\lambda = 05.6\text{cm}$	C-band $\lambda = 05.6\text{cm}$	X-band $\lambda = 03.5\text{cm}$
POLARIZATION	VV	VV	HH, VV, VV/HH, HH/HV, VV/VH	Single: HH, VV, HV, VH Dual: HH/HV, HH/VV, VV/VH
RESOLUTION	Az: 6-30m Rg: 26m	Az: 6-30m Rg: 26m	Az: 28m Rg: 28m	Spotlight: $\leq 1\text{m}$ Stripmap: 3-15m ScanSAR: 30-100m
FRAME SIZE	100km	100km	100km	Spotlight: 10x10km Stripmap: 40x40km ScanSAR: 100x100 - 200x200km
REPEAT CYCLE	35 days	35 days	35 days	Satellite: 16 days Constellation: ~hrs
ACCESS	Restrained	Restrained	Restrained	Commercial; limited proposalbased scientific

A-DinSAR processing

SAR images collected by the space borne sensors have amplitude and phase information in each pixel that compose them. The SAR interferometry technique uses two SAR images of the same area acquired at different times and "interferes" (differences) them, resulting in maps called interferograms that show ground-surface displacement (range change) between the two time periods. Thanks to the availability of large SAR data archives, a stack of independent interferograms can be created from various SAR images of the same illuminated area. This allows to reconstruct displacement time series from selected point scatterers (PS) or distributed scatterers (DS) that are above a phase stability threshold in all the interferograms, using the so-called multitemporal or Advanced Differential radar interferometry (A-DInSAR)



algorithms. Any A-DInSAR algorithm dealing with data stacks, requires a number of conceptual steps that have to be sequentially performed (Casu et al., 2014). These are the SAR image focusing (if raw data is used, not needed in SLC images), the SAR image co-registration using a Digital Elevation Model (DEM), the interferogram generation, the unwrapping of the computed phases and the retrieval of the final displacement time-series. A simplified block diagram of A-DInSAR algorithms is shown in Figure 8 (De Luca et al., 2015).

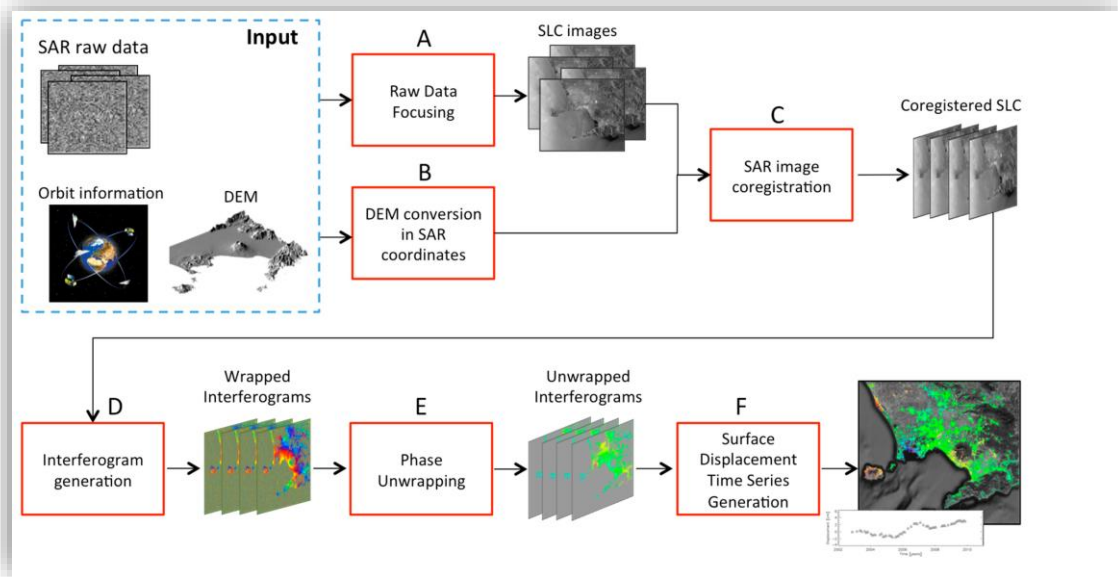


Figure 8. Simplified block diagram of A-DInSAR algorithm steps (De Luca et al., 2015).

Typically, a minimum of 15-20 images is needed to perform an A-DInSAR analysis with C-band (Crosetto et al., 2016), although it is possible to use shorter datasets with X-band due to the higher resolution and the shorter wavelength of this band (Bovenga et al., 2012). In any case, the larger the number of available scenes, the better the quality of the deformation velocity and time series estimation. There are two methods to create the stack of interferograms. The first one uses a single reference SAR image (Single master) so the number of interferograms will be $N-1$, where N is the number of SAR images. The second one uses a small baseline configuration, where a denser interferogram network is created linking multiple SAR images (Multi-master). The criterion to select the punctual targets in the interferograms can be simplified in amplitude and coherence methods. Amplitude selection methods work at full resolution and limit the interferometric processing only to those pixels that behave consistently over a long period of time (PS). Coherence based methods use distributed scatterers (DS), or in other words, areas whose scatter properties are not altered with time, which requires a multilook that lowers the resolution. A comparison of different A-DInSAR algorithms can be found in (Crosetto et al., 2016; Osmanoğlu et al., 2016) and (Minh et al., 2020). The algorithms used to compute the time series of surface displacements in the Alto Guadalentin aquifer are based on the Stanford Method for Persistent Scatterers (StaMPS) software and on

the Stable Point Network (SPN) software. Further details of SPN and StaMPS methods are summarized in Table 3.

Table 3 Comparison of A-DInSAR methods used in Alto Guadalentín aquifer model

METHOD	REFERENCE	SCATTER	PIXEL SELECTION CRITERION	NETWORK
StaMPS	(Hooper et al., 2004)	Point, distributed	Amplitude and phase criterion	Multi-master
SPN	(Crosetto et al., 2008; Duro et al., 2003)	Point, distributed	Amplitude dispersion, coherence, spectral coherence	Multi-master

Groundwater Numerical Model Development and Calibration

In order to develop a groundwater numerical flow model of the Alto Guadalentín aquifer, we have used MODFLOW-2005 with the ModelMuse interface, both developed by the USGS (Harbaugh, 2005; Winston, 2009). Modeling was carried out in two steps; first a steady-state simulation was performed using 1960 data, and second, a transient simulation for the period from 1961 to 2012 was performed using the steady-state simulation model as starting conditions. A model time step of one year was specified because the model input data such as water balance, recharge, and extraction were compiled annually.

The model is composed by three layers using square 100m grid cells over 243.5 km² across the basin. Flow between cells is controlled by Layer-Property Flow Package (LPF) due to its capability to allow later calibration of hydrogeological parameters. The first layer of the model comprises soft soils Plio-Quaternary materials, the second layer is formed by coarse-grained Plio-Quaternary sediments, and the third layer is formed by Miocene material. Due to the aquifer characteristics and the LPF available options all the layers are described as convertible layers.

Model calibration was performed using UCODE 2014 (Poeter et al., 2014) using the graphical interface Model Mate Banta (2011) developed by the IGWMC and USGS to minimize the root mean squared residual through adjustment of hydraulic conductivity and storage coefficients.

Initial hydrogeological parameters have been estimated using data from pumping tests and calibrated information from IGME IGME (1994) and CHS (1992) models. After the calibration phase is carried out over the presented model, hydraulic conductivity (K , cm/s) ranges from 2.5×10^{-3} to 9×10^{-6} depending on the layer. Coarse-grained Plio-Quaternary materials show higher hydraulic conductivity than Plio-Quaternary soft soils and Miocene layers. The calibrated storage coefficients vary from 1.5×10^{-1} to 1×10^{-3} with the highest values corresponding to the coarse-grained Plio-Quaternary layer.

Ideally, a transient groundwater flow model should begin from a steady-state condition. Because pumping from the Alto Guadalentín aquifer began more than 50 years ago, the search for information on steady-state conditions in the aquifer, used as initial condition of the



steady-state simulation step, has to go back to the information gathered by the early studies in 1960. That time was chosen because the system was not suffering significant stress. The piezometric level was between 260 and 320m a.s.l. as seen in Figure 5.

Calibration data

Model calibration has been implemented using 47 piezometric level measurement points spatially distributed with 189 annual piezometric measurements recorded (Figure 5) by IGME and CHS during consecutive measurement campaigns. Low measurement/measurement point ratio and long simulation time indicate that the available time series are not sufficiently long enough to adequately constrain the calibration. Only 4 measuring points have more than 10 years' data, with the longest one being 23 years. 14 of the remaining points present series from 4 to 10 years of piezometric levels. 29 have piezometric levels with less than 4 years, most of them with only one year. None of the 47 series covers the simulation period. The existing data is well distributed spatially but poorly in time. Additionally, near time records are even more limited, bringing to light the necessity of aquifer monitoring improvements. Piezometric level observations were implemented using the Head Observation Package (Hill et al., 2000). Piezometric series presented in Figure 5 show a continuously declining piezometric level from 1970 to more recent times with a slight recovery in some areas near the late 1980s, consistent with the aquifer history of extractions (Figure 3). Recent measured piezometric levels (2009–2012) revealed a nearly stable trend but with lower levels than older data (average decline of 90 m from 1990 to 2009), indicating a net loss of groundwater storage.

Deformation model and validation

Fusion of this groundwater model result with subsidence data resulting from SAR images processing provides the opportunity to analyse both phenomena together and establish relations between them (Ezquerro et al., 2017). Using surface deformation, piezometric level history, and soft soil thickness, we propose an empirical formulation, without geotechnical parameters and time independence, which allows the calculation of surface deformation from piezometric level changes. Parameter calibration was carried out using the ENVISAT results because its time centred position (2003–2010) permits the validation of the model fit for both earlier and later time periods using ERS (1992–2000) and CSK (2011–2012) results, respectively. Two independent variables were used to estimate deformation, piezometric level change, and soft soil thickness. Both linear and nonlinear regression models were considered. The quality of the models to replicate the observed data was assessed using coefficient of determination (r^2). Due to the importance of the soft soils layer the percentage of its thickness over complete Plio-Quaternary sediments thickness was calculated and used to distinguish areas with high percentages (>25%) where described analysis and relationships were done. The empirical deformation models were used to estimate deformation within the range of the simulated piezometric level variation. Accumulated deformation in 1992 and 2012 was estimated and validated with ERS and CSK SAR data by evaluating the ratio error/total displacement.

5 RESULTS AND CONCLUSIONS

A-DinSAR processing in Lorca

Three different sets of images were used from C-band ERS (1992–2000), ENVISAT (2003–2010), and X-band Cosmo-SkyMed (CSK) (2011–2012) satellites. InSAR-derived ground displacements covering the period 1992–2012 (Figure 9) were collected from previous studies (González and Fernández, 2011; Boni et al., 2015; Béjar et al., 2016). Deformation measurements from the ERS dataset are from Rigo et al. (2013). This dataset was processed using DORIS interferometric software (Kampes et al., 2003) to complete the coregistration and interferogram generation phases. Time series were computed using the SBAS approach (Berardino et al., 2002) through StaMPS software (Hooper, et al., 2007) (Figure 8). CSK dataset (from Boni et al., (2015)) was processed using DIAPASON for the interferometric stage and SPN software (Duro et al., 2004) during the final products calculation following the Persistent Scatterer approach.

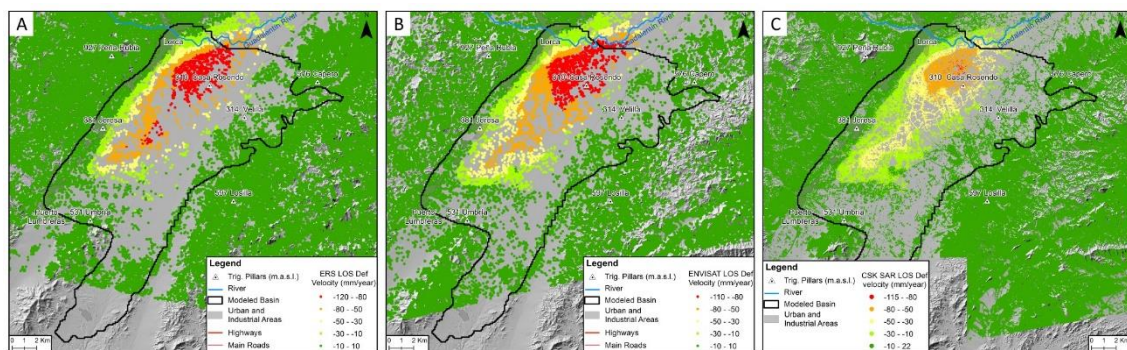


Figure 9. InSAR-derived deformation used in this study. LOS deformation velocities from (a) ERS data (C-band, 1992–2000), (b) ENVISAT data (C-band, 2003–2010), and (c) Cosmo-SkyMed data (X-band, 2011–2012). Figure modified from Boni et al. (2015) and Ezquerro et al. (2017)

Groundwater numerical model

Modeling results present the evolution of the piezometric levels throughout 52 years (1960–2012) across the Alto Guadalentín basin and how the actions on the aquifer have affected them. Figure 10 shows the results at specific and relevant dates. In 1972 during the early expansive phase of the agricultural water use and increased groundwater extractions, piezometric levels were declining slightly and uniformly, and piezometric level depressions began to form in the areas where the wells were concentrated. In 1989, at the end of the period of high, agricultural water use and groundwater extractions when the aquifer was declared partially overexploited, piezometric levels had declined between 100 and 160 m from their original position, creating two steep depressions surrounding the eastern and western well fields. After the measures adopted by the basin management authorities, a decrease in agricultural water use, and consecutive rainy years from 1989 to 1993 (Figure 3), model results in 1993 reflect a slight recovery in some areas of piezometric levels. The inactivity of the



extractive activity in the eastern well field produced the recovery of the piezometric levels over the surrounding area. This fact suggests the ability of the aquifer system to recover its piezometric levels after severe extractions were stopped. Progressive increases in extractions and a lower rainfall period with three severe droughts associated CHS (2015) led to declining piezometric levels by the end of the simulation period in 2012. The active western well field produced a water level decrement of 70m from 1993 and an overall decrement of 40 m throughout the basin.

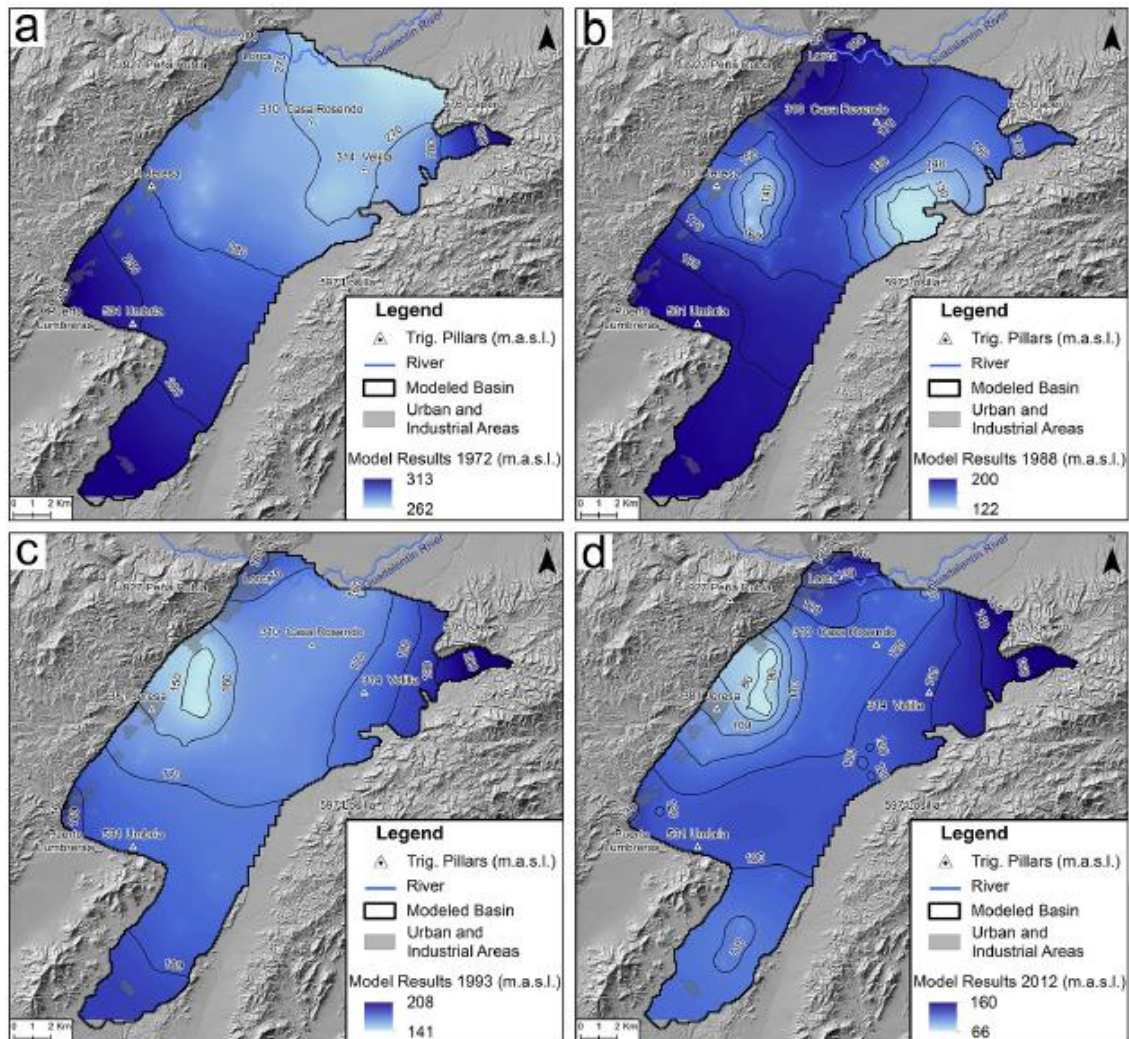


Figure 10. Groundwater model results in different years. Computed hydraulic head spatial distribution 1972 (a), 1988 (b), 1993 (c), and 2012 (d) (Ezquerro et al., 2017)

In order to evaluate the groundwater model results two important factors must be taken into account: its length, 52 years, and the piezometric level global change, between 170 and 210 m. Both of them can generate important differences between results and observations with slight changes in water contributions and uses (specially, pumping rates and watering). Despite these limitations the computed model levels fit well with the observations. Figure 11 shows the



simulated levels against the observed levels at the validation points. These values group around the $X = Y$ line with an RSME of 17.4 m. Average absolute difference between simulated and observed piezometric levels is 14.9 m. Assuming an average piezometric level drop of 190 m, both errors are under 10% of the total water displacement, an acceptable error for a long duration regional model.

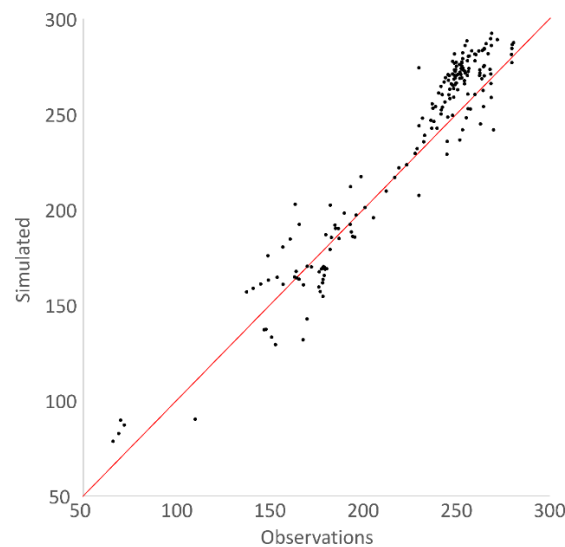


Figure 11. Groundwater model calibration diagram. Black points represent each water level datum observed and its simulated position. Red line is $X = Y$ line

An overall comparison of simulated piezometric data reflects a slight overestimation trend in the modeled level (piezometer 2539-1-001) converging both series towards the 1980s (piezometers 2539-2-043, 2539-6-024). From that date the model shows better results as can be seen in piezometer 2539-2-011. Piezometers related to the well fields (2539-2-011, 2539-2-043, 2539-3-066, or 2539-3-119) display some of the best fits between modeled and observed series, supporting a precise estimation of water extraction effects in the aquifer system dynamic. The northern area, with denser urbanization and specially affected by subsidence processes (Rigo et al., 2013; Boni et al., 2015), is located within the best fitting zone.

SAR deformation model

Statistical analysis of deformation and piezometric change series results in a low correlation between them ($r^2 < 0.05$). Despite the poor relationship observed, this study was able to reveal the presence of at least two data populations in the original data. Previous studies in the Alto Guadalentín basin have already probed the relationship between deformation and soft soil thickness (Boni et al., 2015; Béjar et al., 2016). Taking into account those works, the percentage of soft soils thickness over the complete Plio-Quaternary materials thickness has been computed. Using this parameter to identify the two observed populations, original SAR deformation data were divided into two samples of 1597 (percentage of soft soils over 25%) and 3393 (percentage under 25%) points each one. SAR deformation points with soft soils percentage over 25% show a stronger relationship ($r^2 = 0.61$) with piezometric changes and were selected to calibrate the deformation model.



Exponential term for thickness and linear term for piezometric level changes is disclosed as the best formulation to describe the relationship between water, thickness, and deformation. This correlation range of validity is for soft soils thickness over 10m and piezometric changes from 8.5m to 25 m. Calculated deformations out of the range are subjected to high error or incoherent results. Deformations are overestimated with low water changes while high piezometric variations generate underestimated deformations.

Deformation derived from CSK data (2011-2012) was added to the ENVISAT time series due to its short time span and the previously described problems with water changes out of the validity range. Model results for the period 2003–2012 (Figure 12) show differences between the simulated and measured spatial deformations patterns, but simulated maximum values are close to measured values (difference under 4%). Spatial discrepancy is mainly related to the influence of the soft soil thickness pattern in the model. The increasing error from present to past is caused by one of the most important limitations of this model, the temporal position of the calibration period in the deformation history. Material stress due to water withdraw began in 1960 and the calibrated relation calculated during ENVISAT period is related to an inelastic deformation period. Empirical relations calculated are related to inelastic deformations that need less water changes than elastic ones to generate the same deformation and overestimate ancient deformations.

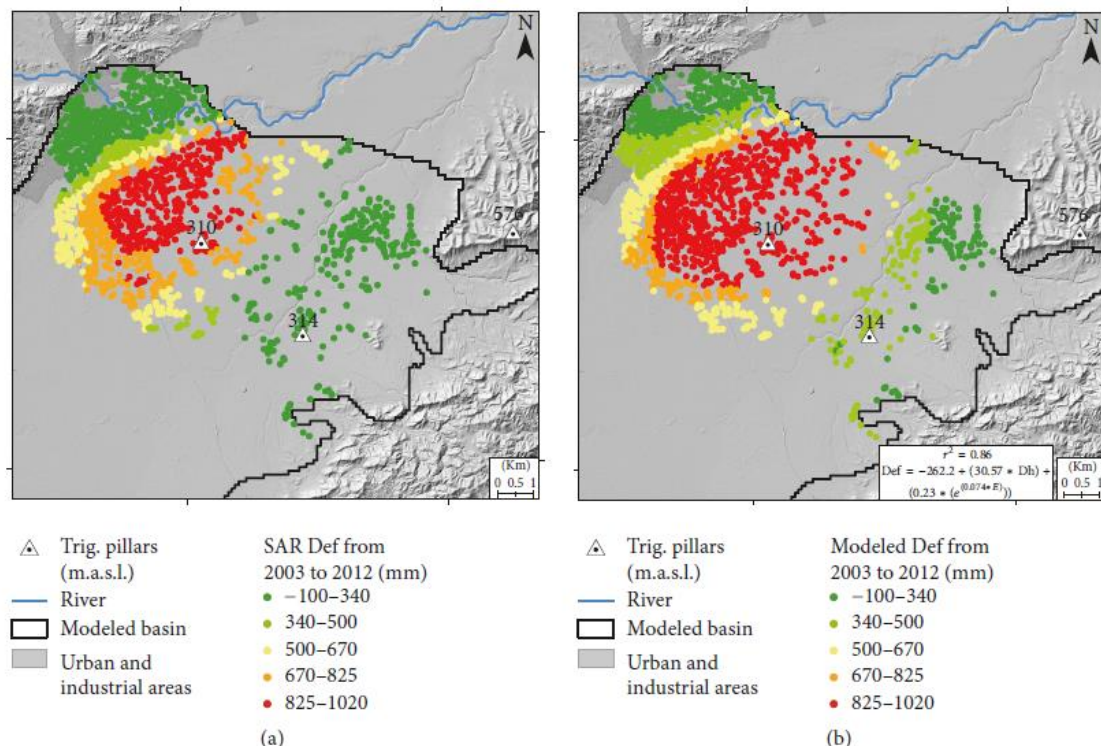


Figure 12. Results of the surface deformation modeled for the period 2003–2012 (ENVISAT + Cosmo-SkyMed). (a) SAR deformation measured from 2003 to 2012. (b) Calculated deformation using an exponential thickness model

Conclusions

It has been presented a hydrogeological model of an aquifer system that has experienced intensive pumping activities generating average piezometric level declines of about 150m during a period of 52 years (1960–2012). The model simulates changes in groundwater flow, from the original steady state conditions in the aquifer system to 2012 conditions, increasing our knowledge about the aquifer system behavior under stress in order to improve its management. The evolution of piezometry from this model is also a valuable constraint for geomechanical modeling aimed at characterizing the Alto Guadalentín basin that has one of the greatest subsidence rates in Europe (11 cm/yr).

The use of DInSAR has led to a better deformation monitoring due to exploitation of its spatial coverage and high-density measurements unattainable by traditional methods. The detailed characterization of the basin materials carried out by Bonì et al. (2015) through geological and SAR deformation data analysis has been used to refine the conceptual groundwater model. These geological updates constitute a first contribution of SAR data to improve water management.

Coupling groundwater flow and subsidence models can be used to refine the original groundwater model and better integrate the deformation data. Thanks to the European Space Agency (ESA) Sentinel-1 constellation, the monitoring of the study area continues today with enhanced characteristics of wide spatial coverage, great temporal resolution (six days' repeat cycle), and high spatial resolution. Future works combining these results with climatic change scenarios could facilitate the integration of piezometric level and deformation predictions into the management of the aquifer system, by assessing variability of water resources storage in the aquifer.

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Data used in this work have used CSK® Products, © ASI (Italian Space Agency), delivered under an ASI licence to use: ASI Project Science Id 408 “Study of surface deformation due to groundwater exploitation in southern Spain”.

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