Zapata-Sierra *et al.*
Environmental Sciences Europe (2022) 34:75
https://doi.org/10.1186/s12302-022-00649-5

Environmental Sciences Europe

RESEARCH Open Access

Water resources availability in southern Europe at the basin scale in response to climate change scenarios

Antonio Jesús Zapata-Sierra*, Lourdes Zapata-Castillo and Francisco Manzano-Agugliaro*

Abstract

Background: Climate and the hydrological cycle are closely linked; therefore, in the most likely scenarios of climate change, the increase in temperature may influence the expected variation in precipitation variation but will also have a major impact on the availability of water resources in the world in general and in southern Europe in particular. As a case study, it was applied to a western Mediterranean basin altered since antiquity. For this study, the medium and long-term water resources were assessed. The known method Soil Moisture Accounting (SMA) has been used. Mainly because due to its great hydrological relevance in mountainous areas, the accumulation and melting of snow. The aim of this research to assess the evolution of runoff distribution and its impact on available water resources under different climate change scenarios.

Results: It was observed clearly a decreasing of precipitation and evapotranspiration and otherwise an increasing of temperature. The major climatic effect is that at present, runoff is already much lower than that predicted in the different basin hydrological policy. Specifically for the studied basin, the available resources are expected to decrease by 50% with respect to the current ones, affecting mainly the current agricultural land uses, which should be reconsidered in the medium term.

Conclusions: It can be concluded that surface water use policy was calculated with climatic assumptions that are no longer met. Consequently, this research reveals the usefulness of basin-scale climate studies in southern Europe to determine the water resources availability in the near future.

Keywords: Mediterranean climate, Climatic change, Sustainability, Water resources, Hydrological cycle, Agriculture

Introduction

It is widely accepted that climate change and water resources availability are strongly linked [25, 40]. Climate change, in particular, affect the hydrology that determines the risk of flooding, the water resources available for human, environmental, and also agricultural needs in the medium term [80]. Changes in the behaviour of natural systems have been observed in the form of temperature increases on a continental scale that cannot be explained solely by natural climatic variations [68]. The scientific community has shown that many small, short- and medium-term factors can alter the climate, especially at the local level. Among these factors there are some associated with human activity as atmospheric turbidity or CO_2 concentration [45]. However, other authors show that the changes cannot be strictly attributed to human activity [73]. However, it is a fact that a change is happening, and it is convenient to implement the measures to avoid this being a problem for people's well-being [42]. The Intergovernmental Panel on Climate Change (IPCC) created in 1998 is the United Nations body for the assessment of scientific knowledge related to climate change. The IPCC has already warned of global warming of 1.5 °C

---

*Correspondence: ajzapata@ual.es; fmanzano@ual.es

Department of Engineering, ceiA3, University of Almeria, Ctra. De Sacramento, s/n, 04120 Almería, Spain

above pre-industrial levels due to various factors such as the emission of greenhouse gas emissions [40]. The path and extent of hydrological changes caused by land use change and land surface retrofitting vary by location and season.

Most projected changes in the water cycle are not expected to be uniform in space or time [21]. Hydrological phenomena must be investigated at two scales, time, and space [20]. Regarding scale levels, the first would be the micro-scale or plot-level [55]. When the study of hydrological processes is applied from the micro-scale level to the basin scale or watersheds, a considerable complexity emerges [84]. So, watersheds are the product of the evolutionary processes of geomorphology, and of human interaction [12]. Climatic changes can affect the water resources available at the basin scale in many ways [6]. However, the IPCC AR5 report was a major breakthrough in the assessment of human influence on the Earth's water cycle, but regional projections of precipitation and water resources remained highly uncertain for a number of reasons including model uncertainty and the strong influence of internal variability. The use of available water resources is being employed in many regions of the world for agricultural irrigation [16]. This can increase agricultural productivity and contribute to the creation of more and higher quality food so necessary in a globalized world with a constantly growing population [4]. The success of agricultural water management policies highlights the limitations of land use [32]. Furthermore, arid, and semi-arid regions are particularly at risk from global environmental change due to their highly fragile climatic conditions [71].Climate change will involve changes in humidity and drought in several regions of the planet [76]. Precipitation is expected to increase in high latitudes, while it will decrease in large parts of the subtropics [22]. Further warming will amplify permafrost thaw [9], loss of seasonal snow cover [33], and melting of glaciers and ice sheets [18]. For cities in warm zones, as urban areas tend to be warmer than their surroundings [48], some aspects of climate change may be amplified [37], such as heat, flooding from heavy precipitation [26], or sea level rise in coastal cities [47].

Other authors indicate that trends in major climatic variables, such as precipitation, snowfall or temperature, have a direct impact on groundwater storage conditions, and thus on spring discharge quantities [49]. Therefore, the analysis of long-term time series of these variables can facilitate the investigation of the possible effects or trends of climate change on the availability of the water resource [31].

In the Mediterranean area, a decrease in precipitation and an increase in maximum temperatures, especially in the warm season, are expected [30]. In addition, to the clear trend towards decreasing precipitation and increasing temperatures throughout the area [78], a greater variability in the amounts and dispersion of the dates of occurrence of each individual event is also expected [65]. These predicted factors may have a dramatic influence on the region's water resources [38].

Mediterranean conditions present very specific constraints for water resources management [2]. These are mainly due to the seasonal mismatch between water availability and water requirements, both in annual and multi-year terms [36]. Moreover, the relationship between water, soil, and environment in this type of climate can increase these problems [13]. In addition, heavily transformed watersheds, especially in terms of agricultural use, suffer a strong impact on soil and water resources, both in terms of quality and quantity [86].

Strong evidence that climate warming combined with direct human demand for groundwater will deplete groundwater resources in already dry regions [41]. The south-eastern Spain can be considered as a semi-arid climate zone. The Almeria area, unlike the rest of the Iberian Peninsula, most of the water resources for the different types of use (supply, irrigation, and industrial uses) do not come from reservoirs. About 80% of the resources come from groundwater [15]. Despite this, in traditional cultivation areas such as olive groves, almond trees or cereals, covering most areas far from the coast, the surface water resource is crucial mainly due to its good quality [27].

It is important to assess the impact on the available resources of this possible new scenario, scarcity of surface water resources, and then it should be considered that hydrological calculations require an adequate scale [72] and a large volume of data is required to obtain proper estimation accuracy [35]. The best way to manage the large geographical information data is to integrate in a Geographic Information Systems (GIS) implemented with a hydrological simulation model [19]. From the predictive analysis point of view, physically based models are more interesting since, once adjusted and contrasted, they can forecast the near future [51].

This manuscript proposes a methodology to analyse the evolution of runoff distribution and its impact on available water resources under different climate change scenarios, thus being able to examine the sustainability of land uses, especially agricultural land uses. For this purpose, this methodology was applied as a case study to a modified basin since antiquity in the western Mediterranean.

The study area: the Almeria River Basin

Territorial framework

The studied basin has 61,845 inhabitants [62], but although the city of Almeria (with 200,000 inhabitants) is outside the basin, it is within its flood zone and receives groundwater from it. The basin situation is shown in Fig. 1.

The Almeria River basin has a very varied vegetation cover, from alpine climate zones to temperate forest, cropland, Mediterranean shrub land and even sub desert in some parts of the basin [5]. The Neolithic [1] and Bronze Age [29] settlements left a deep imprint, as they were peoples who profoundly altered the vegetation cover, mainly by eliminating forests and changing them for pastures and scrublands [57].

The major transformation of the area began with the Arab settlement, with the introduction of irrigated crops [79], such as orange trees, horticulture, sugar cane, etc. From this period, the first catchments of runoff water for irrigation purposes can be dated [14], as well as the galleries and wells for groundwater extraction. These practices have persisted to the present day [63] with a moderate growth in both the number and technology of water catchments. The climate of the area tends to concentrate rainfall events in a few events per year [10], which represents an added difficulty for the use of surface water bodies. Although according to some authors, the climate of this area may have a cyclical behaviour, both for temperature [7] and rainfall [69], others however have not found any specific pattern [8]. At the nineteenth century, the grape dominated the economic activity [28], which has now lost most of its surface area, maintaining only 65 ha. Currently, the basin irrigates 6400 ha, consisting of olive trees (3520 ha), almond trees (840 ha), citrus (800 ha) and greenhouse crops (510 ha).

Spatial data

The physical and hydrological characterization of the basin was carried out using ArcGIS 10.4 implemented with the HEC Geo-HMS toolbar for that version. The delimitation of the sub-basins and their general properties was obtained from the Digital Elevation Model

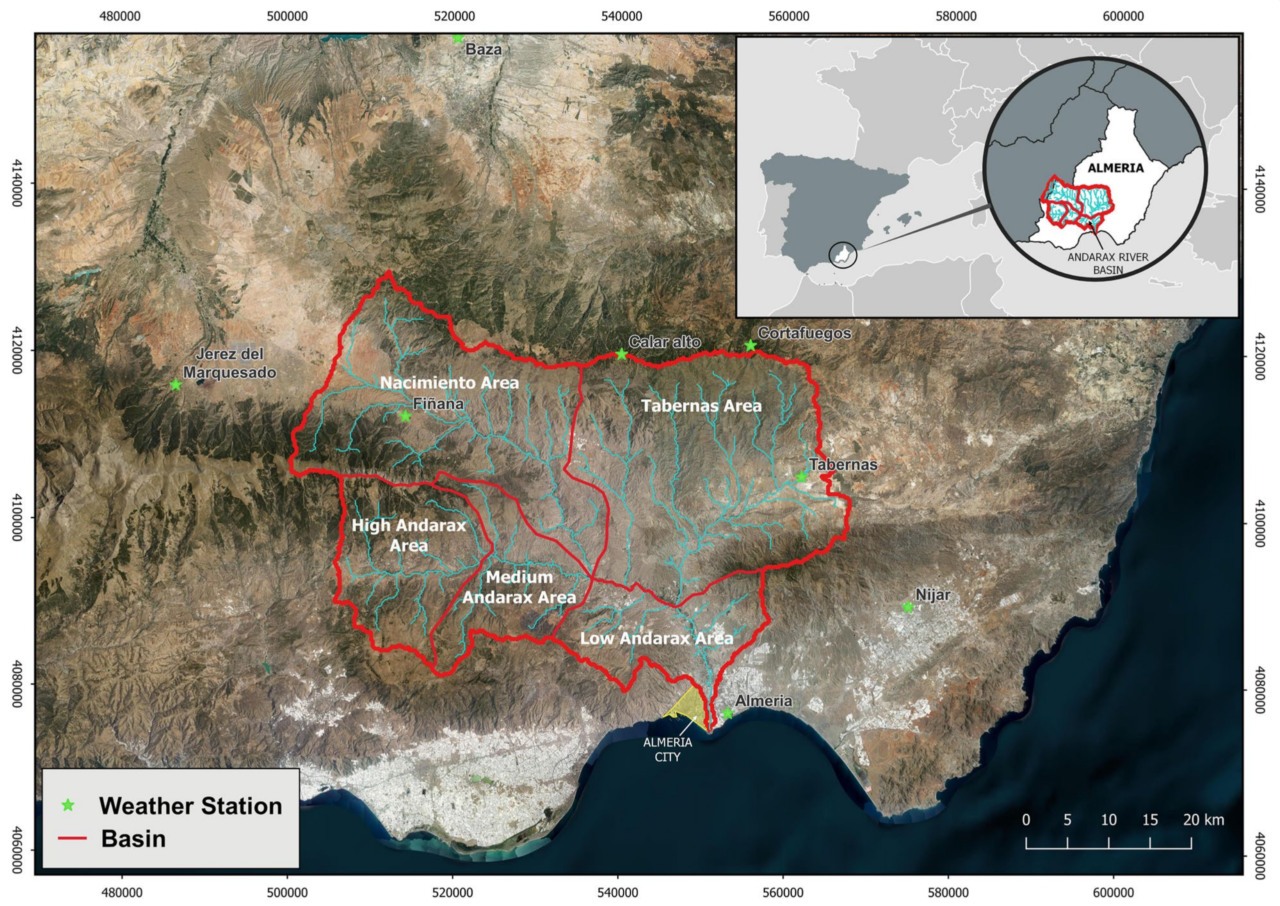

Fig. 1 Location of Almeria River in SE Spain

(DEM) of Andalusia [52], provided by the National Geographic Service. A summary of the basin DEM is shown in Fig. 2. Other data were obtained in vector and raster format from the DEM, Spanish Land Cover Information [74], soil type [82] and geological material [83]. Hydrological values were obtained from the LUCDEME project report [50]. As can be seen in Fig. 2, the elevation of the basin is from sea level to 2300 m above sea level. The main indicators of the basin, Table 1, are a total surface area of 2147 km^2 of which the agricultural surface

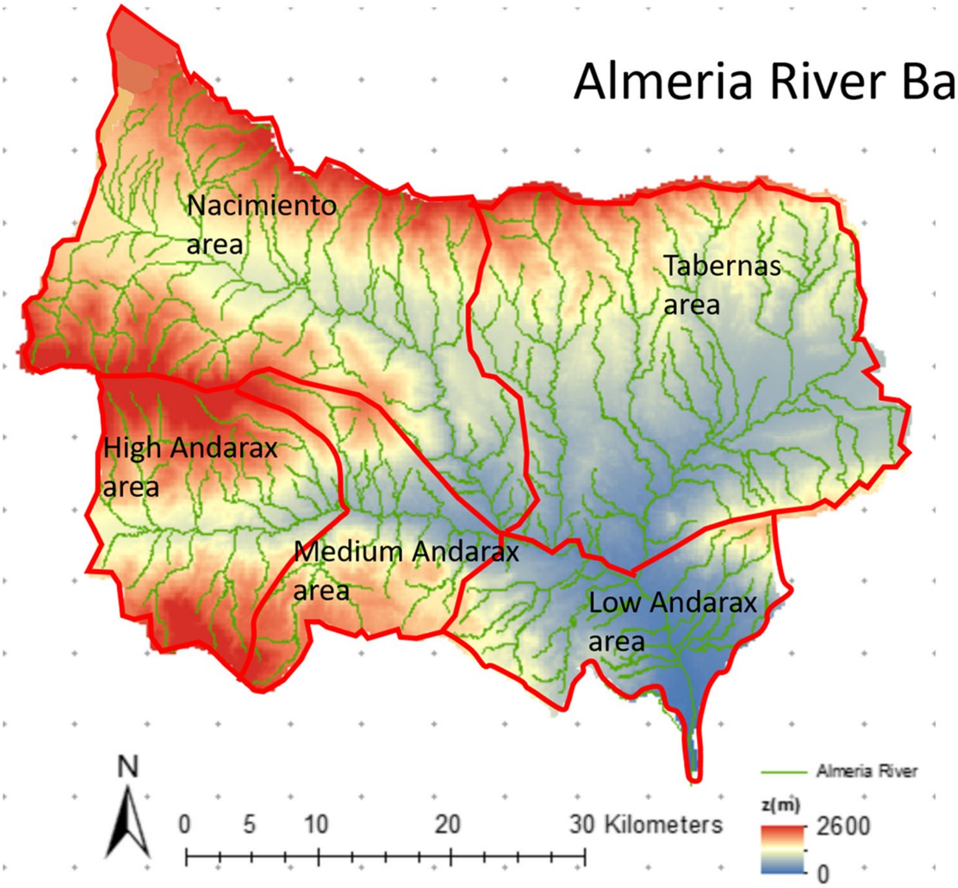

Fig. 2 DEM of Almeria River basin and its main areas

Table 1 UTM coordinates, elevation (Z), annual mean daily temperature (ºC), mean annual precipitation and Evapotranspiration (mm) of studied stations

Weather station	X (m)	Y (m)	Z (m)	T (ºC)	P (mm/year)	ET$_0$ (mm/year)
Almeria	553,282	4,076,780	5	19.01	213.75	1305.36
Nijar	574,960	4,089,720	169	18.13	243.09	1380.03
Tabernas	561,998	4,105,230	502	16.36	241.15	1426.09
Fiñana	514,311	4,112,270	958	15.12	286.83	1490.80
Baza	520,514	4,157,520	718	14.60	360.86	1369.81
Jerez del Marquesado	486,699	4,116,020	1201	13.13	333.26	1317.26
Cortafuegos	555,762	4,120,907	1770	10.47	335.46	935.00
Calar alto	540,267	4,119,775	2168	6.99	279.22	734.23

area is approximately 10%, 42% of which is irrigated, i.e., some 9600 hectares.

Climatic data

The main meteorological parameters used were from the Irrigation Advisory Service (RIA) of the Junta de Andalucía [23]: air temperature, relative humidity, wind speed, wind direction, solar radiation, and precipitation every 20 min. These data allow the calculation of the reference evapotranspiration (ET_0), which is a key element for estimating irrigation needs. For this research, the stations of Baza, Jerez del Marquesado, Fiñana, Tabernas, Nijar and Almeria have been used. The RIA has been operational since 1999 in all the selected stations. Data provided by the Calar Alto Astronomical Observatory [56] every 5 min between 2001 and 2011 were also available.

In 2001, a whole meteorological station was established in the Sierra de los Filabres, located in the so-called Collado de Yuste (municipality of Senes), which for this work has been called Cortafuegos. The position of the meteorological stations is shown in Table 1, where the averages of temperature (T), precipitation (R) and reference evapotranspiration (ET_0) from 2001 to 2020 every 10 min are provided. Note that, RIA stations provide ET_0 data calculated with the FAO-56 Penman–Monteith Equation [3], for the other stations, the same method has been applied.

Table 1 shows the average values for the different measurement stations, e.g. the average rainfall varies between 213 and 360 mm/year, for average temperatures between 7 and 19 °C.

Legally authorized water resources in the Almeria River Basin

The current water balance in the basin is shown in Fig. 3. The Hydrological Plans include a complete water supply using desalinated water for the city of Almeria. It is also planned to reuse reclaimed water for irrigation, both within the study basin and in other areas, see Fig. 3.

The case of surface water resources needs special consideration due to the nature of their catchment. A hydraulic scheme of an intake, adapted to the HEC-HMS model methodology, is shown in Fig. 4.

Evidence of the high degree of change in the basin caused by human use of water resources is reflected in the very large number of catchments. The position of the most relevant ones is shown in Fig. 5 and their names and characteristics in Table 2. They have been grouped into units that respect the basin structure schematized for the HEC model.

Official information [59] was also available and describes, for the years evaluated, 2001–2020, in this research, the legally available resources for urban catchments and for irrigation. This information reports the resources evaluated in previous years and are therefore suitable for assessing the variation of resource availability

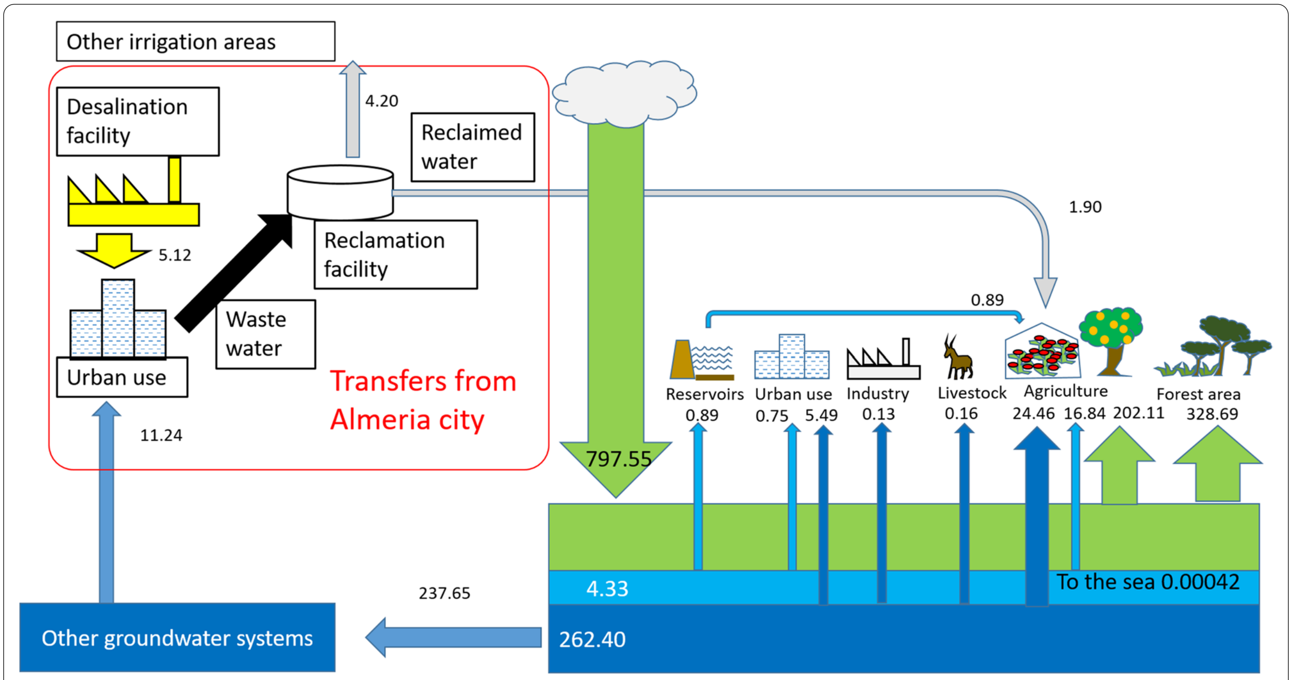

Fig. 3 Water resources balance in the Almeria basin (data in $hm^3 = 10^6\ m^3$). For the city of Almeria the data are according to the 2015–2021 hydrological plan

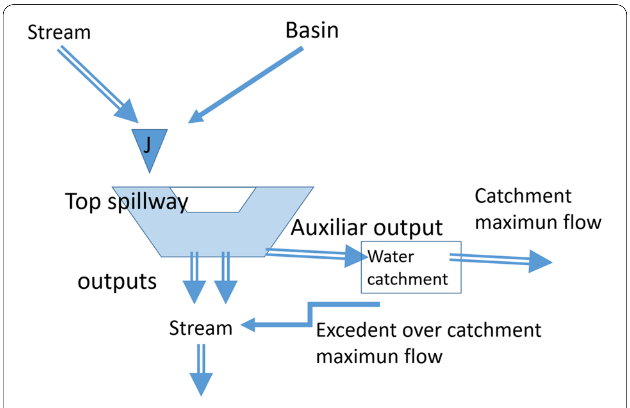

Fig. 4 Water catchment scheme for urban and irrigation purposes

over time. The volumes authorized for irrigation are shown in Table 4.

Urban management in the Almeria River Basin

The average urban consumption in Spain is 92.29 m^3/inhabitant/y, although for the basin studied it is 100.89 m^3/inhabitant/y. Under these conditions, the basin should supply surface water to 7433 inhabitants, which is only the 12% of the current population of 61,845 people. The surface and groundwater resources authorized for urban use, grouped by geographical area, are shown in Table 3.

Agricultural management in the Almeria River Basin

For agricultural use, the water resources legally authorized for irrigation purposes are shown in Table 4. This volume of water resources, for an average consumption of 3600 m^3/ha, implies the possibility of irrigating 4675 ha with surface water. As the basin supports 6400 ha of irrigation, surface water would represent 73% of current irrigation. Intakes have been calculated in the model to be able to switch these quantities. Intakes to urban water supply are accurately identified, but irrigation intakes often involve several catchment points. Regarding irrigation, it should be noted that reclaimed water from the city of Almeria is also used. There are also two small reservoirs at the headwaters of the river source.

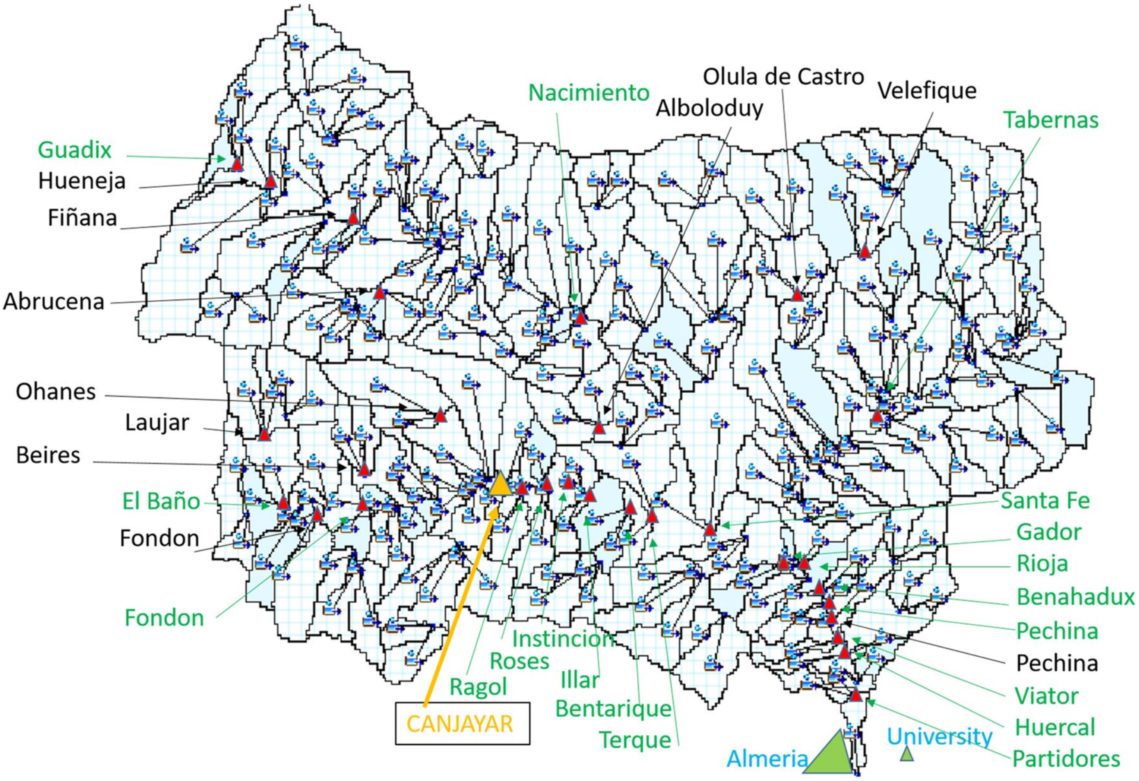

Fig. 5 Sub-basins for Almeria River. Green name for irrigation diversion. Black name for urban water diversion. Diversions as red triangles. Flow data diversion point (Canjayar) in orange. Almeria city and University in Green triangle

Table 2 Surface water intakes for urban water supply

Village	Area	Maximum volume (m^3)	Maximum flow (m^3/s)
Hueneja	Nacimiento	130,000	0.00420
Abrucena	Nacimiento	100,000	0.00350
Fiñana	Nacimiento	60,000	0.02500
Alboloduy	Nacimiento	50,000	0.00180
Laujar de Andarax	High Andarax	90,000	0.00280
Fondon	High Andarax	10,000	0.00035
Ohanes	Medium Andarax	30,000	0.00080
Almocita	Medium Andarax	20,000	0.00060
Beires	Medium Andarax	10,000	0.00030
Canjayar	Medium Andarax	90,000	0.00270
Olula de Castro	Tabernas	10,000	0.00035
Velefique	Tabernas	70,000	0.00228
Pechina	Low Andarax	80,000	0.00240
Total		750,000	

Table 3 Urban consumption legally authorized in the basin (m^3)

Area	Surface	Groundwater	Total
Nacimiento	340,000	440,000	780,000
High Andarax	130,000	200,000	330,000
Medium Andarax	120,000	320,000	440,000
Tabernas	80,000	360,000	440,000
Low Andarax	80,000	4,170,000	4,250,000
Total	750,000	5,490,000	6,240,000

Industrial and livestock management in the Almeria River Basin

The authorized industrial and livestock uses are shown in the Table 5. As a particular feature, all of these resources are groundwater resources.

Table 5 Industrial and livestock uses (m^3)

Area	Industry	Livestock	Total
Nacimiento	0	23,385	23,385
High Andarax	0	9,642	9,642
Medium Andarax	0	13,086	13,086
Tabernas	70,000	101,353	171,353
Low Andarax	60,000	12,534	72,534
Total	130,000	160,000	290,000

Summary of authorized water use in the Almeria River Basin

The resources authorized in the basin can be summarized in Table 6. Groundwater is collected through wells and, to a lesser extent, through drainage galleries. Reclamation is carried out by ozone facility located at the downstream end of the basin and pumped for use primarily in intensive horticulture, since its high boron content makes it unsuitable for citrus cultivation.

Methods

HEC-HMS

The Hydrologic Modelling System (HEC-HMS) is designed to simulate rainfall-runoff processes in dendritic drainage basins [11]. It is suitable for a wide range of geographical areas to solve many potential issues. These include the water supply of large river basins [54, 85], flood hydrology [46], and runoff from small urban or natural catchments [53]. The hydrographs generated by the program independently or in association with other software. This allows assessment of water availability, urban drainage, flow forecasting, and impact of future urbanization, reservoir spillway design, flood damage reduction, floodplain regulation, or system operation.

The software is a multi-purpose system able to model many different river basins or watersheds. A model of the river basin is constructed by segregating the water cycle into tractable parts and building boundaries around the studied basin [17]. Thus, a mathematical model can then describe every flow of mass or energy in the cycle. Several modelling options are available to represent each flow. Each mathematical model is suitable in different environments and under different

Table 4 Water resources legally authorized for irrigation purposes (m^3)

Area	Regulated surface (m^3)	Flowing surface (m^3)	Maximum flow (m^3/s)	Ground water (m^3)	Reclaimed (m^3)	Total (m^3)
Nacimiento	890,000	8,320,000	0.2580	5,390,000	0	14,600,000
High Andarax	0	1,980,000	0.0628	800,000	0	2,780,000
Medium Andarax	0	3,760,000	0.1191	6,980,000	0	10,740,000
Tabernas	0	250,000	0.0078	4,490,000	0	4,740,000
Low Andarax	0	2,530,000	0.0800	6,800,000	1,900,000	11,230,000
Total	890,000	16,840,000		24,460,000	1,900,000	44,090,000

Table 6 Summary of authorized consumption (m^3)

Authorized	Regulated	Flowing surface	Groundwater	Reclaimed	Total
Urban water	0	750,000	5,490,000	0	6,240,000
Irrigation	890,000	16,840,000	24,460,000	1,900,000	44,090,000
Industry	0	0	130,000	0	130,000
Livestock	0	0	160,000	0	160,000
Total	890,000	17,590,000	30,240,000	1,900,000	50,620,000

conditions. The proper alternative involves knowledge of the watershed, the objectives of the hydrologic study, and engineering criteria.

For this research, the medium and long-term assessment of water resources is of specific relevance and a tool of the HEC HMS model is highly suitable for this purpose. This method is known as Soil Moisture Accounting (SMA) and involves several successive balances of the different layers in which water can be stored and consumed within the water-soil–plant cycle [44, 58]. In addition, it is possible to describe the snow storage and melting of snow, a process of huge hydrological relevance in mountainous areas [34]. The snow storage and its later melting reduces the extreme values of runoff and makes it possible to generate a more regular and, therefore, usable flow for water supply [24].

Basin model

The HEC model presents a distinct set of sections; on the one hand, the watershed must be characterized with all the physical properties of soils, surface and vegetation. The basin was divided into sub-basins and their hydrological properties were calculated using a GIS. The complete model was calibrated with the gauging measurements taken during the years 2001 to 2005. The Rawls and Brakensiek transfer function was used for the calibration of the permeability data at different soils [67], the texture and depth data were collected by the LUCDEME Project. Previous works showed that vegetation cover could even multiply the value obtained by this methodology by a factor of 10 [88].

The result of the model calibration process was used to check with data from other years not involved in this adjustment. The adjustment process was performed non-automatically, and thus the concordance index could be used. The model was fitted and tested with a sequence of 4 years of flow gauging data for a station located near the locality of Canjayar, as shown in Fig. 5.

Applying GIS watershed delimitation tools, it was found that the Almeria River basin has 2147 km^2 and was subdivided into 241 sub-basins with 120 river reaches. These elements were hydrologically characterized using available cartography and field measurements for additional measurements, such as channel profiles and catchment measurements.

The year 2003–2004 was selected for the adjustment of permeability as the most sensitive parameter, Fig. 6A. The value was simultaneously modified proportionally in all the elements of the basin to achieve a close result between the hydrograph simulated and the hydrograph measured. For the adjustment, the parameter called agreement index I_a Eq. 1 [81] was used and compared with RMSE (square root of the sum of the squared errors) Eq. 2 and MAE (mean of the errors in absolute value) Eq. 3, Table 7.

Agreement index (as coefficient of variation)

$$I_a = 1 - \frac{\sum_{i=1}^{n} (x_{i.m} - x_{i.e})^2}{\sum_{i=1}^{n} (|x_{i.m}| - |x_{i.e}|)^2} \tag{1}$$

where $x_{i.m}$: the measured values, $x_{i.e}$: the estimated values, n: total number of data.

RMSE (square root of the sum of the squared errors)

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_{i.m} - x_{i.e})^2} \tag{2}$$

MAE (mean of the errors in absolute value)

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |x_{i.m} - x_{i.e}| \tag{3}$$

The values of the adjustment with the different indices obtained were those shown in Table 7. The adjustment of the model was done with year 2003–2004. The validation of the model was performed for the years 2003–2002 (Fig. 6B), 2002–2001 (Fig. 6C), and 2000–2001 (Fig. 6D), for all the years for which measured data were available.

Climate model

Another section of the model is the description of the climate pattern. For this part it is possible to run

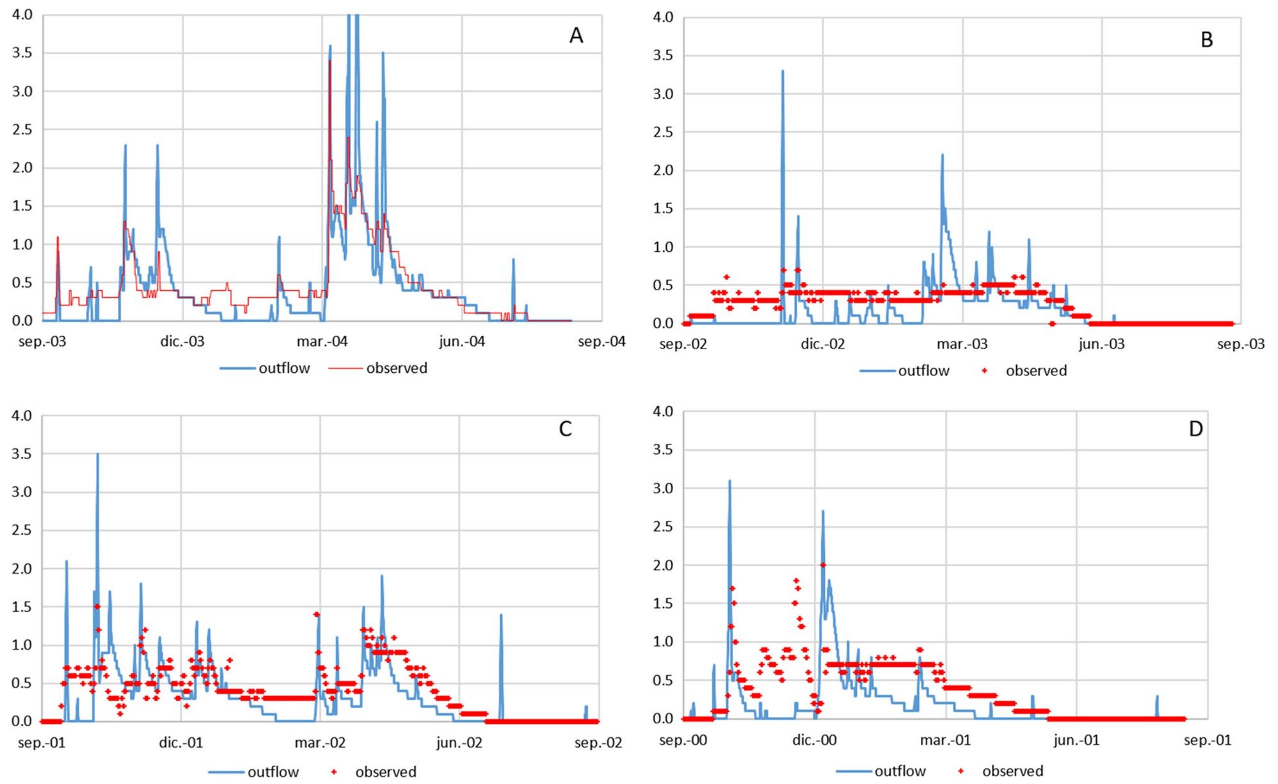

Fig. 6 Adjustment model. **A** Adjustment (2003–2004). **B** Validation 2002–2003. **C** Validation 2001–2002. **D** Validation 2000–2001

Table 7 Assessment of adjustment indexes

	Figure	Year	RMSE	MAE	I_a
Adjustment	Figure 6A	2003–2004	0.4060	0.1984	0.9050
Validation 1	Figure 6B	2002–2003	0.2759	0.1777	0.7587
Validation 2	Figure 6C	2002–2001	0.2440	0.1984	0.9010
Validation 3	Figure 6D	2000–2001	0.3968	0.2472	0.7482

climate data with a large variety of time steps. The model supports data between 1 min and 24 h, but these will be interpolated or grouped to fit the time increment chosen for the calculation. It is possible to set the position of the stations and the centroid of each sub-basin. In this way, an interpolation of each data can be performed by the inverse of the square of the distances, enhanced by data from each sub-basin. This section allows the description of different zones according to the behaviour of the snow. For this it is necessary to specify the temperature gradient and the altitude of each zone.

Hydrological models and in particular HEC-HMS require complete data series. To complete the missing data in the sequence of each meteorological station, the nearby stations have been used. A proportional average has been established with respect to the nearby stations to complete the target station [87]. Those combinations that offered the best correlation coefficient were selected.

Other functionalities of the model allow different time windows for the analysis, allowing an integrated long-term period approach, suitable for resource balance studies, suitable for resource assessment, or short periods, more suitable for studies of extreme events oriented to the design of safety infrastructures. There is a tool available for the input of climatic data, geometric description of specific structures and even measured hydrographs.

Climate scenarios

Annual parameters trends

To determine in the study region the characteristics of the possible climate change, the linear trends of the annual means of each parameter of hydrological interest have been determined. Once the dispersion has been eliminated, it is possible to infer the general trends for each station and their relationship to the specific position of the station in the basin. The linear trend parameters ($y = m \cdot x + b$) of each annual mean

Table 8 Linear trend parameters ($y = m \cdot x + b$). Slope (m) and independent term (b) of the annual linear trends at each station for the years 2000–2020

m

Weather station	T (°C)	H (%)	w (m/s)	R (MJ/m^{2}day)	P (mm)	ET$_0$ (mm/day)
Almeria	– 0.005	0.250	– 0.011	– 0.028	– 1.215	– 0.012
Nijar	0.037	0.072	– 0.014	0.156	0.583	0.016
Tabernas	– 0.023	0.133	– 0.005	0.042	– 4.455	0.000
Fiñana	0.008	– 0.031	– 0.019	– 0.017	– 3.637	– 0.008
Jerez	0.025	– 0.031	– 0.005	0.019	– 1.413	0.000
Baza	0.008	0.322	– 0.018	0.005	1.239	– 0.014
Cortafuegos	0.110	– 0.370	– 0.018	0.315	– 7.754	0.012
Calar Alto	0.063	– 0.284	– 0.038	– 0.144	– 10.085	– 0.001

b

Weather station	T (°C)	H (%)	w (m/s)	R (MJ/m^{2}day)	P (mm)	ET$_0$ (mm/day)
Almeria	28.33	– 803.78	23.35	75.78	2654.21	27.62
Nijar	– 57.03	– 378.79	30.34	– 296.13	– 930.59	– 28.44
Tabernas	62.84	– 407.22	11.46	– 66.55	9198.22	3.62
Fiñana	– 0.18	– 23.38	40.30	52.16	7599.42	19.27
Jerez	– 36.82	– 60.38	11.18	– 20.21	3182.34	3.47
Baza	– 1.90	– 1058.90	38.22	8.34	– 2125.21	31.69
Cortafuegos	– 211.37	800.64	40.11	– 597.27	15,908.71	– 21.12
Calar Alto	– 119.17	639.26	82.20	293.09	20,499.95	4.55

T mean temperature, *H* relative humidity, *w* wind speed, *R* solar radiation, *P* precipitation, *ET$_0$* reference evapotranspiration

climate parameter (y) as a function of year (x) for each meteorological station are shown in Table 8. Note that the equations take $x = 0$ as the origin, which for a graph that starts in the year 2000 does not provide a value of b that matches the intersection with the ordinate axis. However, this is useful if one wants to reproduce the estimated value of each variable when having the full equation.

The temperature increase observed in the trend is less than the natural oscillation over the years. The data indicate that the temperature increases 0.16 °C in 20 years. On the other hand, the variation in precipitation is much more unpredictable. It tends to be lower in all stations, as other authors have found in this area [75]. Precipitation tends to increase with altitude and on average suffers a decrease of 45 mm over the entire basin for the same period, the last 20 years. In general, wind speed shows a decreasing trend [70], as observed by other authors, year after year. Radiation and relative humidity do not show a clear trend. Other authors in this field have also highlighted this aspect [77]. Evapotranspiration, a parameter of great importance in the water balance, shows a decreasing trend, as several researchers have shown [66]. In this context, predictions may not be definitive. Figure 7 shows the variation of the arithmetic mean of the stations available in the basin for annual temperature, precipitation, wind speed and evapotranspiration for the available years.

Monthly parameters trends

Trends by month have been analysed for each station and each variable of hydrological importance. As an example, the slope of each regression line for the monthly mean temperature is shown in Appendix 1, and the slope (m) of the regression line for monthly precipitation is shown in Appendix 2. It has been observed that in the area the evolution is different at each month of the year.

There is a certain trend for temperatures to increase in the cold months, traditionally the rainiest months in this area. As for precipitation in these same months, the trend is to decrease. This reduces snow accumulation in the months when precipitation usually falls as snow. Therefore, runoff will flow faster through the basin and the water that

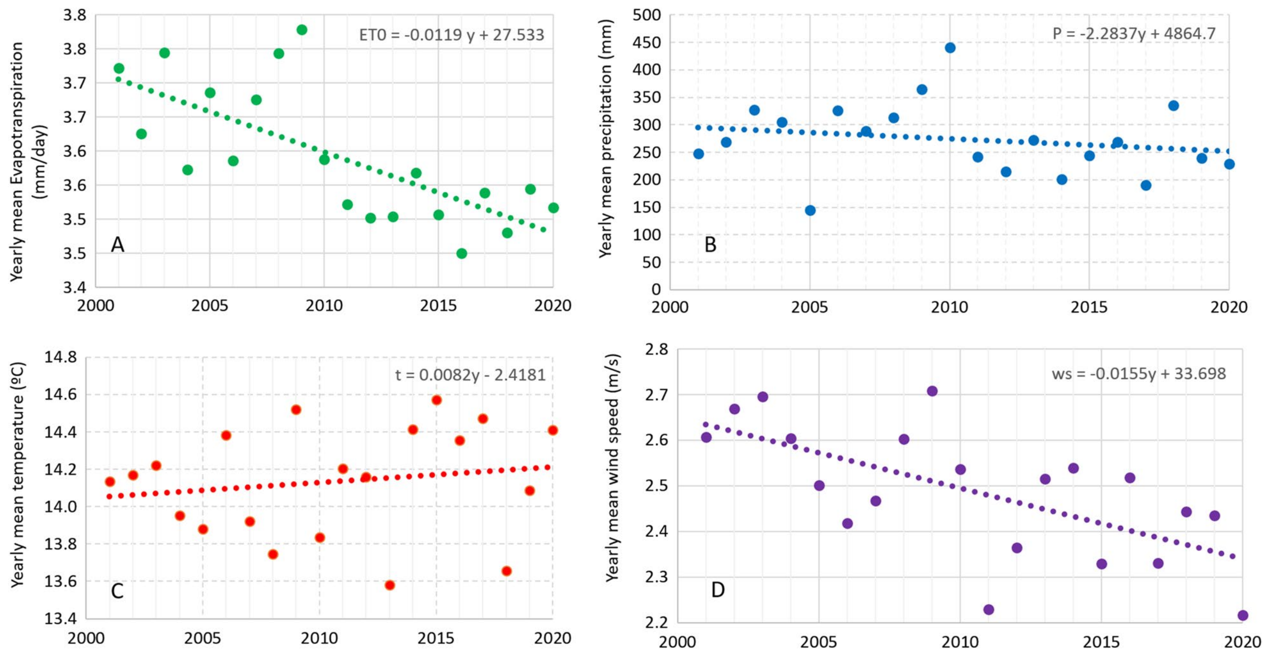

Fig. 7 Yearly mean values for the whole basin. **A** Mean yearly evolution of reference evapotranspiration, **B** precipitation, **C** temperature, and **D** wind speed

constitutes the river base flow will decrease. This effect is more prominent towards the upper areas of the basin than in the lower areas. For this reason, monthly rather than annual trends should be highlighted.

Predicted climate change scenarios

HEC-HMS model requires temperature, precipitation, and evapotranspiration series for the calculations. When establishing scenarios for the near future, it must be

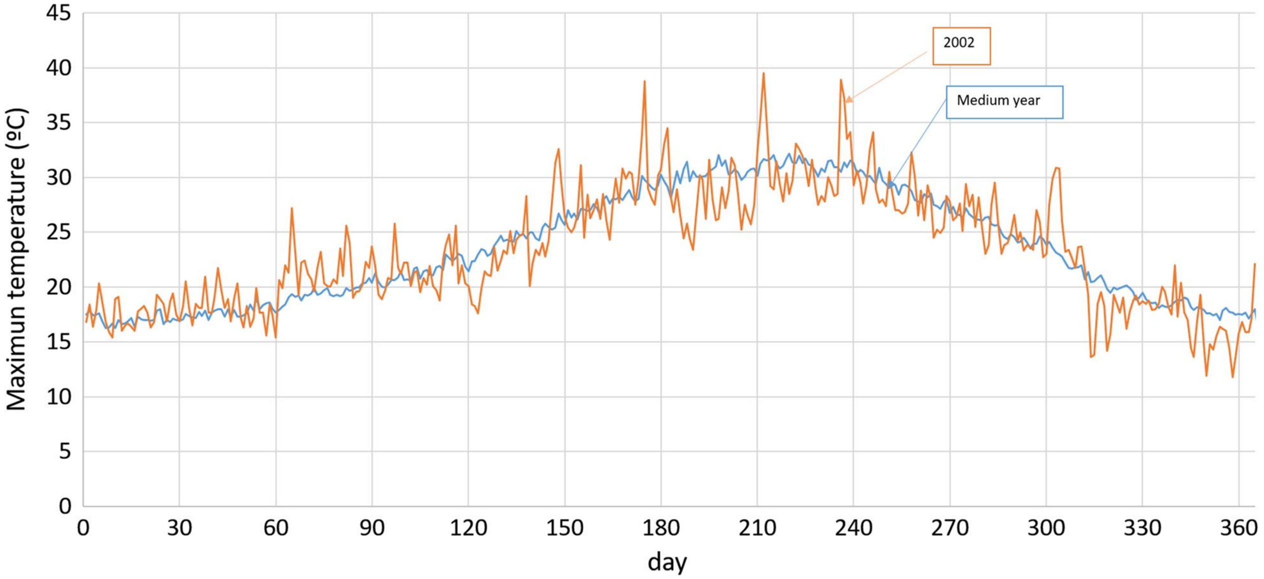

Fig. 8 Mean year (blue) compared with a current year 2022 (orange) for maximum temperature in Almeria's station

considered that climate data always present an unpredictable component that disappears when calculating the average of all the years, as shown in the example in Fig. 8 which shows the evolution of the average daily temperatures for the available years compared to the actual measurements for 2002.

The three parameters; T, P and ET_0, used by the model are usually related to each other and it is necessary to work with a sequence as natural as possible. Since each season shows a slightly different behaviour, the year that is closest to the median of each series in the maximum number of seasons must be found. To select the scenario, the trend will be applied to the year that is the median for most stations.

Each series of annual values has been ordered and the distance, in absolute value positions, of each year to the median has been calculated. The proposed index, Index of closeness (*Ic*), is determined for the mean annual temperature, annual precipitation and mean annual reference evapotranspiration at the whole stations analysed. Thus, the indexes of each variable for each meteorological station were summed and the lowest value was selected. In this proposed method, that year is the one which, for most of the stations and variables, is closest to the median. As can be seen in Table 9, the years 2016 and 2011 satisfy the requirements of being very close to the median for the set of stations and climatic parameters of the basin.

Table 9 Index of closeness, (*Ic*) to the median for each variable and year

Year	ET_0	T	P	Total
2000	62	49	27	138
2001	42	41	31	114
2002	26	17	17	60
2003	39	24	36	99
2004	33	15	33	81
2005	40	22	52	114
2006	19	22	31	72
2007	29	29	30	88
2008	34	37	34	105
2009	46	41	46	133
2010	26	41	54	121
2011	33	**9**	*13*	*55*
2012	33	*14*	22	69
2013	32	44	37	113
2014	26	40	28	94
2015	*18*	43	26	87
2016	**17**	27	**10**	**54**
2017	28	49	43	120
2018	31	39	39	109
2019	27	22	34	83
2020	25	41	23	89

In bold the closest value, in italics the second closest value and in underlined the third closest value

$$Ic_{(y_i)} = \sum_{S=1}^{S=n} \left| y_i - y_m \right| \tag{4}$$

With y_i: position in the ordered series for year i, y_m: position in the ordered series for the median year, S: meteorological station.

The main reason for choosing this method is that it is very difficult to replicate the random behaviour of precipitation in a medium-term projection. To avoid excessive smoothing of the precipitation series, which is critical for a hydrological simulation, the median year will be considered, and the climate change scenarios will be built on it. This proposed method has been successfully employed to simulate precipitation scenarios by other authors [43, 64]. This effect is not as strong for the rest of the parameters.

In view of the results, 2011 will be considered as a representative year. The monthly trend of this year's data will be removed to obtain the random component of each series, which will then be added to the average data for each time horizon.

Since the average year, 2010, the scenarios considered are, first, the year 2020 to compare with measured data, and the years 2030 and 2040 to compare the resource foreseen in the official hydrological plan. Thus, it will be able to check the fit of the proposed method. The hydrological years (from September to August) resulting from this calculation are 2009–2010, 2019–2020, 2029–2030 and 2039–2040. An exponential trend has been considered appropriate to justify that in the medium term the parameter does not disappear and become zero, which would be the case with a linear trend. For example, considering that precipitation would reach zero is considered unrealistic. Note that some studies highlight limitations in the confidence levels of regional runoff, groundwater recharge and water scarcity responses [21].

Predicted trend of water resources

The results of the simulations between the hydrological years 2001 and 2020 have been analyzed, as well as the projected scenarios for 2020, 2030 and 2040. Thus, the HEC-HMS model allows obtaining precipitation distributions by applying the method of the inverse of the square of the distances, so the cumulative precipitation in the basin must be calculated considering the influence of the DEM, which improves the accuracy of the averages. The surface-weighted average precipitation for the entire basin has been obtained as shown in Fig. 9. Note that, according to the altitude, higher annual averages can be

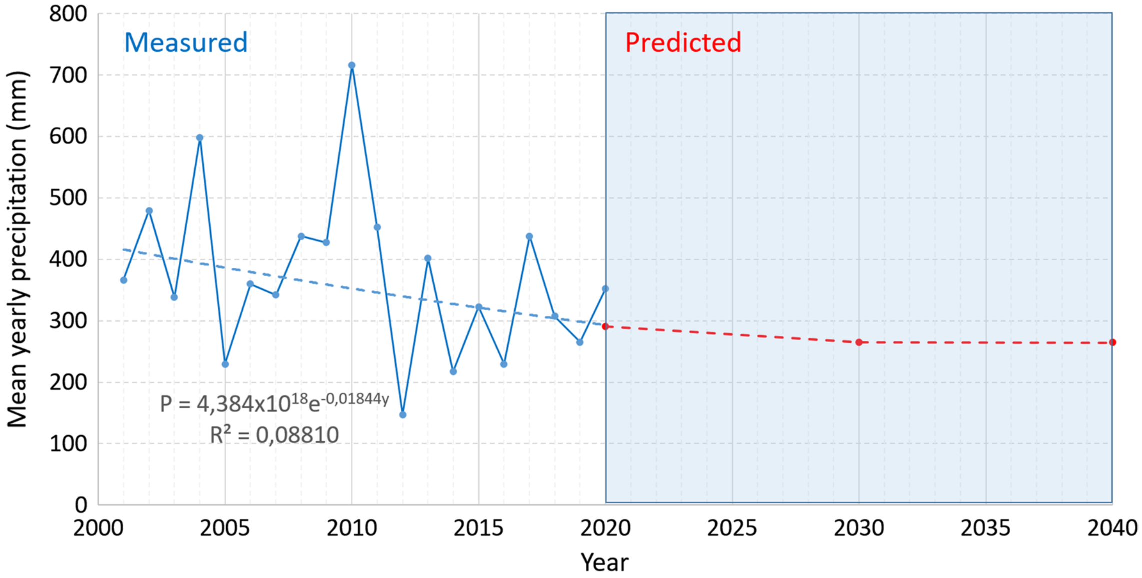

Fig. 9 Evolution of yearly mean precipitation for the entire basin (analyzed years in blue) and predicted trend (in red)

achieved than the simple average obtained by gauging stations in the lower areas of the basin, which is where the settlements are usually located.

The current precipitation behaviour is clearly downward, with wide oscillations around the trend line, see the period 2001–2020. An exponential trend line has been used because the values are very close to zero and negative values could occur with other types of representations. It is observed that this type of trend seems to continue with the points representing the evolution of the climate change scenarios, 2020, 2030 and 2040. This mathematical behaviour allow confirming that the calculation of the scenarios is adequate for the foreseeable evolution of the local climate.

Predicted trend of snow cover

The snow cover estimated by the model has been analysed over the historical data series. The HEC model operates by establishing a temperature gradient and identifying several terrain bands at similar elevations. This approach allows estimating snowfall in areas where there are no weather stations and is particularly suitable for high altitude terrain such as mountain areas. To obtain this type of predictions it is necessary to have the temperature series of the area, as well as the temperature and precipitation gradient with altitude. In the case of the study, this information has been obtained from the detailed study carried out in the LUCDEME project [50].

It has been found that snow cover is highly unpredictable, although it shows a clear trend towards progressive decrease. Figure 10 shows the evolution of snow cover in the years analysed and the predicted values for 2030 and 2040. The predicted obtained from the climate change scenarios, red line in Fig. 10, matches the general trend obtained with the current data for the area, dashed blue line.

Predicted trend of Runoff

Runoff discharge to the sea for the entire basin is shown in Fig. 11, for the period analyzed up to 2020. The points are the annual discharge, obtained by the model itself, and the dashed blue line shows the trend over the period studied. The trend shows a clearly downward, which is consistent with the projected scenarios, 2020, 2030 and 2040. It seems foreseeable, taking into account these assessments, that most of the years there will be no discharges to the sea, which has already been observed in the area.

Peak flows, which is estimated at the end of the basin, are an important hydrological parameter used for the calculation of civil engineering structures. The model allows prediction of peak flows. It is observed that they will increase slightly in the future. In other words, there will be a progressive transformation of this river into a seasonal stream, with runoff associated only with extreme precipitation events. This situation increases

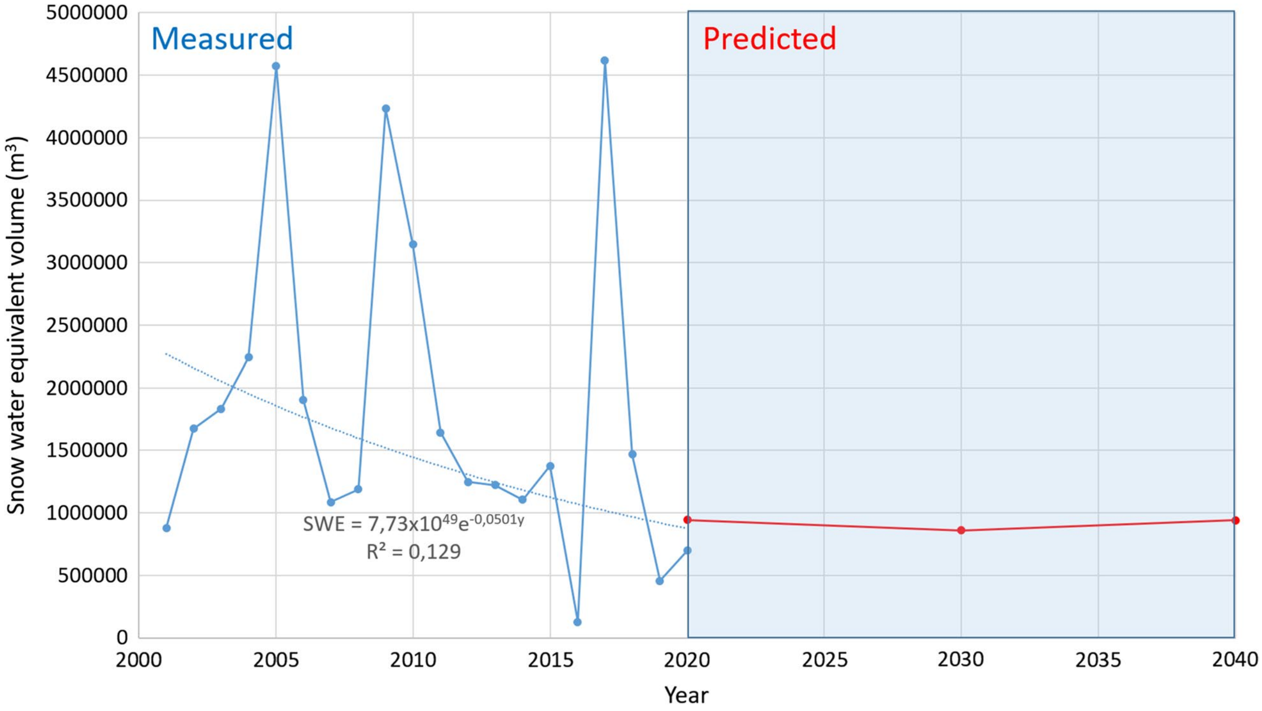

Fig. 10 Snow water equivalent volume (analysed years in blue) and predicted trend (in red)

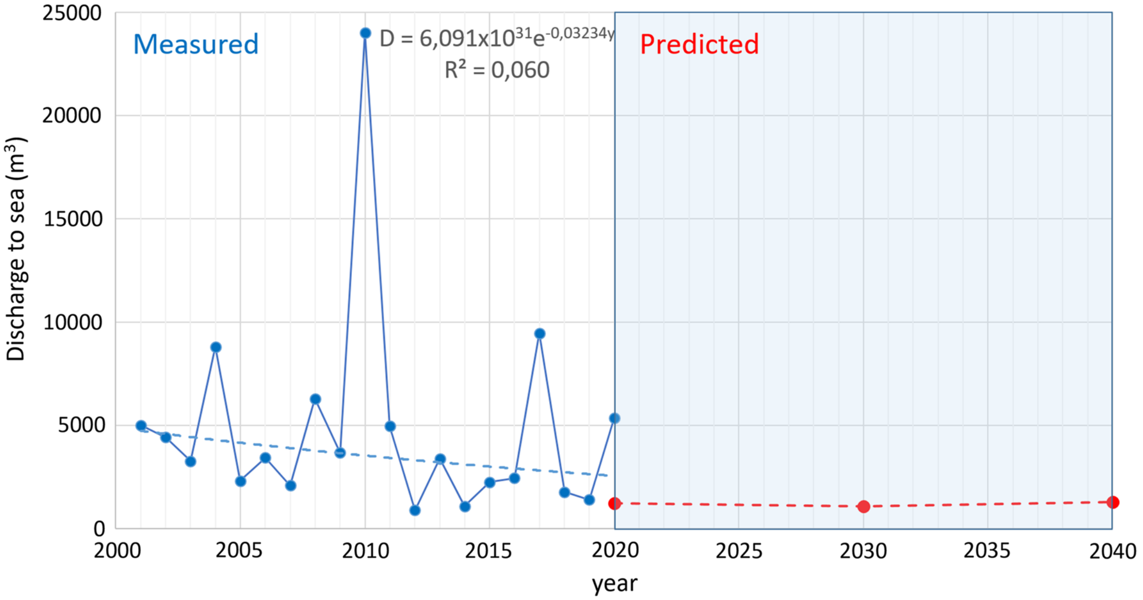

Fig. 11 Yearly basin discharge to sea (m^3) (analyzed years in blue) and predicted trend (in red)

the hydrological risks in the area, as well as potential runoff damage. The evolution of peak flows and their future forecast is shown in Fig. 12.

The dependence of direct surface runoff on winter snow accumulation was also studied. This estimation considers the volumes moving in all the watercourses

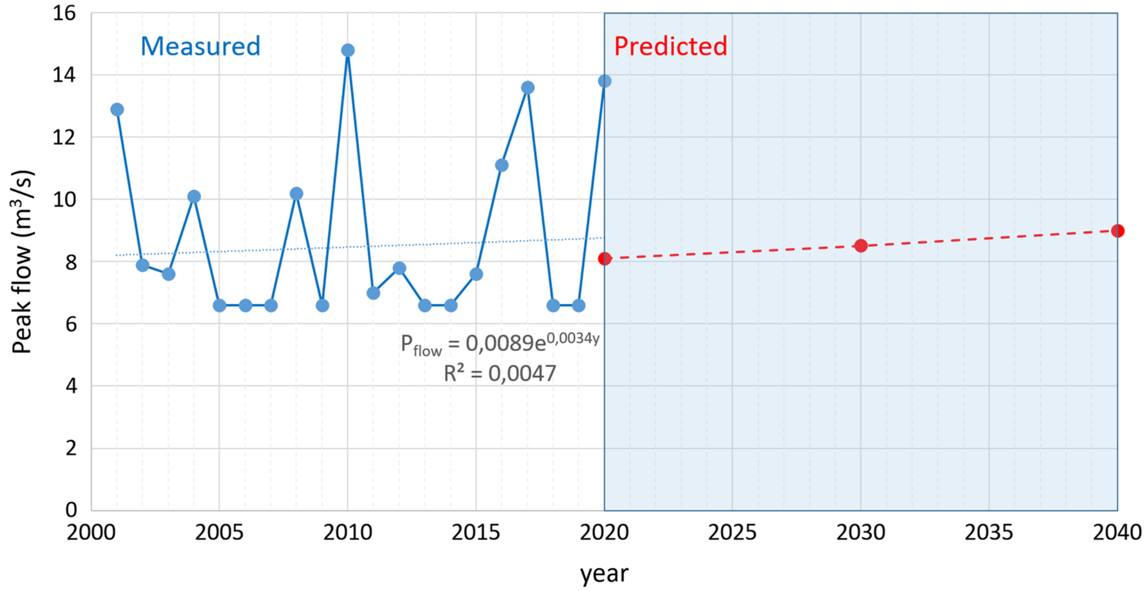

Fig. 12 Yearly evolution of peak flow at the end of the basin (analysed years in blue) and predicted trend (in red)

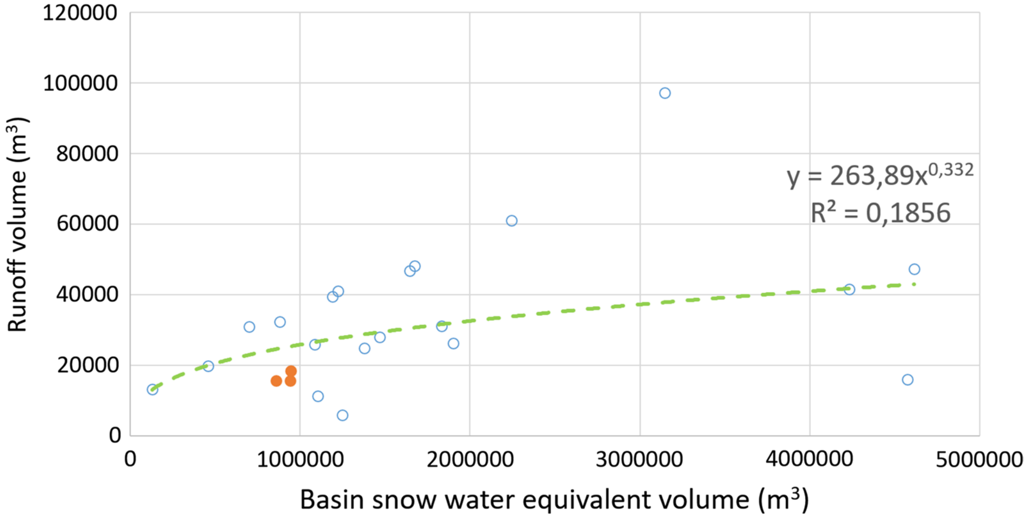

Fig. 13 Relation between snow water equivalent and runoff volume for the entire basin. Dots in orange are the predicted scenarios (2020, 2030 and 2040)

of the basin that can be used. The data show a relationship between runoff volume and snow cover, as shown in Fig. 13. This relationship reports the close relationship between this aspect of climate and the possibility of using surface water resources. In addition, in Fig. 13, the three scenarios analysed are represented as orange dots, and it can be observed that they are close to the actual situation as shown in the data.

Predicted trend water supply through surface and riverbeds

The HEC-HMS program provides an estimate, for each basin, of the recharge sheet at each instant. It can be summed by weighting the surface area of each sub-basin and in this way; the complete recharge of the system can be estimated. This estimate, by year, is shown in Fig. 14.

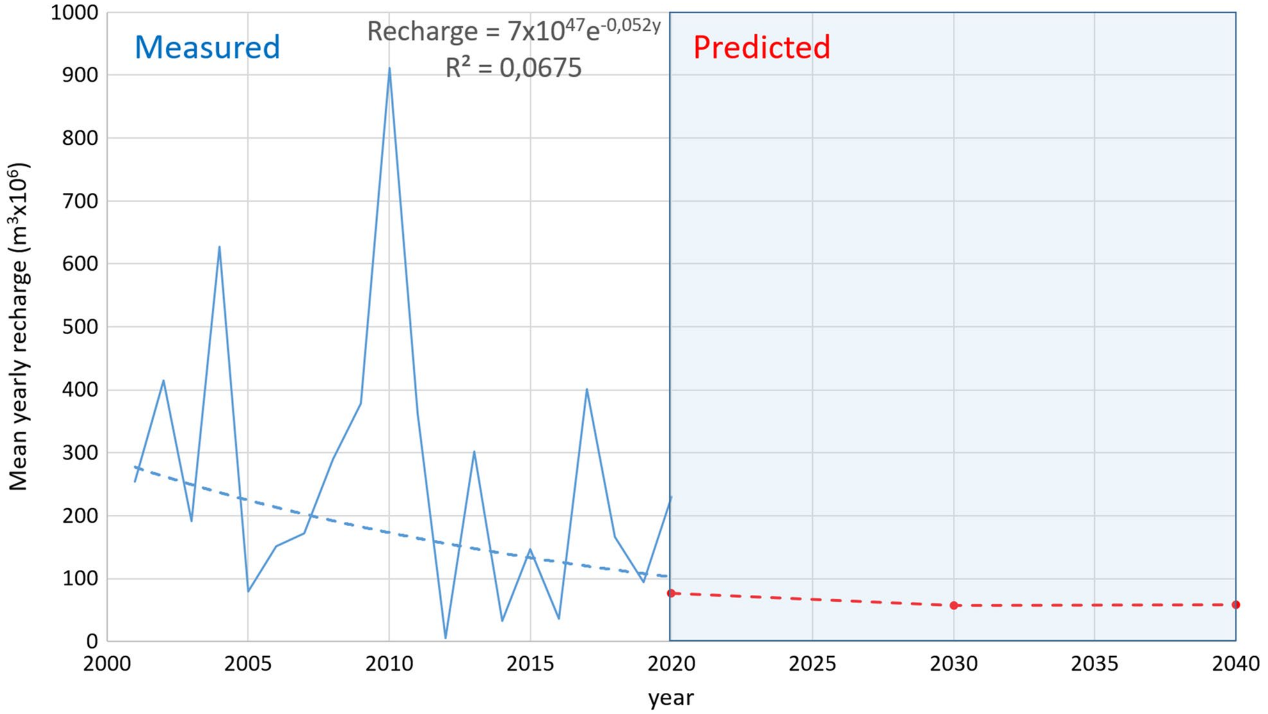

Fig. 14 Yearly aquifer recharge, (analyzed years in blue) and predicted trend (in red)

Table 10 Total needs of the basin (m^3) by areas

	N	HA	MA	LA	T	Total
Urban	780,000	330,000	440,000	4,250,000	440,000	6,240,000
Irrigation	14,600,000	2,780,000	10,740,000	11,230,000	4740,000	44,090,000
Industry	0	0	0	60,000	70,000	130,000
Livestock	23,385	9642	13,086	101,353	12,534	160,000
Total	14,403,385	3,119,642	11,193,086	15,641,353	5,262,535	50,620,000

The trend is clearly downward, although there are occasional episodes of high recharge (every 250 hm^3 represents approximately 100 mm of recharge, hm$^3 = 10^6$ m^3).

If we calculate it, in each area, we see that the situation is very different and so are the forecasts. In all cases, the drop in recharges exceeds 50%.

By areas, the calculated and forecasted values have been accumulated and are shown in Table 11. This table shows the average values for the years available, and the average value projected in the scenario presented. The calculation has been broken down into surface water values for urban and irrigation use, as well as recharge from deep infiltration from the soil and from infiltration in the riverbeds. The basin also receives a contribution of 1,900,000 m^3 of reclaimed water for irrigation in the Low Andarax area. On the other hand, the general needs of the Basin, presented in Table 6, can be distributed by areas as shown in Table 10.

The situation is variable for each area, the middle (MA), Lower Andarax (LA) and Tabernas (T) will be clearly affected by the change in resource availability. In contrast, other parts of the basin as High Andarax (HA), will be able to cover their needs. On the other hand, the current recharge came to meet the high groundwater demand of the Campo de Dalias, since the groundwater body is connected. In the projected scenario, this contribution will be greatly reduced.

Expected trend in water resources availability

After analyzing the series of results obtained for the available data and for the scenarios, it was found that the surface legal water approved by the Basin Hydrological

Plan has not been reached, neither for urban supply nor for irrigation (Fig. 15). Therefore, if this approved volume of water is used, it will be done by taking the water from the aquifers or by using significantly less water for agriculture. Figure 15 shows that the lines are staggered because they represent the successive official hydrological plans, i.e., the possibility of using this resource, according to their period of application. Therefore, there

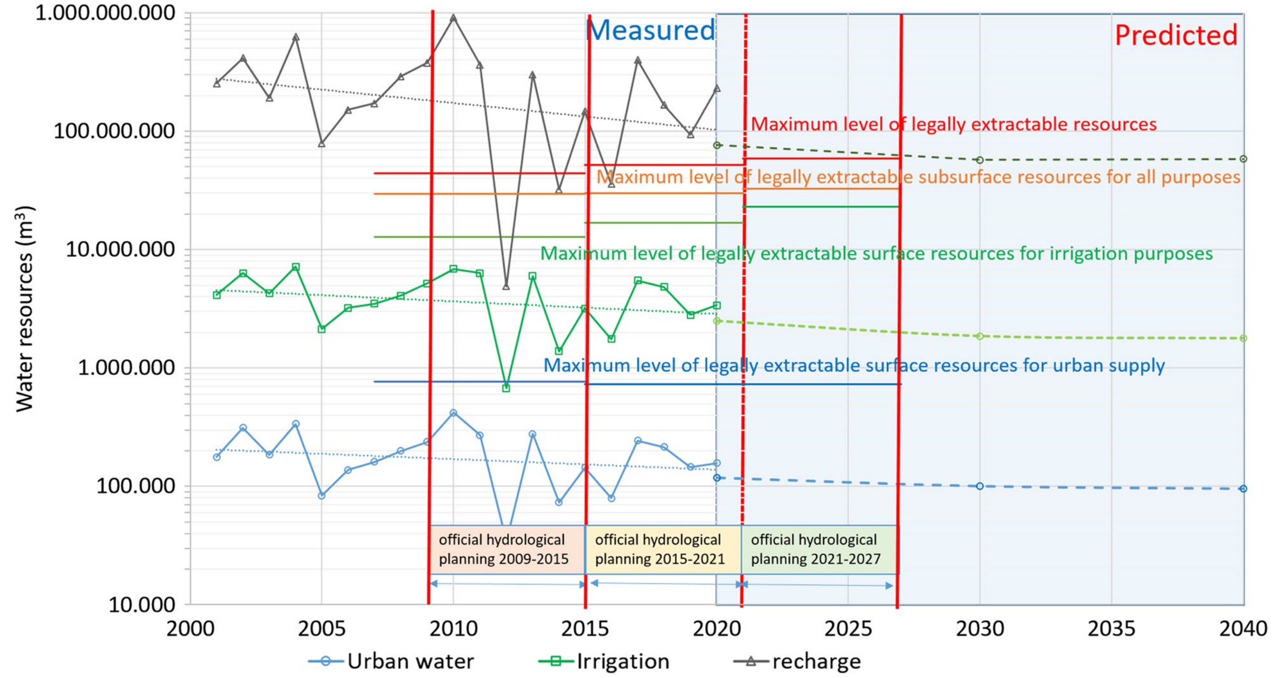

Fig. 15 Evolution of surface resources derived for supply and irrigation from 2001 to 2020 and the 2020, 2030 and 2040 scenarios. In blue and green, maximum level of surface resources that can be legally extracted urban supply, irrigation. In orange, maximum level of groundwater resources for all purposes. In red, total volume of water resources, legally extractable form the basin

Table 11 Surface resources, actual mean and projected (m^3)

		N	HA	MA	LA	*T*	Total
Urban use	Mean	93,113	38,505	119,896	20,940	3066	276,520
	Projected	52,155	13,288	112,005	11,898	521	189,867
Irrigation purposes	Mean	97,099	692,684	2,090,632	1,161,187	14,094	4,055,696
	Projected	91,910	426,300	698,416	733,732	9621	1,959,979
Total	Mean	191,213	731,190	2,210,527	1,182,126	17,159	4,332,215
	Projected	144,064	439,588	810,420	745,630	10,142	2,149,844

Table 12 Percentage of satisfaction over the approved maximum extractable for urban supply

	N	HA	MA	LA	*T*	Total
Approved maximum extractable (m^3)	340,000	130,000	120,000	80,000	80,000	750,000
% Current/maximum	27.68	29.62	99.91	26.17	3.83	36.87
% Scenarios/maximum	15.34	10.22	93.34	14.87	0.65	25.32
% Scenarios/actual	55.42	34.51	93.42	56.82	16.99	68.66

are 3 periods of 6 years, from 2009 to 2015 [59], from 2015 to 2021 [60], and from 2021 to 2027 [61]. The figure shows in the same colour, for the main uses, what each 6-year hydrological plan establishes. In a continuous line it can be observed for each of these uses what was estimated in this research, and in a dashed line the estimated trend or predicted.

It can be observed that surface resources decrease drastically in the near future. By areas, the estimated average surface resources were as obtained in Table 11. Urban supply needs from surface resources are generally low compared to irrigation. There is an average trend to catch less than 50% of the approve water volumes. Supply is met by an average of 36.85% in the years analyzed, although the scenarios predict that only 25.32% of this type of resource will be available.

The situation by zone is highly diverse in percentage terms over the approved maximum extractable for urban supply, as shown in Table 12. In the middle zone of the Almeria River (MA), the supply needs are currently satisfied with surface water resources for the years analyzed and would only drop to 93% in the close future. For other zones, a greater decrease is expected, with the short-term loss of this resource.

The situation in the Tabernas area is especially worrisome. Here the surface resource is already much lower than the official planning, based on historical data. In the near future, the situation will become even more unfavourable.

According to data from the Spanish National Institute of Statistics [39], the average urban consumption in Andalusia is 177 litters/inhabitant/day, i.e., 64 m^3/year. The hydrological plans allocate 100 m^3/year per inhabitant to the area, slightly more than the regional average. This means that 7300 people can be supplied with surface water, i.e., 12% of the current basin's population. Under current and projected circumstances, the population that can be supplied by surface water resources will be reduced in the same amounts as the reduction of these resources. This context has already been observed and each community has been perforating emergency wells for its supply in the driest years. In the foreseen scenario, these wells will be in operation almost every year.

As for irrigation, the maximum extractable approved volume of water is 17,730,000 m^3, Table 13, but the average for the last 20 years is 4,055,696 m^3, only 22.87% of the planned volume. This means that 1126 ha can currently be irrigated with surface water resources. However, if the predictions presented in this research are fulfilled, the available volume will be 2,149,845 m^3, 11.05% of the actual volume. This means that only 544 ha could be irrigated with surface water. A summary of this situation is shown in Table 13.

The lack of surface resources will be made up for with groundwater resources. Their situation is not much better, Table 14.

Also, in this case, the situation is highly variable on each area considered. The Middle Andarax area will

Table 13 Percentage of satisfaction over the legal maximum extractable for irrigation purposes

	N	HA	MA	LA	*T*	Total
Approved maximum extractable	9,210,000	1,980,000	3,760,000	2,530,000	250,000	17,730,000
% Current/maximum	1.05	34.98	55.60	45.90	5.64	22.87
% Scenarios/maximum	1.00	21.53	18.57	29.00	3.85	11.05
% Scenarios/actual	96.66	61.54	33.41	63.19	68.26	48.33

Table 14 Ground water resources, mean and projected

		N	HA	MA	LA	*T*	Total
Surface recharge	Mean	87,341,229	58,728,531	17,388,295	26,087,354	44,961,478	234,506,887
	Projected	22,456,749	20,936,318	3,737,296	2,090,573	65,917	49,286,853
River recharge	Mean	7,935,659	7,984,911	4,544,289	5,224,645	2,213,436	27,902,940
	Projected	4,926,724	3,836,800	1,979,526	2,858,831	882,239	14,484,119
Total	Mean	95,276,887	66,713,442	21,932,584	31,312,000	47,174,914	262,409,827
	Projected	27,383,473	24,773,118	5,716,822	4,949,404	948,155	63,770,972

Table 15 Percentage of satisfaction over the legal maximum extractable for groundwater

	N	HA	MA	LA	*T*	Total
Approved maximum extractable (m^3)	5,853,385	1,009,642	7,313,086	11,131,353	4,932,535	30,240,000
% Scenarios/maximum			78.17	44.46	19.22	
% Scenarios/actual	28.74	37.13	26.07	15.81	2.01	24.30

better resist future changes, with volumes around 50% of the predicted values. A decrease is expected in the future, but in other areas with the projected scenarios, they will have to take adequate measures for the future. Both in the case of urban supply and in the case of irrigation, the decrease in surface water is being covered by increased groundwater withdrawal. The obvious drawback is that this resource has a poorer chemical quality, which is negative for crop productivity.

The System currently has the capacity to supply groundwater to meet the needs of all the areas. In the near future, some districts will no longer have this possibility. In all cases, there is a significant decrease in the census of renewable groundwater resources. The current calculated recharge is around 262.4 hm^3 ($hm^3 = 10^6\ m^3$) on average. The data indicate that in the near future it will be reduced to 63.7 hm^3. In this projected scenario, the basin would only be able to export about 17 hm^3. At present, some 218 hm^3 would be exported, and an important fraction of 64.7 hm^3 can be received in the Campo de Dalias aquifer, which is connected to the upper and middle Andarax area. In the near future only 11.6 hm^3 will be available, which would force a greater use of desalinated water, also compromising the current recovery plan for this important aquifer.

Given that the volume of groundwater resources is much higher than the volume of surface resources, Table 15 practically reflects the situation of total resources, which, although for the entire basin decrease to 25.25%, there are districts where the decrease is almost total. These districts are located in the eastern and lower part of the basin. In any case, the future scenario suggests at least the limitation of crops with higher water demand. The inhabitants of the area who, in the last century, have gone from growing grapes, with moderate water demand, to growing olive trees, with lower needs, have already understood this situation. In the lower areas, greenhouse crops are replacing open-air horticultural crops, with only 40% of the water needs compared to the previous ones.

Conclusions

In this manuscript, a methodology for assessing climate change in semiarid climates has been proposed. It has been applied in southern Spain as a case study. Scenarios for the years 2020, 2030 and 2040 have been carried out. This methodology has established a proposal to determine the best reference year to establish medium-term projections. For this purpose, the index of closeness has been proposed for the main climatic parameter such as precipitation, temperature, and reference evapotranspiration. The proposed index determines the most characteristic year of a series of years considering producing future scenarios as close as possible to a natural year.

The trend observed in the 20 years of data analysed for the climate of the area clearly shows an increase in evapotranspiration and temperatures, but a decrease in precipitation. Since the climate trend is relatively moderate, part of this trend can be attributed to natural climate oscillations. However, although the changes in the climatic parameters studied are slight, a strong effect on surface water resources has been detected. Thus, the trend in the volume of surface water resources is continuously decreasing, which allows us to confirm that there is a trend superimposed on the natural oscillation. At present, surface runoff is already much lower than that foreseen in the Basin Hydrological Plans. This has already led to changes in the crops in the area.

This study offers the novelty of a monthly inter-annual study, instead of only by year. It has been detected that the monthly changes especially affect surface water resources because it is more relevant in the months when these should be expected in greater quantity. In view of these results, it is clear that the approved surface water withdrawals were estimated with climatic assumptions that are no longer met. This situation, which is already happening, and the trend studied means that the surface water resource is becoming increasingly scarce, affecting the sustainability of agricultural land use, especially with current crops. The rest of the needs will be satisfied with groundwater, increasing the degree of overexploitation by the aquifers in the area, despite the high degree of technification in the irrigation use. Therefore, it is urgent to adjust water resource management and land use criteria in a more realistic approach. For example, for the area studied, over a 20-year horizon, i.e., 2040, a 50% decrease in available surface water resources compared to current resources is to be expected. Finally, this research opens new perspectives for the study of climate change in semi-arid areas for agricultural land use.

Appendix 1

See Table 16.

Table 16 Slope (m) of the trend analyzed by month for the temperature [T (ºC)] in each weather station

Month	Almeria	Nijar	Tabernas	Fiñana	Jerez	Baza	Cortafuegos	Calar	Average
January	− 0.010	0.023	− 0.032	0.012	0.009	− 0.005	0.031	− 0.147	− 0.015
February	0.016	0.041	0.010	0.030	0.035	0.040	0.066	− 0.052	0.023
March	− 0.031	0.002	− 0.064	− 0.054	− 0.072	− 0.042	0.007	− 0.035	− 0.036
April	0.000	0.003	− 0.025	− 0.013	0.007	0.011	− 0.021	0.017	− 0.003
May	0.027	0.028	0.011	0.043	0.080	0.066	− 0.093	− 0.068	0.012
June	− 0.083	− 0.081	− 0.094	− 0.074	− 0.076	− 0.054	− 0.072	− 0.386	− 0.115
July	0.025	0.016	− 0.009	0.016	0.039	0.030	0.002	0.201	0.040
August	0.015	0.020	− 0.033	0.017	0.032	0.025	0.053	0.123	0.032
September	0.031	0.020	− 0.014	0.020	0.028	0.015	0.052	− 0.146	0.001
October	− 0.041	− 0.018	− 0.063	− 0.004	0.030	− 0.040	0.100	− 0.094	− 0.016
November	− 0.004	0.015	0.017	0.015	0.080	0.054	− 0.014	0.168	0.042
December	0.003	0.037	0.023	0.078	0.105	0.004	0.111	− 0.038	0.040

Appendix 2

See Table 17.

Table 17 Slope (m) of the trend analyzed by month for the precipitation in each weather station [P (mm)]

Month	Almeria	Nijar	Tabernas	Fiñana	Jerez	Baza	Cortafuegos	Calar	Average
January	− 0.486	− 0.762	− 0.467	− 0.087	− 0.005	− 0.127	− 0.390	3.773	0.181
February	− 1.106	− 1.545	− 1.042	− 1.757	− 0.931	− 0.737	− 5.266	1.966	− 1.302
March	0.563	− 0.055	0.187	0.134	1.214	1.628	− 2.251	0.030	0.181
April	− 0.349	− 1.126	− 1.055	− 0.011	0.227	0.886	− 0.846	− 3.785	− 0.757
May	− 0.938	− 1.159	− 0.934	− 0.363	− 1.053	− 0.969	− 1.418	2.510	− 0.541
June	0.093	− 0.104	− 0.135	− 0.173	− 0.929	− 1.392	− 0.152	− 2.118	− 0.614
July	− 0.023	− 0.087	− 0.033	− 0.221	0.492	0.042	− 0.330	− 0.060	− 0.027
August	0.451	0.355	0.421	− 0.112	0.495	0.004	0.144	2.173	0.491
September	0.491	3.359	1.119	0.119	0.240	1.062	− 0.554	9.042	1.860
October	1.458	0.697	− 1.002	− 1.391	− 1.541	− 0.388	− 1.289	− 0.353	− 0.486
November	− 0.703	− 1.147	− 1.322	0.453	1.245	0.711	− 1.989	− 5.246	− 1.000
December	− 0.780	− 0.061	− 0.229	− 0.361	− 0.924	0.486	− 0.043	6.423	0.564

Acknowledgements

The authors would like to thank CIAIMBITAL for their support in this research.

Author contributions

AZ-S and FM-A contributed to conceptualization; AZ-S and LZ-C was involved in methodology; AZ-S and FM-A performed validation; AZS and LZ-C did formal analysis; AZ-S, LZ-C and FM-A contributed to writing—original draft preparation; AZ-S and FM-A were involved in writing—review and editing; AZ-S and FM-A performed supervision. All authors have read and approved the final manuscript.

Funding

This research received funding by University of Almeria under the project "Action Program for the Recovery of the Good State of the Groundwater reservoir Es060msbt060.008 "Aguas" River.

Availability of data and materials

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

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

Received: 26 April 2022 Accepted: 23 July 2022

References

1. Acosta Martínez P (1983) Estado actual de la Prehistoria andaluza: Neolítico y Calcolítico. Habis 14:195–206
2. Aldaya MM, Custodio E, Llamas R, Fernández MF, García J, Ródenas MÁ (2019) An academic analysis with recommendations for water management and planning at the basin scale: a review of water planning in the Segura River Basin. Sci Total Environ 662:755–768
3. Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao Rome 300(9):D05109
4. Aznar-Sánchez JA, Piquer-Rodríguez M, Velasco-Muñoz JF, Manzano-Agugliaro F (2019) Worldwide research trends on sustainable land use in agriculture. Land Use Policy 87:104069
5. Benet AS, Cantón Y, Lázaro R, Puigdefábregas J (2009) Weathering and erosion in the Tabernas Sub-Desert, Almería. Cuad Investig Geogr 35(1):141–163
6. Boithias L, Acuña V, Vergoñós L, Ziv G, Marcé R, Sabater S (2014) Assessment of the water supply: demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives. Sci Total Environ 470:567–577
7. Brunetti M, Maugeri M, Nanni T (2000) Variations of temperature and precipitation in Italy from 1866 to 1995. Theoret Appl Climatol 65(3):165–174
8. Camuffo D, Bertolin C, Diodato N, Cocheo C, Barriendos M, Dominguez-Castro F, Nunes MF (2013) Western Mediterranean precipitation over the last 300 years from instrumental observations. Clim Change 117(1):85–101
9. Carpino OA, Berg AA, Quinton WL, Adams JR (2018) Climate change and permafrost thaw-induced boreal forest loss in northwestern Canada. Environ Res Lett 13(8):084018
10. Castillo Requena JM (1997) Precipitaciones y avenidas en Almería durante el período normalizado 1961–1990: contribución al estudio de los paisajes del agua. Papeles de geografía, Murcia, p 26
11. Charley WJ (1995) The hydrologic modeling system (HEC-HMS): design and development issues (No. 149). US Army Corps of Engineers, Hydrologic Engineering Center, Davis
12. Collet L, Ruelland D, Estupina VB, Dezetter A, Servat E (2015) Water supply sustainability and adaptation strategies under anthropogenic and climatic changes of a meso-scale Mediterranean catchment. Sci Total Environ 536:589–602
13. Correia FN (1999) Water resources in the Mediterranean region. Water Int 24(1):22–30
14. Cressier P (1991) Agua, fortificaciones y poblamiento: el aporte de la arqueología a los estudios sobre el sureste peninsular. Aragón en la Edad Media 9:403–428
15. Custodio E, Andreu-Rodes M, Aragón R, Estrela T, Ferrer J, García-Aróstegui L, Manzano M, Rodríguez-Hernández L, Sahuquillo A, Del Villar A (2016) Groundwater intensive use and mining in south-eastern peninsular Spain: hydrogeological, economic and social aspects. Sci Total Environ 559(15):302–316
16. Das B, Singh A, Panda SN, Yasuda H (2015) Optimal land and water resources allocation policies for sustainable irrigated agriculture. Land Use Policy 42:527–537
17. Dastorani MT, Khodaparast R, Talebi A, Vafakhah M, Dashti J (2011) Determination of the ability of HEC-HMS model components in rainfall-run-off simulation. Res J Environ Sci 5(10):790
18. DeBeer CM, Sharp M, Schuster-Wallace C (2020) Glaciers and ice sheets. Encyclopedia of the World's Biomes. Elsevier, Amsterdam, pp 182–194
19. DeVantier BA, Feldman AD (1993) Review of GIS applications in hydrologic modeling. J Water Resour Plan Manag 119(2):246–261
20. Dooge JCJ (1984) Waters of the earth. GeoJournal 8(4):325–340
21. Douville H, Raghavan K, Renwick J, Allan RP, Arias PA, Barlow M, Cerezo-Mota R, Cherchi A, Gan TY, Gergis J, Jiang D, Khan A, Pokam Mba W, Rosenfeld D, Tierney J, Zolina O (2021) Water cycle changes. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (eds) Climate Change 2021: The Physical Science Basis Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 1055–1210. https://doi.org/10.1017/9781009157896.010
22. Duratorre T, Bombelli GM, Menduni G, Bocchiola D (2011) Hydropower potential in the alps under climate change scenarios. The Chavonne Plant, Val D'Aosta. Water 2020:12
23. Estaciones Agroclimáticas SAR (2021) https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/inicio_estaciones. Accessed on Dec 15, 2021
24. Etter S, Addor N, Huss M, Finger D (2017) Climate change impacts on future snow, ice and rain runoff in a Swiss mountain catchment using multi-dataset calibration. J Hydrol Reg Stud 13:222–239
25. Feldbauer J, Kneis D, Hegewald T, Berendonk TU, Petzoldt T (2020) Managing climate change in drinking water reservoirs: potentials and limitations of dynamic withdrawal strategies. Environ Sci Eur 32(1):1–17
26. Forestieri A, Arnone E, Blenkinsop S, Candela A, Fowler H, Noto LV (2018) The impact of climate change on extreme precipitation in Sicily, Italy. Hydrol Process 32(3):332–348
27. Galdeano-Gómez E, Aznar-Sánchez JA, Pérez-Mesa JC (2011) The complexity of theories on rural development in Europe: an analysis of the paradigmatic case of Almería (South-east Spain). Sociol Rural 51(1):54–78
28. De Haro Gil MD, Sanchez Picón A, (2020) La uva de Almería. Un cultivo comercial que construyó un paisaje agrario en la montaña mediterránea (siglos XIX y XX) Gaz Antropol. 36 (1), artículo 03, http://hdl.handle.net/10481/63253
29. Gilman A, Thornes JB (2014) Land-use and prehistory in south-east Spain. Routledge, Milton Parkn
30. Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. Global Planet Change 63(2–3):90–104
31. Gizzi M, Mondani M, Taddia G, Suozzi E, Lo Russo S (2022) Aosta valley mountain springs: a preliminary analysis for understanding variations in water resource availability under climate change. Water 14(7):1004
32. Grindlay AL, Zamorano M, Rodríguez MI, Molero E, Urrea MA (2011) Implementation of the European Water Framework Directive: integration of hydrological and regional planning at the Segura River Basin, south-east Spain. Land Use Policy 28(1):242–256
33. Grogan DS, Burakowski EA, Contosta AR (2020) Snowmelt control on spring hydrology declines as the vernal window lengthens. Environ Res Lett 15(11):114040
34. Gyawali R, Watkins DW (2013) Continuous hydrologic modeling of snow-affected watersheds in the Great Lakes basin using HEC-HMS. J Hydrol Eng 18(1):29–39
35. Haberlandt U (2010) From hydrological modelling to decision support. Adv Geosci 27:11–19
36. Haubrock PJ, Pilotto F, Haase P (2020) Do changes in temperature affect EU Water Framework Directive compliant assessment results of central European streams? Environ Sci Eur 32(1):1–13
37. Hobbie SE, Grimm NB (2020) Nature-based approaches to managing climate change impacts in cities. Philos Trans R Soc B 375(1794):20190124
38. Iglesias A, Garrote L, Diz A, Schlickenrieder J, Martin-Carrasco F (2011) Re-thinking water policy priorities in the Mediterranean region in view of climate change. Environ Sci Policy 14(7):744–757
39. INE (2018) https://www.ine.es/prensa/essa_2016.pdf. Accessed on June 15, 2022
40. IPCC (2018) Summary for policymakers. In: Masson-Delmotte V et al (eds) Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above preindustrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. IPCC, Geneva, pp 1–30
41. Jia G, Shevliakova E, Artaxo P, De Noblet-Ducoudré N, Houghton R, House J, Kitajima K, Lennard C, Popp A, Sirin A, Sukumar R, Verchot L (2019) Land–climate interactions. In: Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner HO, Roberts DC, Zhai P, Slade R, Connors S, van Diemen R, Ferrat M, Haughey E, Luz S, Neogi S, Pathak M, Petzold J, Portugal Pereira J, Vyas P, Huntley E, Kissick K, Belkacemi M, Malley J (eds) Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. IPCC, Geneva
42. Jones HP, Hole DG, Zavaleta ES (2012) Harnessing nature to help people adapt to climate change. Nat Clim Chang 2(7):504–509

43. Kara F, Yucel I, Akyurek Z (2016) Climate change impacts on extreme precipitation of water supply area in Istanbul: use of ensemble climate modelling and geo-statistical downscaling. Hydrol Sci J 61(14):2481–2495
44. Keshta E, Gad MA, Amin D (2019) A long–term response-based rainfall-runoff hydrologic model: case study of the Upper Blue Nile. Hydrology 6(3):69
45. Klingelhöfer D, Müller R, Braun M, Brüggmann D, Groneberg DA (2020) Climate change: does international research fulfillfulfil global demands and necessities? Environ Sci Eur 32(1):1–21
46. Knebl MR, Yang ZL, Hutchison K, Maidment DR (2005) Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event. J Environ Manage 75(4):325–336
47. Kulp SA, Strauss BH (2019) New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. Nat Commun 10(1):1–12
48. Leal Filho W, Icaza LE, Neht A, Klavins M, Morgan EA (2018) Coping with the impacts of urban heat islands. A literature based study on understanding urban heat vulnerability and the need for resilience in cities in a global climate change context. J Clean Prod 171:1140–1149
49. Leone G, Pagnozzi M, Catani V, Ventafridda G, Esposito L, Fiorillo F (2021) A hundred years of Caposele spring discharge measurements: trends and statistics for understanding water resource availability under climate change. Stoch Env Res Risk Assess 35(2):345–370
50. LUCDEME https://www.miteco.gob.es/es/biodiversidad/temas/desertificacion-restauracion/lucha-contra-la-desertificacion/lch_lucdeme.aspx. Acceso Mar 2017
51. Mahlman JD (1997) Uncertainties in projections of human-caused climate warming. Science. https://doi.org/10.1126/science.278.5342.1416
52. Mapa de Elevaciones del Terreno de Andalucía (DEM) (2017) http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.04dc44281e5d53cf8ca78ca731525ea0/?vgnextoid=f6284d9721fa3410VgnVCM2000000624e50aRCRD&vgnextchannel=f27b1df1d514e310VgnVCM2000000624e50aRCRD&vgnextfmt=rediam&lr=lang_es. Acceso Mar 2017
53. McDaniel RD, O’Donnell FC (2019) Assessment of hydrologic alteration metrics for detecting urbanization impacts. Water 11(5):1017
54. Meenu R, Rehana S, Mujumdar PP (2013) Assessment of hydrologic impacts of climate change in Tunga-Bhadra river basin, India with HEC-HMS and SDSM. Hydrol Process 27(11):1572–1589
55. Negi GCS (2001) The need for micro-scale and meso-scale hydrological research in the Himalayan mountains. Environ Conserv 28(2):95–98
56. Observatorio Astronómico Calar Alto (2011) https://www.caha.es/es/meteorolog%C3%ADa/estacion-metereologica. Acceso 24 Jun 2021
57. Orengo HA, Ejarque A, Albiach R (2014) Water management and land-use practices from the Iron-Age to the Roman period in Eastern Iberia. J Archaeol Sci 49:265–275
58. Ouédraogo WAA, Raude JM, Gathenya JM (2018) Continuous modeling of the Mkurumudzi River catchment in Kenya using the HEC-HMS conceptual model: calibration, validation, model performance evaluation and sensitivity analysis. Hydrology 5(3):44
59. P.H.C.M.A. Plan Hidrológico de las Cuencas Mediterráneas Andaluzas 2009–2015. http://www.juntadeandalucia.es/medioambiente/site/portalweb/menuitem.7e1cf4ddf59bb227a9ebe205510e1ca/vgnextoid=6d3173f2c746a310VgnVCM2000000624e50aRCRD&vgnextchannel=49f97b8e31a5510VgnVCM2000000624e50aRCRD. Accessed June 15 2022
60. P.H.C.M.A. Plan Hidrológico de las Cuencas Mediterráneas Andaluzas 2015–2021. https://www.juntadeandalucia.es/medioambiente/portal/landing-page/-/asset_publisher/4V1kD5gLiJkq/content/plan-hidrol-c3-b3gico-de-las-cuencas-mediterr-c3-a1neas-2015-2021/20151. Accessed on June 15, 2022
61. P.H.C.M.A. Plan Hidrológico de las Cuencas Mediterráneas Andaluzas 2021–2027. https://www.juntadeandalucia.es/medioambiente/portal/landing-page/-/asset_publisher/4V1kD5gLiJkq/content/documentos-previos-al-plan-hidrol-c3-b3gico-cuencas-mediterr-c3-a1neas-andaluzas-2021-2027/20151. Accessed on June 15, 2022
62. Padrón de Almería (2020) https://padron.com.es/almer%C3%ADa/. Accessed on Dec 15, 2021
63. Pantaléon-Cano J, Yll EI, Pérez-Obiol R, Roure JM (2003) Palynological evidence for vegetational history in semi-arid areas of the western Mediterranean (Almería, Spain). Holocene 13(1):109–119
64. Paroissien JB, Darboux F, Couturier A, Devillers B, Mouillot F, Raclot D, Le Bissonnais Y (2015) A method for modeling the effects of climate and land use changes on erosion and sustainability of soil in a Mediterranean watershed (Languedoc, France). J Environ Manag 150:57–68
65. Parra MJE, Rodrigo FS, Díez AYC (1997) Estudio de variaciones climáticas en Almería. Recursos Naturales y Medio Ambiente en el sureste peninsular. Instituto de Estudios Almerienses, Almería, pp 489–501
66. Poyatos López R (2006) Measuring and modelling transpiration of pine and oak forest stands in a Mediterranean mountain area (Vallcebre, NE Spain). Universitat de Barcelona, Barcelona
67. Rawls WJ, Brakensiek DL, Miller N (1983) Green-Ampt infiltration parameters from soils data. J Hydraul Eng 109(1):62–70
68. Rosenzweig C, Karoly D, Vicarelli M, Neofotis P, Wu Q, Casassa G, Imeson A (2008) Attributing physical and biological impacts to anthropogenic climate change. Nature 453(7193):353–357
69. Sala JQ, Montón Chiva E, Escrig Barberá J (2000) La evolución de las precipitaciones en la cuenca occidental del Mediterráneo ¿tendencias o ciclos? Investig Geogr 24:17–35
70. Serrano SMV, Camino ER, Castro FD, Molina CA (2017) An updated review on recent trends in observational surface atmospheric variables and their extremes over Spain. Cuad Investig Geogr 43:209–232
71. Shirmohammadi B, Malekian A, Salajegheh A, Taheri B, Azarnivand H, Malek Z, Verburg PH (2020) Scenario analysis for integrated water resources management under future land use change in the Urmia Lake region. Iran Land Use Policy 90:104299
72. Shrestha R, Tachikawa Y, Takara K (2006) Input data resolution analysis for distributed hydrological modeling. J Hydrol 319(1–4):36–50
73. Singer SF (2011) Nature—not human activity—rules the climate. International Seminar on Nuclear War and Planetary Emergencies 43rd Session. World Scientific, Singapore, p 341
74. SIOSE Sistema de Información de Ocupación del Suelo en España 1:10.000 (2013) http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.dc2a45ec0662d3cf8ca78ca731525ea0/?vgnextoid=fa0d7c119370f210VgnVCM2000000624e50aRCRD&lr=lang_es&lr=lang_es. Acceso Mar 2017
75. Touhami I, Chirino E, Andreu JM, Sánchez JR, Moutahir H, Bellot J (2015) Assessment of climate change impacts on soil water balance and aquifer recharge in a semiarid region in south east Spain. J Hydrol 527:619–629
76. Trenberth KE (2011) Changes in precipitation with climate change. Climate Res 47(1–2):123–138
77. Vicente-Serrano SM, Azorin-Molina C, Sanchez-Lorenzo A, Morán-Tejeda E, Lorenzo-Lacruz J, Revuelto J, Espejo F (2014) Temporal evolution of surface humidity in Spain: recent trends and possible physical mechanisms. Clim Dyn 42(9–10):2655–2674
78. Villarejo VC, Lopez CM (2014) Water use in arid rural systems and the integration of water and agricultural policies in Europe: the case of Andarax river basin. Environ Dev Sustain 16(4):957–975
79. Watson AM (1974) The Arab agricultural revolution and its diffusion, 700–1100. J Econ History. 34(1):8–35. https://doi.org/10.1017/S0022050700079602
80. Wheater H, Evans E (2009) Land use, water management and future flood risk. Land Use Policy 26:S251–S264
81. Willmott CJ (1982) Some comments on the evaluation of model performance. Bull Am Meteorol Soc. 63(11):1309–1313. https://doi.org/10.1175/1520-0477(1982)063%3c1309:SCOTEO%3e2.0.CO;2
82. WMS Mapa de Suelos de Andalucía (2017) http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.04dc44281e5d53cf8ca78ca731525ea0/?vgnextoid=0a45239671e0a210VgnVCM2000000624e50aRCRD&vgnextchannel=859c7c119370f210VgnVCM2000000624e50aRCRD&vgnextfmt=rediam&lr=lang_es. Acceso Mar 2017
83. WMS Mapa Geológico de Andalucía (2017) http://www.juntadeandalucia.es/medioambiente/site/rediam/menuitem.04dc44281e5d53cf8ca78ca731525ea0/?vgnextoid=c1bc9cd553ff9210VgnVCM2000000624e50aRCRD&vgnextchannel=859c7c119370f210VgnVCM2000000624e50aRCRD&vgnextfmt=rediam&lr=lang_es. Acceso Mar 2017
84. Yang R, Wu S, Wu X, Ptak M, Li X, Sojka M, Zhu S (2022) Quantifying the impacts of climate variation, damming, and flow regulation on river thermal dynamics: a case study of the Włocławek Reservoir in the Vistula River, Poland. Environ Sci Eur 34(1):1–11

85. Yilmaz AG, Imteaz MA, Ogwuda O (2012) Accuracy of HEC-HMS and LBRM models in simulating snow runoffs in Upper Euphrates Basin. J Hydrol Eng 17(2):342–347
86. Zalidis G, Stamatiadis S, Takavakoglou V, Eskridge K, Misopolinos N (2002) Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology. Agr Ecosyst Environ 88(2):137–146
87. Zapata-Sierra AJ, Cama-Pinto A, Montoya FG, Alcayde A, Manzano-Agugliaro F (2019) Wind missing data arrangement using wavelet based techniques for getting maximum likelihood. Energy Convers Manage 185:552–561
88. Zapata-Sierra A, Manzano-Agugliaro F (2008) Influence of six tree species on water infiltration in soil. Agrociencia 42(7):835–845

Publisher's Note