



# Assessing Climate Change Impacts on Future Reliability of Water Supply Systems Served by Karst Aquifers

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## Abstract

This study proposes a modelling chain to assess climate change impacts on the future reliability of water supply systems fed by karst aquifers. EURO-CORDEX projections under Representative Concentration Pathways 4.5 and 8.5 are used to estimate spring discharge for 2021–2050 and 2041–2070. A regression model relates minimum annual spring discharge to the Standardized Precipitation-Evapotranspiration Index (SPEI), and reliability curves are derived after bias correction. The method is applied to four main karst aquifers in Central Italy that supply Rome and nearby areas. Specific results suggest a general decrease of reliability in the future scenarios. A general decline in aquifer reliability is projected, especially for 2041–2070. Aquifer Peschiera shows decreases of ~11% (near-future) and ~8% (mid-future); Le Capore up to ~13%; Simbrivio ~6% to ~9%; Acqua Marcia ~8%. The proposed methodology could be beneficial to water managers, as it offers support for planning adaptation measures that can reduce the impacts of climate change.

**Keywords** Spring discharge · Reliability · SPEI · EURO-Cordex · RCMs

## 1 Introduction

Groundwater in the saturated zone accounts for 30% of the Earth's freshwater (UNESCO 2008), providing drinking water for about half of the global population and supporting other uses (Rosenzweig et al. 2004; Green et al. 2011; Kløve et al. 2014; Ollivier et al. 2020). Many studies have highlighted a potential future decrease of water availability on the globe due to climate change (Zollo et al. 2016; Nistor and Man 2019; Peres et al. 2019; Yin et al. 2020; Todaro et al. 2022). Climate change, in combination with an observed

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increasing trend of groundwater exploitation, is expected to lead to an increase of water scarcity issues in the future (Wada et al. 2010; Hartmann et al. 2014; Borah 2025; Rosete et al. 2025; Şen 2021).

Within this context, karst aquifers are an important source for potable water supply in many regions across the globe (Stevanović 2019; Rahbar et al. 2022) including the Mediterranean region, which is also a hotspot for climate change (Giorgi 2006; Tuel and Eltahir 2020; IPCC 2013).

Only a limited number of studies have focused on the quantification of the future impacts of climate change on water availability from these systems. Some studies analyze precipitation and temperature trends, and by hydrological modelling, attempt to estimate trends for spring discharge, thus being affected by the limitation of being unlinked to possible greenhouse gas emission pathways (Chaparinia et al. 2025; Jia et al. 2017; Lukač Reberski et al. 2020; Mo et al. 2023). On the other hand, studies focusing on future impacts based climate models (e.g., Valdes-Abellan et al. 2020; Hosseinizadeh et al. 2019; and Sivelle et al. 2021), lack of an analysis of the potential impacts on the probability of satisfying a given water demand, i.e., the so-called reliability for water supply. This assessment is important for water utilities that need to plan adaptation measures to be implemented in the short, medium and long-term.

In this study, we advance from the existing body of literature by using GCM-RCM (Global Circulation Model– Regional Circulation Model) combinations (hereafter, simply, climate models CMs) and by estimating the impacts of climate change in terms of reliability curves that express the probability of providing a given total spring discharge (i.e. water availability) to the water supply system, taking into account also environmental needs.

To this aim a modelling chain is proposed. First, we use an empirical regressive model for estimating minimum annual spring discharge through the Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), which represents an improvement of a previously developed model based on the Standardized Precipitation Index (SPI) (Romano et al. 2013; Guyennon et al. 2024). Climate projections of the EURO-CORDEX initiative are then considered (Jacob et al. 2014; <https://www.euro-cordex.net/>), for two Representative Concentration Pathways (RCPs), RCP4.5 (intermediate emissions scenario) and RCP8.5 (high emissions scenario), as well as two future time horizons, namely, the near future (NF, 2021–2050) and the mid-term future (MF, 2041–2070). We capitalize on a previous study (Peres et al. 2020) to preselect climate models based on their reliability in the Mediterranean region. The preselected models are then used to estimate future changes of aquifer discharge, after the application of a global bias correction procedure.

Thus, the novelty of this study lies in the integration of climate model projections with an empirical discharge model to produce probabilistic reliability curves for karst aquifers, a methodological advancement that explicitly links future climate scenarios with the likelihood of meeting water supply demands—a perspective that is currently lacking in the existing literature.

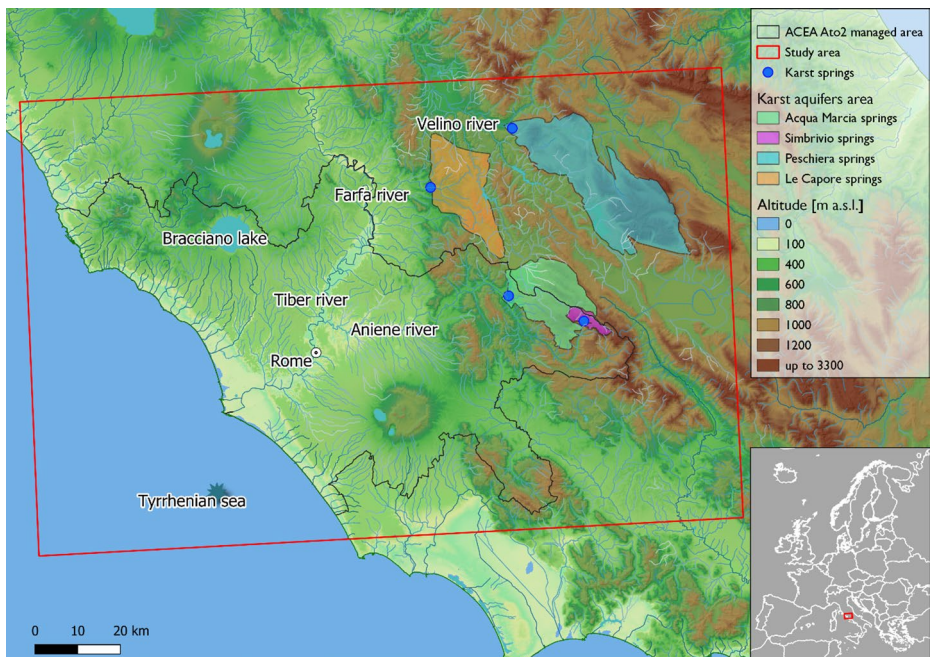
The proposed methodology is demonstrated with reference to the main karst aquifers located in Central Italy that supply over 4 million of users in the vicinity of Rome by the water utility ACEA Ato2.

## 2 Study Area

We focus on a group of aquifers in Central Italy delimited by the Tyrrhenian Sea and the Apennine ridge, to the West and East, respectively, which are exploited by water utility ACEA Ato2 to supply the city of Rome and its surroundings. The whole area is about 5,400 km<sup>2</sup> in extent, with a water distribution network of more than 15,000 km (Passaretti et al. 2022). Specifically, four springs are considered, i.e., Pescara, Le Capore, Acqua Marcia and Simbrivio (Fig. 1). Table 1 summarizes the hydrological characteristics of the selected karst aquifers. As can be seen from the data in the table there is a significant range of variability of climate and hydrology across the considered aquifers. In addition to the data in Table 1, it is worth mentioning that, as demonstrated by Guyennon et al. (2024), minimum spring discharge occurrences are not simultaneous for all aquifers; specifically, maximum spring yield for the main aquifer (i.e., Pescara) occurs when the other aquifers provide the minimum spring yield.

The Pescara karst springs, located about 70 km at north-east of Rome in the upper valley of the Velino river, and Le Capore springs set on the upper valley of the Farfa river, serve a strategic aqueduct system supplying over 80% of the water demand of the city of Rome. The remaining 20% is mostly provided by the Acqua Marcia springs bordered by the middle valley of the Aniene river. The Simbrivio springs, located within the southern sector of the Simbruini Mountains, supply the homonymous aqueduct system. Although with a smaller yield compared to Pescara-Capore and Acqua Marcia aqueducts, the Simbrivio aqueduct allows supplying water to more than 500,000 users in the surroundings of the city of Rome.

It is worth noting, for a more accurate assessment of climate change impacts, that the current water demand supplied by each aquifer can be significantly lower than the available



**Fig. 1** Case study area with location and recharge areas of aquifers

**Table 1** Main hydrological components for each selected aquifer: recharge area extension, mean annual precipitation (Avg PR), mean annual air temperature (Avg TAS), mean annual reference evapotranspiration (Avg ET<sub>0</sub>), sample size of spring yield time series, mean annual of minimum spring yield (Avg Q), coefficient of variation of minimum spring yield (CV Q)

| Aquifer      | Recharge area<br>[km <sup>2</sup> ] | Avg PR<br>[mm/year] | Avg TAS<br>[°C/year] | Avg ET <sub>0</sub><br>[mm/year] | Spring yield sample size<br>[year] | Avg Q<br>[m <sup>3</sup> /s] | CV Q<br>[-]            | Months of<br>Q minima |
|--------------|-------------------------------------|---------------------|----------------------|----------------------------------|------------------------------------|------------------------------|------------------------|-----------------------|
| Peschiera    | 595                                 | 1102                | 7.9                  | 836                              | 14                                 | 16.69                        | $8.04 \times 10^{-2}$  | Jan–Mar               |
| Le Capore    | 270                                 | 1191                | 12.5                 | 1010                             | 18                                 | 4.35                         | $5.69 \times 10^{-2}$  | Aug–Oct               |
| Acqua Marcia | 256                                 | 1089                | 9.3                  | 858                              | 28                                 | 3.85                         | $17.65 \times 10^{-2}$ | Sep–Nov               |
| Simbrivio    | 30                                  | 1052                | 7.4                  | 779                              | 21                                 | 0.16                         | $33.43 \times 10^{-2}$ | Aug–Oct               |

water. For example, in the case of the Peschiera springs, only about 50% of the spring yield is actually used to meet water demand. Moreover, the springs' response to recharge is influenced by meteo-climatic processes that develop over roughly a year or more. This, in turn, gives the water supply system considerable resilience in terms of maintaining a constant water availability over time.

### 3 Methodology and Preliminary Analyses

The first step of the proposed modelling chain consists in retrieving observed and CM data of the primary hydrological variables, i.e., precipitation and air temperature. Then, by comparing CMs simulations and observations in the control period, the reliability of selected CMs is assessed. Afterwards, projected changes of primary hydrological variables and of reference evapotranspiration are computed under various CMIP5 (Coupled Model Intercomparison Project Phase 5) scenarios and future periods—specifically, as already mentioned, RCP4.5 and 8.5 and near future (NF, 2021–2050) and mid-term future (MF, 2041–2070). In the subsequent step, the Standardized Precipitation-Evapotranspiration Index (SPEI) is computed. The SPEI is plugged into a regressive model, to estimate the minimum spring yield (or discharge) at each year of interest. After bias correction, we estimate temporal reliability associated with any water availability level (water supply reliability curves, briefly “reliability curves” - RCs). Comparison between RCs in future periods versus those in the control period provides a measure of the impact of climate change on water resources. The steps are described in detail in the ensuing sub-sections.

#### 3.1 Hydrological Data and Climate Model Selection

In the present study, we have considered the following primary hydrological variables: Precipitation (PR), Average air temperature (TAS), minimum air temperature (TASMIN), and air maximum temperature (TASMAX). For the climate projections we used CMs of the EURO-CORDEX initiative (<https://www.euro-cordex.net/>), which have a grid size of  $0.11^\circ$ —approximately 12.5 km. Three CMs were selected out of 19 based on our previous evaluation study (Peres et al. 2020), in order to retain models with acceptable biases. The performances of the CMs, in terms of mean error ( $e$ ) and root mean squared error ( $S_E$ ) are shown in Table 2. Specifically, the performances have been obtained by comparing the observed and CM-simulated monthly average of primary climatic variables on the entire spring area for the period 1990–2005 (16 years in total) with reference to mean monthly precipitation, mean air temperature data and reference evapotranspiration estimated by the Hargreaves formula. In the following analyses, we present results for each of the three best-performing RCMs individually, as well as for their ensemble mean (EM BEST3).

#### 3.2 Standardized Precipitation-Evapotranspiration Index and Spring Yield Estimation

The SPEI (Vicente-Serrano et al. 2010) is a well-known drought indicator that can be used for determining the onset, duration and magnitude of drought conditions with respect to normal conditions. In our case, it is used for estimating spring yield by a regressive model. The

**Table 2** Performance of CMs assessed over the 1990–2005 period based on their ability to reproduce the statistical characteristics of observed climate, using mean error (e) and root mean square error ( $S_E$ ) for each variable: precipitation (PR), average (TAS), minimum (TASMIN), and maximum air temperature (TASMAX)

| CM        | GCM                       | RCM                   | PR            |           | TAS           |           | ET0           |           |
|-----------|---------------------------|-----------------------|---------------|-----------|---------------|-----------|---------------|-----------|
|           |                           |                       | $S_E$<br>(mm) | e<br>(mm) | $S_E$<br>(°C) | e<br>(°C) | $S_E$<br>(mm) | e<br>(mm) |
| CNRM-CCLM | CNRM-CERFACS-<br>CNRM-CM5 | CLMcom-<br>CCLM4-8-17 | 26.86         | 7.19      | 1.09          | -0.78     | 12.25         | -10.45    |
| Had-CCLM  | MOHC-HadGEM2-ES           | CLMcom-<br>CCLM4-8-17 | 38.25         | -27.99    | 1.61          | 0.49      | 5.63          | -2.66     |
| Had-RACM  | MOHC-HadGEM2-ES           | KNMI-RAC-<br>MO22E    | 32.44         | -14.86    | 1.47          | -0.90     | 6.33          | 4.30      |

R SPEI package (<https://cran.r-project.org/web/packages/SPEI/index.html>) has been used to compute the index, using reference evapotranspiration computed from the Hargreaves formula. Impacts of climate change on droughts can be assessed by comparing future versus control period statistics of SPEI. To this aim, a traditional “static” approach for this assessment was used, i.e., the future SPEI was computed considering the distribution parameters obtained for the control scenario (Peres et al. 2023).

After SPEI computation, the following relationship was used for the estimation of monthly minimum spring yield of an aquifer in a given hydrological year (Guyennon et al. 2024):

$$\hat{Q} = f(SPEI) = \alpha SPEI_{k,m} + \beta \quad (2)$$

where the subscript  $i$  indicates the selected aquifer within the water supply system,  $k$  is the time scale at which SPEI is aggregated, and  $m$  is the month to which the index refers (a value for each hydrological year). The use of regressive models is common for management purposes, and the adopted model derives from a previous version based on the Standardized Precipitation Index used for the case study area (Romano et al. 2013, 2017; Diodato et al. 2014; Torresan et al. 2020). The parameters of the regression,  $\alpha$  and  $\beta$ , are estimated using the method of least squares. Time scale and months of SPEI were calibrated as those providing the highest maximum Pearson correlation coefficient  $R$ , between observed and regression output values. The model was validated, for each aquifer, based on randomly removing 20% of the entire data set, and repeating this procedure 50 times, to ensure robustness of the results (Klemeš 1986; Arsenault et al. 2018). As shown in Table 3, the calibrated model has performances that are similar to those presented in Romano et al. (2013), i.e., a Pearson coefficient  $R$  with observed discharge series ranging around 0.70, both for calibration and validation.

### 3.3 Reliability-water Availability Curves and bias Correction

We consider Reliability-water availability curves (briefly “reliability curves”—RCs) as those linking spring yield and reliability. More precisely, a RC expresses the percentage of years (y-axis) in which discharge is always greater than a given value  $Q$  (i.e., exceedance frequency):

**Table 3** Estimated parameters derived from the regressive model used to forecast minimum spring yield for each selected aquifer: Temporal aggregation scale ( $k$ ) at which SPEI is aggregated, the month ( $m$ ) to which the SPEI refers, the regression parameters  $\alpha$  and  $\beta$  estimated using the method of least squares and the unit of measurement of the minimum spring yield evaluated

| Aquifer      | Best aggregation scale $k$ | Best month $m$ | $\alpha$<br>[m <sup>3</sup> /s] | $\beta$<br>[m <sup>3</sup> /s] | $R$ (calib.) | $R$ (valid.) |
|--------------|----------------------------|----------------|---------------------------------|--------------------------------|--------------|--------------|
| Peschiera    | 14                         | November       | 0.79                            | 16.8                           | 0.68         | 0.68         |
| Le Capore    | 11                         | September      | 0.14                            | 4.30                           | 0.71         | 0.71         |
| Acqua Marcia | 15                         | December       | 0.51                            | 3.84                           | 0.73         | 0.64         |
| Simbrivio    | 10                         | May            | 0.03                            | 0.16                           | 0.69         | 0.68         |

$$r(Q) = 100 \frac{\sum_{t=1}^N I(Q_t - Q)}{N} \quad (3)$$

where:

$$I(Q) = \begin{cases} 0, & Q < 0 \\ 1, & Q \geq 0 \end{cases} \quad (4)$$

given that  $Q_t$  represents the minimum monthly spring discharge for year  $t$ , where  $t = 1, 2, \dots, N$ .

We derived RCs for both control and future scenarios, as their comparison allows to measure the potential future impacts of climate change on water availability in the area of interest. In other words, Eq. (3) was applied to spring yield series computed from the regres-

sive model by using CM simulations in the control period  $\hat{Q}_{c, CM} = f(SPEI_{c, CM})$ , and

in the generic future scenario  $\hat{Q}_{f, CM} = f(SPEI_{f, CM})$ .

The derived reliability curves referred to the control period are adjusted by a global bias correction procedure. In particular, we brought the empirical distribution of spring yield estimated by the regression model and CM model in the control period,

$\hat{Q}_{c, CM} = f(SPEI_{c, CM})$ , to coincide with the one estimated using the regression model

with observed SPEI  $\hat{Q}_0 = f(SPEI_0)$ .

The correction consists of applying the following equations:

$$\hat{Q}_{0, corr}(\hat{Q}_{c, CM}) = F_{ref}^{-1}\left(F_0\left(\hat{Q}_{c, CM}\right)\right); F_{c, corr} = F_0 \quad (5)$$

$$\hat{Q}_{f, corr}(\hat{Q}_{f, CM}) = F_{ref}^{-1}\left(F_0\left(\hat{Q}_{f, CM}\right)\right); F_{f, corr} = F_0 \quad (6)$$

where  $F_{ref}$  is the ECDF (Empirical Cumulative Distribution Function) of the reference spring yield (minimum values calculated using observed SPEI),  $F_{ref}^{-1}$  is its inverse,  $F_0$  is the ECDF of spring yield calculated from observed SPEI,  $F_{c, corr}$  and  $F_{f, corr}$  are the corrected ECDFs for the control and the future period, respectively.

## 4 Results and Discussion

### 4.1 Projected Changes of Hydrological Variables and SPEI

The variations of the three main climatic variables are summarized in Table 4. Specifically, for the group of aquifers as a whole, future changes of annual precipitation, annual average air temperature, and annual reference evapotranspiration ( $ET_0$ ), are shown for each of the scenario and period combinations. In addition to the variations assessed by each of the three best models considered in this study, Table 4 also reports the corresponding values averaged across these models (EM BEST3).

All CMs agree in projecting a significant increase of temperature and, consequently, of reference evapotranspiration. Overall, with reference to EM BEST3, there is an increase in mean annual temperature of more than 1.5 °C for the NF, and 2.15 °C and 2.74 °C for the MF, respectively for RCP 4.5 and RCP 8.5. In terms of reference evapotranspiration, this involves an increase about 50 mm for the NF, and 69.04 mm (RCP 4.5) and 83.62 mm (RCP 8.5) for the MF. Looking at the variations in precipitation, a general decrease is projected, especially for the MF. However, for the NF, the direction of change may change across CMs. More in detail, it can be seen that for the NF and RCP 4.5, 2 out of 3 cm predict an increase in average annual precipitation, while this occurs only for 1 CM in the high-emission scenario (RCP 8.5). Nevertheless, considering the ensemble mean of the best 3 models, a decrease in precipitation prevails for all future periods and scenarios. In more detail, the decrease for the NF is relatively small (an average of −8 mm for RCP 4.5, and approximately −16 mm for RCP 8.5), while for the MF, the decrease is considerably larger, with a higher decrease for RCP4.5 (−74.92 mm) than for RCP8.5 (−44.72 mm). This, however, in terms of SPEI and thus spring yield, is balanced by the greater increase in temperature and, therefore, of evapotranspiration corresponding to the latter scenario.

Changes in both precipitation and temperature are reflected in changes of the 30-years average of Standardized Precipitation-Evapotranspiration Index (SPEI). Figure 2 shows

**Table 4** Variations in mean annual precipitation (PR, [mm]), mean air temperature (TAS, [°C]) and reference evapotranspiration ( $ET_0$ , [mm]) over all aquifers, with reference to RCP 4.5 and RCP 8.5, for near future (2021–2050) and for mid-term future (2041–2070)

| RCM       | Variable | HIST<br>(1971–2000) | $\Delta$ RCP 4.5<br>(2021–2050) | $\Delta$ RCP 8.5<br>(2021–2050) | $\Delta$ RCP 4.5<br>(2041–2070) | $\Delta$ RCP 8.5<br>(2041–2070) |
|-----------|----------|---------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Had-CCLM  | PR       | 1014.9              | 7.23                            | −15.34                          | −104.96                         | −97.91                          |
|           | TAS      | 9.48                | 1.9                             | 2.12                            | 2.67                            | 3.23                            |
|           | $ET_0$   | 833.76              | 69.33                           | 71.52                           | 97.7                            | 114.53                          |
| Had-RACM  | PR       | 1211.06             | 81.54                           | 60.37                           | −29.08                          | 3.28                            |
|           | TAS      | 8.01                | 1.81                            | 2.06                            | 2.52                            | 3.13                            |
|           | $ET_0$   | 914.53              | 49.13                           | 49.15                           | 67.07                           | 84.2                            |
| CNRM-CCLM | PR       | 1429.15             | −112.75                         | −92.71                          | −90.72                          | −39.53                          |
|           | TAS      | 8.32                | 0.87                            | 1.11                            | 1.26                            | 1.85                            |
|           | $ET_0$   | 740.52              | 33.21                           | 35.3                            | 42.35                           | 52.13                           |
| EM BEST3  | PR       | 1218.37             | −7.99                           | −15.89                          | −74.92                          | −44.72                          |
|           | TAS      | 8.60                | 1.53                            | 1.76                            | 2.15                            | 2.74                            |
|           | $ET_0$   | 829.60              | 50.56                           | 51.99                           | 69.04                           | 83.62                           |

how the variations of SPEI increase with the aggregation scale ( $k$ ) of the index, with reference to both NF and MF and the ensemble of the best three climate models.

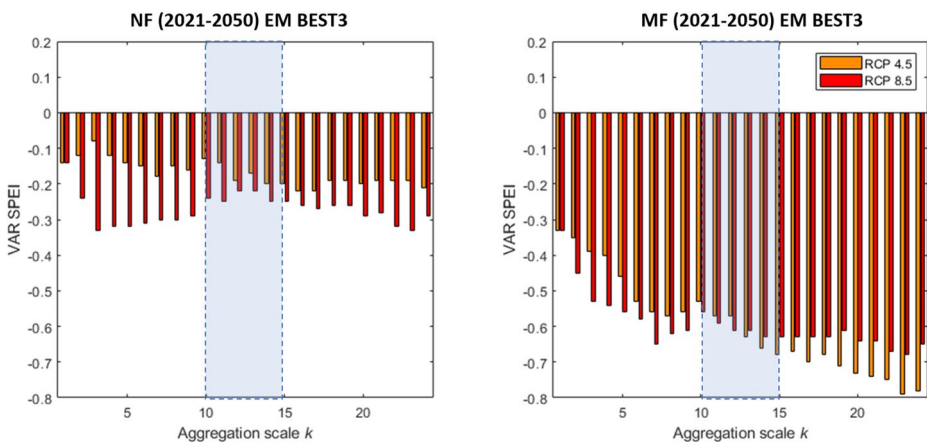
Reductions in SPEI are significantly larger for the MF than the NF. For the aggregation scales of greater interest, i.e., those involved in spring yield estimation (Table 3), i.e.,  $10 \leq k \leq 15$ , reductions of about  $-0.3$  and  $-0.6$  are observed for RCP 4.5 and RCP 8.5, respectively. The future decrease of SPEI average indicates that droughts are predicted to be more likely due to climate change, as confirmed by previous studies in the Mediterranean area (Peres et al. 2023).

## 4.2 Projected Changes of reliability-water Availability Curves

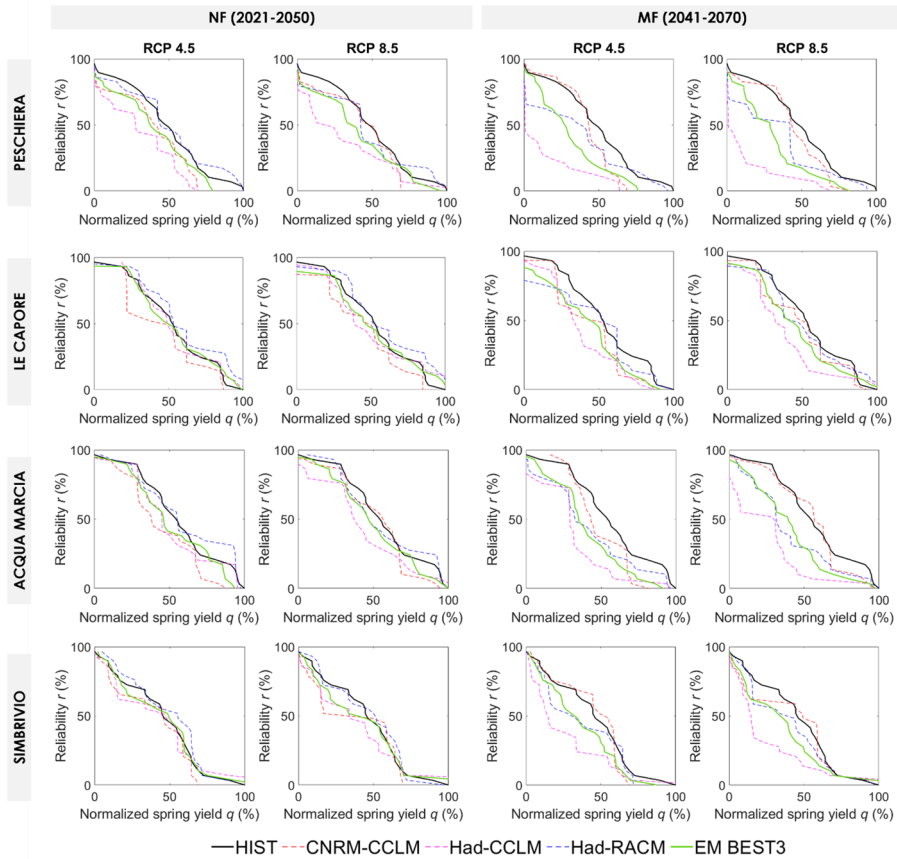
Figure 3 presents the RCs for each aquifer and for all future scenarios and periods, after the application of global bias correction. In order to make the RCs of the different aquifers more readily comparable, the series of minimum spring yield have been normalized with respect to the minimum and to the maximum value of the series of annual minima of spring yield in the control period, i.e.,  $q [\%] = 100 \bullet (Q - Q_{c,\min}) / (Q_{c,\max} - Q_{c,\min})$ .

Looking at the NF, RCs for RCP4.5 are mostly centered around the one corresponding to the control period; in this case the future ensemble RCs almost coincide with those in the control period for aquifers Le Capore, and Simbrivio, while for the other two aquifers there is a general decrease in reliability. In NF, the future curves obtained with the different CMs tend to be lower than the observed one in RCP8.5 with respect to RCP4.5. This is reflected on the ensemble average, even though the changes for Le Capore and Simbrivio remain quite low even in RCP8.5. Going to the MF, a general decrease of reliability is projected, which can be more significant in RCP4.5 than in RCP8.5. There is also, with respect to the NF, a greater level of variability in predictions across different CMs. The largest decreases in reliability are observed for Peschiera and Acqua Marcia aquifers, for which Had-CCLM model indicates the most significant one.

From the analysis of Fig. 3 and Table 5 shows the changes in reliability of specific values of normalized spring yield. Specific changes in reliability for the lower values of spring yield



**Fig. 2** Projected changes in SPEI for both the near and mid-term future (2021–2050 and 2041–2070, respectively) and in relation to the three best climate models. The blue window highlights the typical aggregation scales for the regressive model used to estimate spring yield



**Fig. 3** Reliability curves for each aquifer and for both RCPs (4.5, 8.5) and both temporal horizons (2021–2050, 2041–2070). In x-axis, normalized minimum spring yield with respect to the minimum and maximum values of the control period

(corresponding to high values of reliability, and thus of major interest from a management point of view) allow express more directly the potential impacts of climate change under the considered scenarios. As can be seen from the table, changes in reliability are generally negative. Focusing on the tenth-percentile of the minimum spring yield (i.e.,  $q=10\%$ ), it can be seen that an appreciable decrease of reliability is projected for the Peschiera springs, where, for both RCPs, changes are slightly above  $-11\%$  in the NF and about  $-8\%$  in the MF. A lower decrease is projected in the NF for Le Capore (about  $-1.5\%$  in RCP4.5 and  $-6.5\%$  in RCP8.5) and Simbrivio (about  $-6\%$  for RCP8.5); Acqua Marcia is the aquifer showing the smallest reduction in reliability among those where a decrease is projected (less than  $-1\%$ ), while a slight increase is predicted for Simbrivio (about  $+2.4\%$  in the RCP 4.5). In the MF, moderate changes are observed for Acqua Marcia (about  $-8\%$  under both RCPs), Simbrivio (about  $-6\%$  in RCP4.5 and  $-9\%$  in RCP8.5) and for Le Capore (about  $-6\%$  in RCP8.5). The most appreciable, but isolated, decrease is foreseen for Le Capore in RCP4.5 (about  $-13\%$ ).

**Table 5** Changes (future minus control period) of reliability for different levels of normalized spring yield for all analyzed aquifers, for both scenarios and future periods

| Normalized spring yield $q$ [%] | $r$ [%]           | Peschiera |           | Le Capore |           | Acqua Marcia |           | Simbrivio |           |
|---------------------------------|-------------------|-----------|-----------|-----------|-----------|--------------|-----------|-----------|-----------|
|                                 |                   | 2021–2050 | 2041–2070 | 2021–2050 | 2041–2070 | 2021–2050    | 2041–2070 | 2021–2050 | 2041–2070 |
| 5                               | $\Delta_{RCP4.5}$ | −5.67     | −1.39     | −2.31     | −9.10     | −0.80        | −1.47     | 0.16      | −2.77     |
|                                 | $\Delta_{RCP8.5}$ | −10.17    | −6.88     | −6.78     | −5.29     | −0.85        | −4.49     | −2.43     | −6.53     |
| 10                              | $\Delta_{RCP4.5}$ | −10.68    | −7.68     | −1.45     | −13.10    | −0.14        | −7.82     | 2.39      | −5.66     |
|                                 | $\Delta_{RCP8.5}$ | −11.60    | −7.50     | −6.50     | −5.57     | −0.98        | −7.83     | −5.77     | −8.62     |

Though these changes are appreciable, it can be stated that the consequences on the reliability of the water supply system fed by the analyzed aquifers can be deemed as not critical, as the current and expected exploitation of aquifers is considerably less water demand. The presence of this margin, coupled with the observation that the maximum spring yield in this aquifer occurs almost simultaneously with the minimum spring discharge of the other aquifers (Guyennon et al. 2024), plays a crucial role in enhancing the present and future resilience of the system to meet water demands. Nevertheless, the outcomes of this study indicate that climate change impacts need to be taken into consideration, and that it is increasingly crucial to plan and implement effective measures for climate change adaptation. Water managers and stakeholders need thus to shift to a holistic approach that enables the implementation of measures for sustainable water resource management (Rossi and Peres 2023). These efforts could include reducing water consumption, conservation strategies, wastewater reuse and other measures to enhance water supply system resilience.

## 5 Conclusions

This study introduces a methodology to assess the impacts of climate change on the reliability of water supply systems fed by karst aquifers, applied to a case study in Central Italy. To address uncertainties associated with both climate and hydrological models, the analysis incorporates ensemble averaging and bias correction, ensuring more robust and interpretable results. The case study results suggest limited changes in precipitation in the near future (2021–2050), with average decreases of approximately −8 mm under RCP4.5 and −16 mm under RCP8.5. However, more substantial reductions are projected for the mid-term period (2041–2070), particularly under RCP4.5 (−74.9 mm) and RCP8.5 (−44.7 mm). These are accompanied by a notable increase in mean annual temperature, exceeding 1.5 °C in the near future and reaching up to 2.74 °C in the mid-term future. As a consequence, a moderate decline in spring yield reliability is expected, with more pronounced impacts in the mid-term horizon. Among the aquifers analyzed, Peschiera and Le Capore show the largest projected reductions, while Acqua Marcia exhibits minimal changes and even slight improvements in some scenarios. Despite these projected shifts, the system as a whole remains resilient. Current and forecasted extraction rates are significantly below sustainable thresholds, and the asynchronous behavior of aquifers—where peaks in discharge from one source coincide with lows in others—enhances overall supply stability. These findings underline the value of incorporating climate impact assessments into long-term planning.

The study shown how even with simplified modelling approaches, important insights can be gained to support the development of adaptive strategies aimed to ensure the continued reliability of water resources under evolving climate conditions.

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**Data Availability** All hydrological data referred to the study area were provided by ACEA Ato2, Department of Water Resource Protection, Rome, Italy. Climate projections of the EURO-CORDEX initiative are available at <https://www.euro-cordex.net/>.

## Declarations

**Ethical Approval** Nothing to declare.

**Consent to Publish** All authors agree upon publication of the present paper.

**Competing interests** Part of the research presented in the paper derives from the consultancy agreement mentioned between ACEA Ato2 and DICAR (AC was the principal investigator of the agreement).

## References

- Arsenault R, Brissette F, Martel JL (2018) The hazards of split-sample validation in hydrological model calibration. *J Hydrol* 566:346–362. <https://doi.org/10.1016/J.JHYDROL.2018.09.027>
- Borah G (2025) Urban water stress: climate change implications for water supply in cities. *Water Conserv Sci Eng* 10:1–16. <https://doi.org/10.1007/S41101-025-00344-5/FIGURES/5>
- Chaparinia F, Hadei M, Yaghmaeian K et al (2025) Evaluation of climate indices related to water resources in Iran over the past 3 decades. *Sci Rep* 15:11846. <https://doi.org/10.1038/s41598-025-95370-7>
- Diodato N, Guerriero L, Fiorillo F et al (2014) Predicting monthly spring discharges using a simple statistical model. *Water Resour Manag* 28:969–978. <https://doi.org/10.1007/S11269-014-0527-0/FIGURES/5>
- Giorgi F (2006) Climate change hot-spots. *Geophys Res Lett* 33:8707. <https://doi.org/10.1029/2006GL025734>
- Green TR, Taniguchi M, Kooi H et al (2011) Beneath the surface of global change: impacts of climate change on groundwater. *J Hydrol* 405:532–560. <https://doi.org/10.1016/J.JHYDROL.2011.05.002>
- Guyennon N, Passaretti S, Mineo C, Boscariorl E, Petrangeli AB, Varriale A, Romano E (2024) A parsimonious model for springs discharge reconstruction and forecast for drought management: lessons from a case study in central Italy. *J Hydrology: Reg Stud* 56:102021. <https://doi.org/10.1016/j.ejrh.2024.102021>
- Hartmann A, Goldscheider N, Wagener T et al (2014) Karst water resources in a changing world: review of hydrological modeling approaches. *Rev Geophys* 52:218–242. <https://doi.org/10.1002/2013RG000443>
- Hosseinzadeh A, Zarei H, Akhondali AM et al (2019) Potential impacts of climate change on groundwater resources: A multi-regional modelling assessment. *J Earth Syst Sci* 128:131. <https://doi.org/10.1007/s12040-019-1134-5>

- IPCC (2013) Climate Change 2013: The Physical Science Basis. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 1535. <https://doi.org/10.1017/CBO9781107415324>
- Jacob D, Petersen J, Eggert B et al (2014) EURO-CORDEX: new high-resolution climate change projections for European impact research. *Reg Environ Chang* 14:563–578. <https://doi.org/10.1007/S10113-013-0499-2/FIGURES/8>
- Jia Z, Zang H, Zheng X, Xu Y (2017) Climate change and its influence on the karst groundwater recharge in the Jinci Spring Region, Northern China. *Water* 9:267. <https://doi.org/10.3390/W9040267>
- Klemeš V (1986) Operational testing of hydrological simulation models. *Hydrol Sci J* 31:13–24. <https://doi.org/10.1080/02626668609491024>
- Kløve B, Ala-Aho P, Bertrand G et al (2014) Climate change impacts on groundwater and dependent ecosystems. *J Hydrol* 518:250–266. <https://doi.org/10.1016/J.JHYDROL.2013.06.037>
- Lukač Reberski J, Rubinić J, Terzić J, Radišić M (2020) Climate change impacts on groundwater resources in the coastal karstic Adriatic area: A case study from the dinaric karst. *Nat Resour Res* 29:1975–1988. <https://doi.org/10.1007/S11053-019-09558-6/FIGURES/6>
- Mo C, Lai S, Yang Q et al (2023) A comprehensive assessment of runoff dynamics in response to climate change and human activities in a typical karst watershed, Southwest China. *J Environ Manage* 332:117380. <https://doi.org/10.1016/j.jenvman.2023.117380>
- Nistor MM, Man TC (2019) Water availability variation under climate change in Turkey during 21 St century. *Carpathian J Earth Environ Sci* 14:19–28. <https://doi.org/10.26471/CJEES/2019/014/054>
- Ollivier C, Mazzilli N, Oliso A et al (2020) Karst recharge-discharge semi distributed model to assess Spatial variability of flows. *Sci Total Environ* 703:134368. <https://doi.org/10.1016/J.SCITOTENV.2019.134368>
- Passaretti S, Mineo C, Varriale A, Cosentino C (2022) A technical note on the application of a water budget model at regional scale: a water manager's approach towards a sustainable water resources management. *Water* 14:712. <https://doi.org/10.3390/W14050712>
- Peres DJ, Modica R, Cancelliere A (2019) Assessing future impacts of climate change on water supply system performance: application to the Pozzillo Reservoir in Sicily, Italy. *Water* 11:2531. <https://doi.org/10.3390/W11122531>
- Peres DJ, Senatore A, Nanni P et al (2020) Evaluation of EURO-CORDEX (Coordinated regional climate downscaling experiment for the Euro-Mediterranean area) historical simulations by high-quality observational datasets in Southern Italy: insights on drought assessment. *Nat Hazards Earth Syst Sci* 20:3057–3082. <https://doi.org/10.5194/NHESS-20-3057-2020>
- Peres DJ, Bonaccorso B, Palazzolo N et al (2023) A dynamic approach for assessing climate change impacts on drought: an analysis in Southern Italy. 1–16. <https://doi.org/10.1080/02626667.2023.2217332>
- Rahbar A, Mirarabi A, Nakhacai M et al (2022) A comparative analysis of Data-Driven models (SVR, ANFIS, and ANNs) for daily karst spring discharge prediction. *Water Resour Manage* 36:589–609. <https://doi.org/10.1007/S11269-021-03041-9>
- Romano E, Del Bon A, Petrangeli AB, Preziosi E (2013) Generating synthetic time series of springs discharge in relation to standardized precipitation indices. Case study in central Italy. *J Hydrol* 507:86–99. <https://doi.org/10.1016/J.JHYDROL.2013.10.020>
- Romano E, Guyennon N, Del Bon A et al (2017) Robust method to quantify the risk of shortage for water supply systems. *J Hydrol Eng* 22:04017021. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001540/SUPPL\\_FILE/SUPPLEMENTAL\\_DATA\\_HE.1943-5584.0001540\\_ROMANO.PDF](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001540/SUPPL_FILE/SUPPLEMENTAL_DATA_HE.1943-5584.0001540_ROMANO.PDF)
- Rosenzweig C, Strzepek KM, Major DC et al (2004) Water resources for agriculture in a changing climate: international case studies. *Glob Environ Chang* 14:345–360. <https://doi.org/10.1016/J.GLOENVCHA.2004.09.003>
- Rosete EA, Alejo LA, Balderama OF et al (2025) Mitigating future water scarcity through comprehensive assessment of climate and socio-environmental impacts in river basins. *Theor Appl Climatol* 2025 1566 156:1–14. <https://doi.org/10.1007/S00704-025-05583-Z>
- Rossi G, Peres DJ (2023) Climatic and other global changes as current challenges in improving water systems management: lessons from the case of Italy. *Water Resour Manage* 37:2387–2402. <https://doi.org/10.1007/s11269-023-03424-0>
- Şen Z (2021) Reservoirs for water supply under climate change impact—a review. *Water Resour Manage* 35:3827–3843. <https://doi.org/10.1007/s11269-021-02925-0>
- Sivelle V, Jourde H, Bittner D et al (2021) Assessment of the relative impacts of climate changes and anthropogenic forcing on spring discharge of a mediterranean karst system. *J Hydrol* 598. <https://doi.org/10.1016/j.jhydrol.2021.126396>
- Stevanović Z (2019) Karst waters in potable water supply: a global scale overview. *Environ Earth Sci* 78:1–12. <https://doi.org/10.1007/S12665-019-8670-9/FIGURES/8>

- Todaro V, D'Oria M, Secci D et al (2022) Climate Change over the Mediterranean Region: Local Temperature and Precipitation Variations at Five Pilot Sites. *Water* 14:2499. <https://doi.org/10.3390/W14162499>
- Torresan F, Fabbri P, Piccinini L et al (2020) Defining the hydrogeological behavior of karst springs through an integrated analysis: a case study in the berici mountains area (Vicenza, NE Italy). *Hydrogeol J* 28:1229–1247. <https://doi.org/10.1007/S10040-020-02122-0/FIGURES/11>
- Tuel A, Eltahir EAB (2020) Why is the mediterranean a climate change hot spot?? *J Clim* 33:5829–5843. <https://doi.org/10.1175/JCLI-D-19-0910.1>
- UNESCO (2008) Groundwater resources assessment under the pressures of humanity and climate change (GRAPHIC): a framework document. GRAPHIC Series Number 2. 2008th ed. United Nations Educational, Scientific, and Cultural Organization (UNESCO), Paris Available in. <https://unesdoc.unesco.org/ark:/48223/pf0000163172>
- Valdes-Abellan J, Pardo MA, Jodar-Abellan A et al (2020) Climate change impact on karstic aquifer hydrodynamics in Southern Europe semi-arid region using the KAGIS model. *Sci Total Environ* 723:138110. <https://doi.org/10.1016/J.SCITOTENV.2020.138110>
- Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J Clim* 23:1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>
- Wada Y, Van Beek LPH, Van Kempen CM et al (2010) Global depletion of groundwater resources. *Geophys Res Lett* 37. <https://doi.org/10.1029/2010GL044571>
- Yin J, Guo S, Gu L et al (2020) Projected changes of bivariate flood quantiles and Estimation uncertainty based on multi-model ensembles over China. *J Hydrol* 585:124760. <https://doi.org/10.1016/J.JHYDROL.2020.124760>
- Zollo AL, Rillo V, Bucchignani E et al (2016) Extreme temperature and precipitation events over Italy: assessment of high-resolution simulations with COSMO-CLM and future scenarios. *Int J Climatol* 36:987–1004. <https://doi.org/10.1002/JOC.4401>

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