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FORESEEING GROUNDWATER RESOURCES

Evaluation of national and regional groundwater resources under climate change scenarios using a GIS-based water budget procedure

G. Braca[1] · M. Bussettini[1] · D. Ducci[2] · B. Lastoria[1] · S. Mariani[1]

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Abstract

The present study investigates the impact of climate change on the availability of groundwater resources in Italy and in Campania region (Southern Italy). A 20-year average from 1996 to 2015 of annual water budget components (namely total precipitation, actual evapotranspiration, surface runoff and aquifer recharge) has been evaluated over a 1-km resolution grid and have been projected considering four climate change scenarios (from the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change) and three different future 20-year time periods (2020–2039, 2040–2059 and 2080–2099). The groundwater balance has been carried out on a yearly basis using the "Nationwide GIS-based regular gridded hydrological water budget" procedure, which has been developed by the Italian National Institute for Environmental Protection and Research (ISPRA). The different scenarios of groundwater resources have been compared and matched to the 20-year average of latest historical values related to the period 1996–2015, leading to interesting considerations about the future depletion of groundwater resources. Nationwide results have been compared with those of Campania region, in order to underline the significant differences of climate change impact on groundwater resources at local scale, especially in a typical Mediterranean climate where groundwater resources represent the main source of water for human needs.

Keywords Water budget · Water resources · Groundwater · Climate change scenarios · Downscaling · GIS

1 Introduction

In the last years, water scarcity and drought severely affected Southern Europe. This is particularly true in Italy, as pointed out in the recent literature (see, e.g., Ducci and Tranfaglia 2008; Fiorillo and Guadagno 2012; Ducci and Polemio 2018).

Drought particularly afflicts Southern Italy in different ways, mainly depending on the area hydrogeological setup and on the physical processes of precipitation–recharge interaction. Ducci and Tranfaglia (2008) found a groundwater recharge of 30% lower than in the previous 30 years for the whole Campania region (Southern Italy), due to rainfall decrease and temperature increase. The 1987–1993 period was probably the most critical in Southern Italy, due to a long period of rainfall scarcity and historical minima reached by spring discharges. After this period, several drought events also occurred, as in 2002, 2007–2008, 2011 and 2017. The severity of these drought events has highlighted the need to evaluate the effects of possible future meteorological drought due to climate change on groundwater resource availability.

Moreover, water scarcity and drought seem to be worsened in a near future, due to the increase of water demand, often exceeding availability and sustainability of water resources, also due to temperature increase and to quantity/

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D. Ducci
daniela.ducci@unina.it

G. Braca
giovanni.braca@isprambiente.it

1 Italian National Institute for Environmental Protection and Research (ISPRA), via Brancati 48, 00144 Rome, Italy

2 Department of Civil, Architectural and Environmental Engineering, University of Naples Federico II, Piazzale Tecchio, 80, 80125 Naples, Italy

distribution precipitation variation (even if in different ways from north to south of Italy) (Toreti et al. 2009). Temperature increase and quantity/distribution variation of precipitation threaten to undermine water resource availability and, consequently, social and economic activities strongly related to them.

The Water Framework Directive 2000/60/EC (WFD) has introduced a legal framework for sustainable management of water resources across Europe. The WFD does not explicitly require the evaluation of changes in temperature and precipitation and its effects on groundwater resources. However, in the document on the application of water balances for supporting the WFD implementation (European Commission 2015), it is recommended to assess water balances for future situations where global changes can affect the hydrological cycle. This assessment is required to identify those actions necessary to enhance the resilience of aquatic systems.

In this context, the Italian National Institute for Environmental Protection and Research (ISPRA) has recently developed the automatic “Nationwide GIS-based hydrological budget on a regular grid” procedure, named BIGBANG (Italian acronym of “Bilancio Idrologico GIS BAsed a scala Nazionale su Griglia regolare”) and currently at version 1.0, to evaluate the water budget components at monthly and annual temporal scale and in spatially distributed approach. This kind of approach also permits to analyze clipped parts (e.g., regions, hydrographic districts, river basins, etc.), to relate each other and to compare them to the whole territory as well. Using BIGBANG 1.0 procedure, the water budget comparison between a part and the whole territory provides a good agreement with local and more detailed analysis (Braca and Ducci 2018).

The annual value of water budget components can be evaluated either by aggregating the monthly values or by a direct calculation of water balance on yearly components.

In this context, the BIGBANG 1.0 procedure has been applied directly on a yearly basis as first approach to face the effects of possible future drought events associated with different climate change scenarios.

This study could represent a “proof of concept” for the suitability of BIGBANG procedure, to simulate water balance under future climatic scenarios, to respond to the needs of decision makers, to plan water resources affected by climate change.

2 Materials and methods

The Italian territory, with a total area of about 301,000 km^2, and Campania region located in Southern Italy, with a total area of about 13,500 km^2, are both investigated in this study (Fig. 1). Campania region has been selected due to the importance of groundwater resources that cover almost all its drinking water needs and part of the neighboring Puglia region population. In future developments of this study, the analysis will be performed for each of the twenty Italian regions.

The methodology applied in this study, which aims to assess the impact of climate change on water resources and, in particular, on groundwater ones, consists of the following steps:

1. Assessment of water balance model;
2. Identification of climate change scenarios or greenhouse gases emissions scenarios (GGES);
3. Selection of future time horizons where to project the observed hydrological variables and water balance components;
4. Setting of global circulation models (GCMs) solutions;
5. Downscaling of GCMs solutions at local scale on more dense grid;
6. Projection of water balance components and hydrological variables to future time horizons.

It is important to underline that most of the above-mentioned steps are (more or less) source of uncertainty and, therefore, the evaluated impacts will reflect this uncertainty and need to be carefully read. As a matter of fact, Chen et al. (2011) pointed out that GCM, GGES and downscaling process are the major sources of uncertainty in the assessment of climate change impact on water resources.

In the following sections, each step of the methodology is described.

2.1 The groundwater budget model

ISPRA BIGBANG is a spatially distributed procedure, which has been implemented over a proprietary GIS platform (ESRI ArcGIS 10.1, ESRI 2012) using Python programming language.

The hydrological components of total precipitation, actual evapotranspiration, surface runoff and groundwater recharge are evaluated over the European Environmental Agency (EEA) 1-km reference grid, in the ETRS89 Datum, using a Lambert azimuthal equal area (LAEA) projection (European Environmental Agency 2017). Figure 2 shows the nested 10-km and 100-km grids (the 1-km grid is not reported since cells are too small to be clearly displayed).

BIGBANG procedure is developed to use reliable geo-referenced environmental information at very high resolution, currently and increasingly available on the WEB, in a format easy to read and to use by GIS. The widespread use of WEB resources, also available in the future, represents one of the main ideas underlying this study comparing previous similar works (Álvarez et al. 2005). This first version of BIGBANG

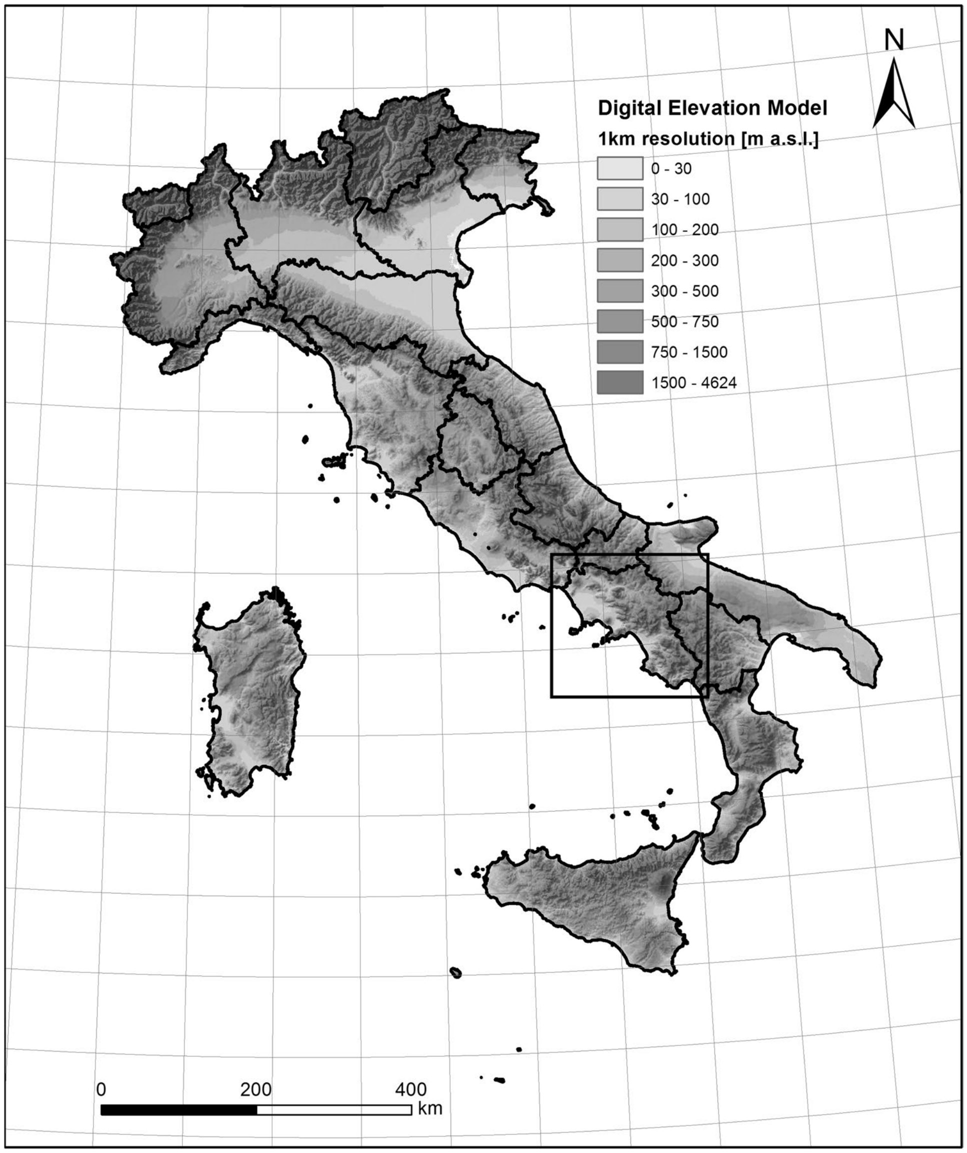

Fig. 1 The investigated area: Italy and Campania region (in the frame)

uses gridded data from different sources: monthly temperature grids from ISPRA SCIA, hydrogeological units and soil sealing rate from ISPRA SINAnet, LUCAS TopSoil data (Tóth et al. 2013) from ESDAC-European Soil Data Centre (the last two are used only in BIGBANG at monthly scale).

In this study, all factors of the water balance (total precipitation, actual evapotranspiration, surface runoff and aquifer recharge) are calculated at annual scale. Accordingly, the annual actual evapotranspiration has been calculated using Turc's empirical formula (Turc 1961):

$$E = \begin{cases} \frac{P}{\sqrt{0.9+P^2/L^2}} & \text{if } P^2/L^2 \geq 0.1 \\ P & \text{if } P^2/L^2 < 0.1 \end{cases} \tag{1}$$

where P is the annual total precipitation in millimeters and $L = 300 + 025T + 0.05T^3$ is the capacity of atmosphere to evaporate water and T is the average annual temperature in Celsius degrees.

The components have been averaged over a 20-year period and expressed in millimeters. In the 20-year average annual balance, the change in soil moisture storage volume is neglected. The applied averaged yearly scale balance model is expressed by the following equation:

$$P - E = R + G \tag{2}$$

where P is the total precipitation, E is the actual evapotranspiration, G is the groundwater recharge, estimated as a percentage of the term $(P - E)$ in function of the permeability of the outcropping hydrogeological units derived from ISPRA SINAnet digital map, expressed as Potential Infiltration Rate (Fig. 3), and R is the surface runoff calculated by difference. Total precipitation is calculated over the EEA 1-km reference grid by interpolating, using standard tools

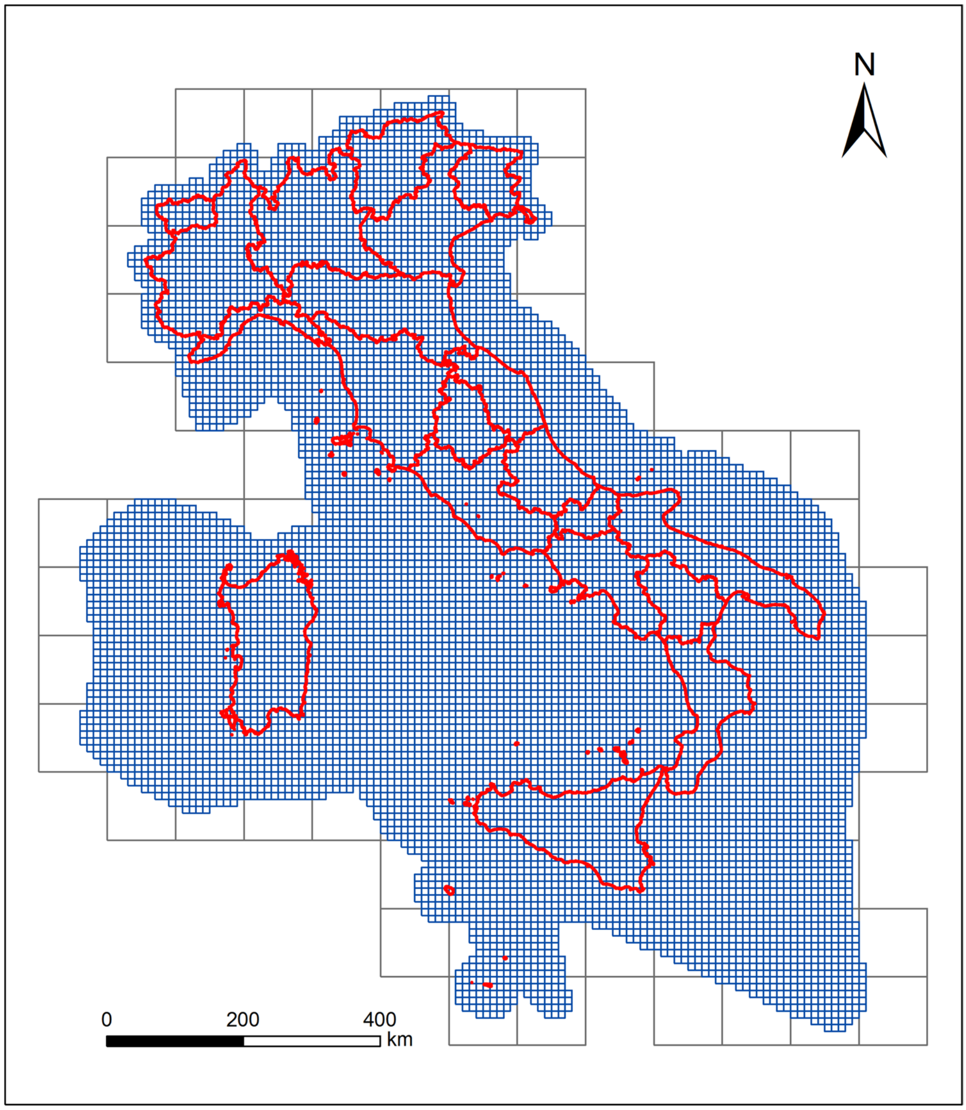

Fig. 2 European Environmental Agency reference grids for Italy: 100 km and 10 km resolution (the 100 km resolution grid is only visible around the edges)

embedded in ESRI ArcGIS 10.1 platform, the point data of monthly precipitation data from about 2000 rain gauge, made available by the Italian regional hydrological services.

2.2 Climate change scenarios and future time horizons for projections

Availability of water resources is evaluated according to four different emission scenarios as defined by the United Nations Intergovernmental Panel on Climate Change (IPCC) in the Fifth Assessment Report (AR5, IPCC 2014). In this report, scenarios are based on Representative Concentration Pathways (RCPs) (van Vuuren et al. 2011), which provide concentrations of atmospheric greenhouse gas (GHG) and the trajectory that is taken over time to reach those concentrations (Fig. 4).

The considered scenarios (Wayne 2013) include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and a very high GHG emissions scenario (RCP8.5). Scenarios without additional efforts to constrain emissions lead to pathways ranging between RCP6.0 and RCP8.5. The RCP2.6 is representative of a scenario that aims to keep global warming likely below 2 °C above pre-industrial temperatures (Table 1).

The observed hydrological variables and water balance components are projected, for each of the four emission scenarios, on three future time horizons: short, medium and long term.

The short-term projection is related to the 20-year period ranging 2020–2039 and it is briefly identified with its central year 2030. Likewise, the medium term projection is associated with the 20-year period 2040–2059 and it is briefly

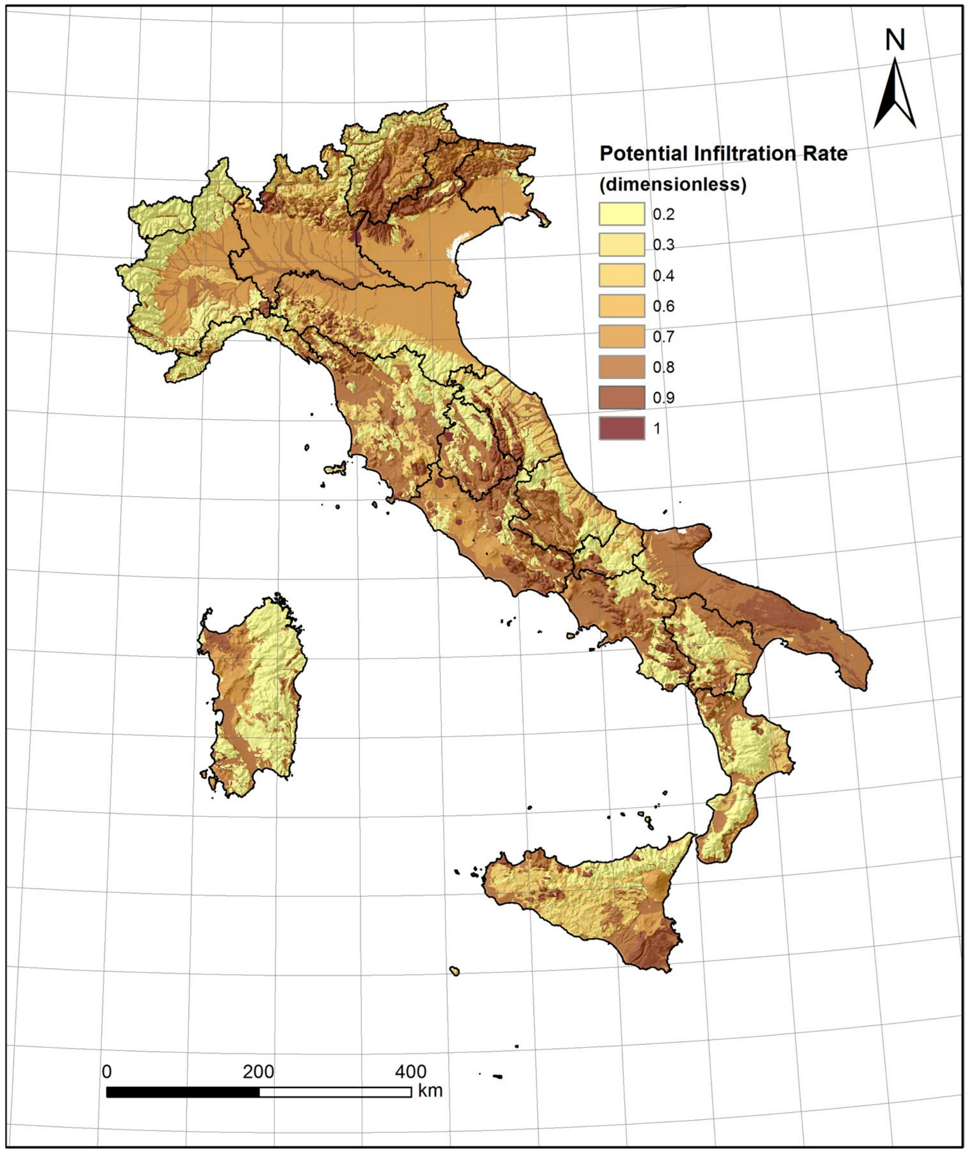

Fig. 3 Potential infiltration rate resulting from outcropping hydrogeological units derived from ISPRA digital map

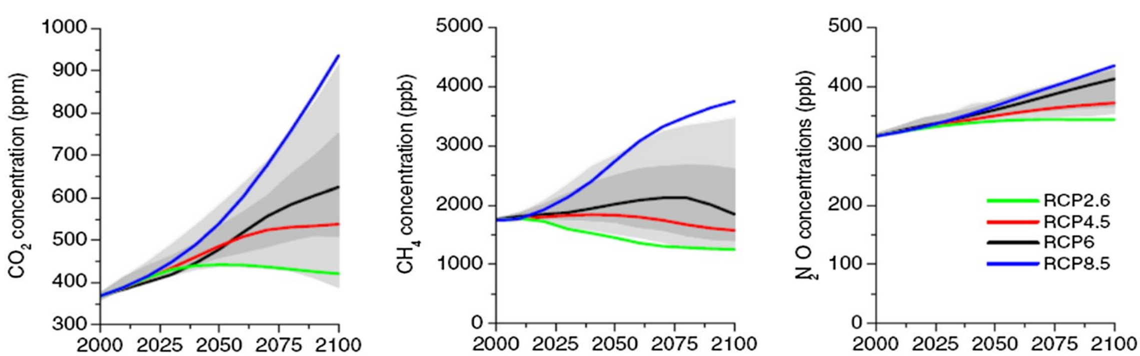

Fig. 4 Trends in concentrations of greenhouse gases From Wayne (2013), published under the terms of the Creative Commons Attribution 3.0

identified with its central year 2050. The long-term projection is related to 20-year period 2080–2099 and it is identified with its central year 2090. The period of historical observations, called “baseline period” and used for calibrating the projections, is the 20-year period 1996–2015 identified with the year 2005.

Table 1 Temperature anomaly over pre-industrial levels and SRES comparisons based on nearest temperature anomaly Reproduced from Wayne (2013)

Name	Radiative forcing	CO2 equiv (p.p.m.)	Temp anomaly (°C)	Pathway	SRES temp anomaly equiv
RCP8.5	8.5 Wm^2 in 2100	1370	4.9	Rising	SRES A1F1
RCP6.0	6.0 Wm^2 post 2100	850	3.0	Stabilization without overshoot	SRES B2
RCP4.5	4.5 Wm^2 post 2100	650	2.4	Stabilization without overshoot	SRES B1
RCP2.6 (RCP3PD)	3 Wm^2 before 2100 declining to 2.6 Wm^2 by 2100	490	1.5	Peak and decline	None

2.3 General circulation models

The general circulation models (CGMs) are numerical models that provide simulation of atmospheric variables at global scale also under climate change scenarios defined by the IPCC, mainly making assumptions on future greenhouse gas concentrations. GCMs simulate the dynamic of atmosphere on a coarse grid (usually ranging from 100 to 300 km) and thus many physical phenomena that occur at smaller scale cannot be properly modeled. For that reason, the solutions of GCMs in their original form cannot be used to assess the impact on water resources in the hydrological models. It is necessary to perform the so-called process of downscaling by which, using additional information, it is possible to obtain high-resolution information from low-resolution variables. Next section describes the downscaling method used in this study.

The global climate simulations used in this study have been produced at the United States National Center for Atmospheric Research (NCAR) by the Community Climate System Model (CCSM4) for the IPCC AR5 (available in GIS format at http://www.gisclimatechange.org).

The CCSM4 forecasts are generated on a Gaussian grid, where each grid point can only be identified by latitude and longitude. In the CCSM4 model output, longitudes are equally spaced at 1.25°, while latitudes vary in spacing slightly around 0.9424°. Approximate spatial dimension of the global climate projections is 105 km. The part of global grid covering Italy is shown in Fig. 5.

The hydrological variables from CCSM4 used in this study are the monthly air temperature and the amount of monthly precipitation. They are relative to the so called model run *ensemble average* that is the average of a collection of runs of the model which differ in the initial conditions.

The annual values of air temperature and monthly precipitation derive from the monthly ones by, respectively, averaging and summarizing over the year.

2.4 Downscaling method

As mentioned before, in order to obtain high-resolution information from low-resolution variables provided by GCMs, it is required to carry out the downscaling process to solve the poor resolution of the data. There are many downscaling techniques, different in sophistication and applicability, which can be classified in two main categories: dynamical and statistical (Smid and Costa 2017).

Dynamical downscaling requires regional climate models (RCMs) running on a more dense grid nested in the GCM coarse grid using the GCM solutions as boundary and initial conditions. Dynamical downscaling needs high computational resources and is too expensive for operational use and generally do not give significantly better results for temperature and precipitation (Sarr et al. 2015).

On the contrary, statistical downscaling is computationally inexpensive and it is based on statistical relationships between the coarse GCM solution and measurement. The statistical relationships are established during a calibration period (baseline period) in the past or in the present and then they are applied in different future time periods assuming temporal stationarity.

The downscaling method applied to derive the hydrological parameters from global climate scenarios over the BIGBANG 1-km grid is the "delta method" (Chen et al. 2011; Camici et al. 2014), which is the simplest but more reasonable method for averaged values of annual precipitation and mean annual temperature. This method is applied for each cell of the 1-km grid and the reference time is the central year of the averaging 20-year period.

Delta method assumes that the 20-year average annual precipitation related to the climate change scenario at the future time t, $\bar{P}_t$ (Fig. 6), can be obtained by the 20-year average annual precipitation observed at time t_0, $\bar{P}_{t_0,\mathrm{obs}}$ corrected by the ratio of the average GCM simulated future precipitation at time t, $\bar{P}_{t,\mathrm{GCM}}$ and the average precipitation

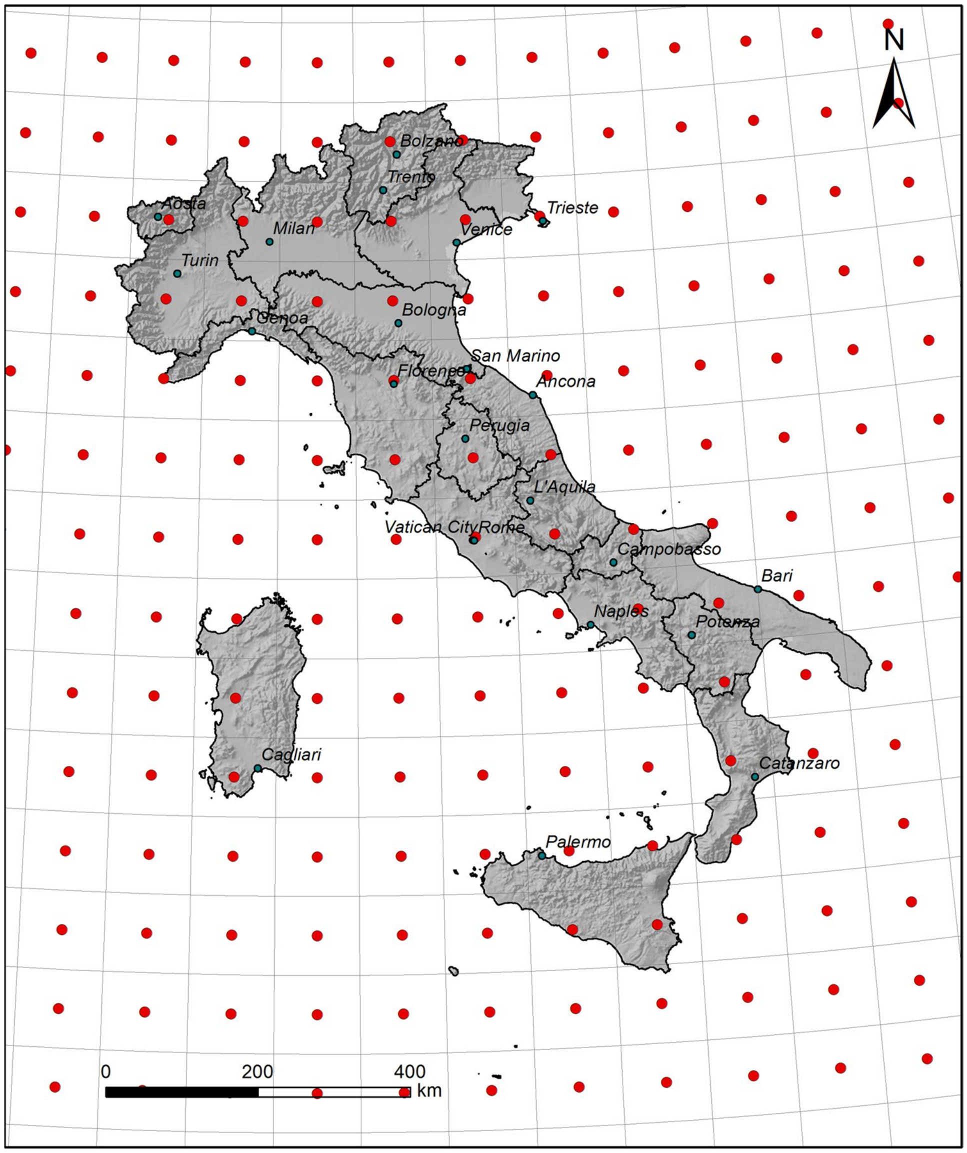

Fig. 5 NCAR CCSM4 global circulation model grid over Italy

historical simulation (or reanalysis) performed by the same GCM at time t_0, $\bar{P}_{t_0,\mathrm{GCM}}$:

$$\bar{P}_t = \bar{P}_{t_0,\mathrm{obs}} \times \frac{\bar{P}_{t,\mathrm{GCM}}}{\bar{P}_{t_0,\mathrm{GCM}}} \tag{3}$$

Similarly, the 20-year average annual mean temperature related to the climate change scenario at the future time t, $\bar{T}_t$, (Fig. 7) can be expressed as follows:

$$\bar{T}_t = \bar{T}_{t_0,\mathrm{obs}} + \left(\bar{T}_{t,\mathrm{GCM}} - \bar{T}_{t_0,\mathrm{GCM}}\right) \tag{4}$$

where $\overline{T}_{t_0,\mathrm{obs}}$ is the 20-year average temperature observed at time t_0, derived from ISPRA SCIA System (Fioravanti et al. 2010) and the additive term for correction is the difference between the average GCM simulated future temperature at time t, $\overline{T}_{t,\mathrm{GCM}}$, and the temperature historical simulation (or reanalysis) at time t_0, $\overline{T}_{t_0,\mathrm{GCM}}$. Equations 3 and 4 are evaluated for each cell of the grid and the GCM solutions of precipitation and temperature are interpolated over the BIGBANG 1-km grid by means of the spline method (Hijmans et al. 2005).

The main disadvantage of delta method is that the future scenarios and the historical observations differ only in terms of their respective means, while all other statistical properties of the data remain the same. However, this can be more acceptable for water resource analyses when the main concern, as in the present study, is the evaluation of the hydrological variables in terms of annual averaged values and not in terms of the extreme ones.

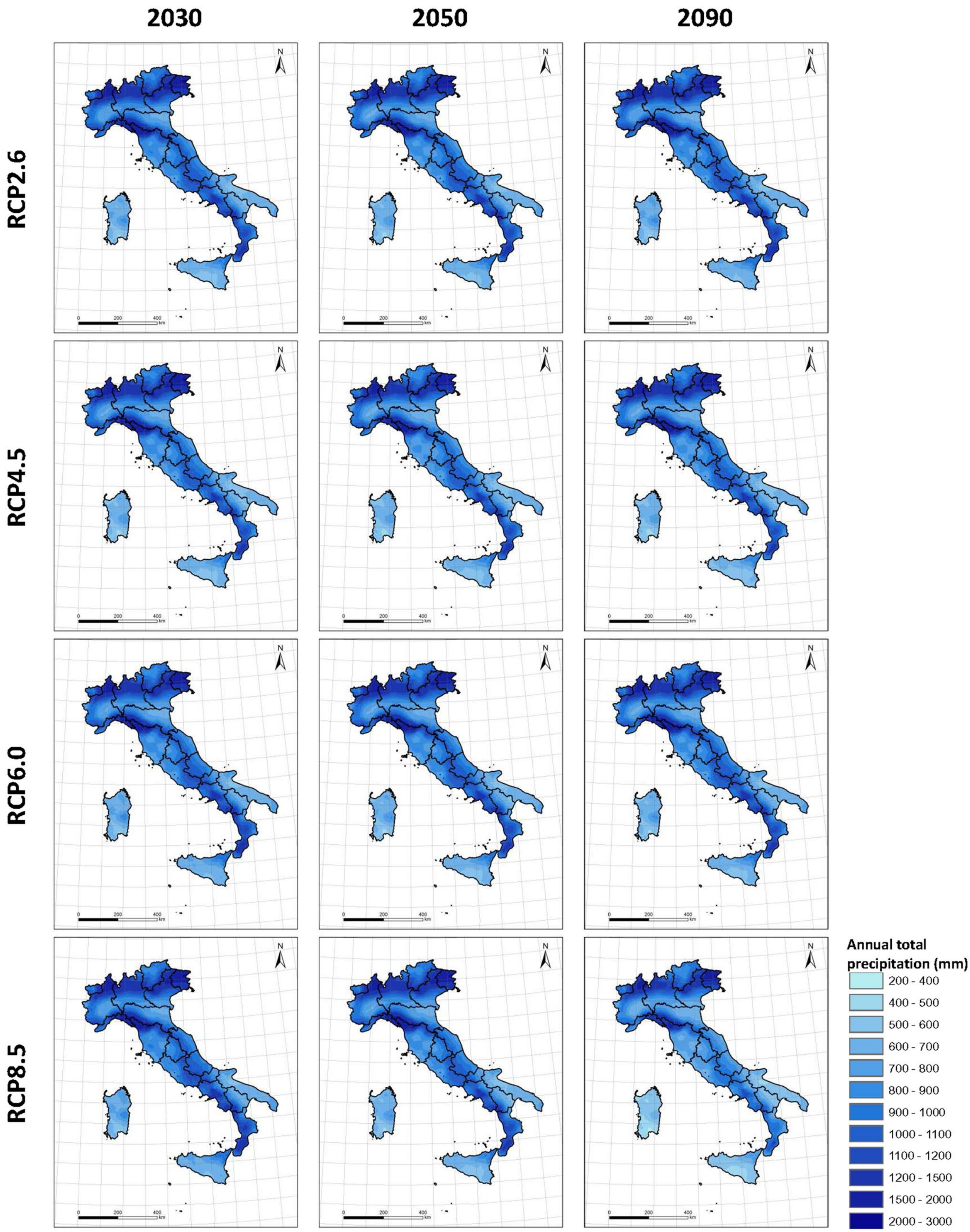

Fig. 6 Projections of 20-year average of annual total precipitation (mm) for four emission scenarios (rows) and three time horizons (columns)

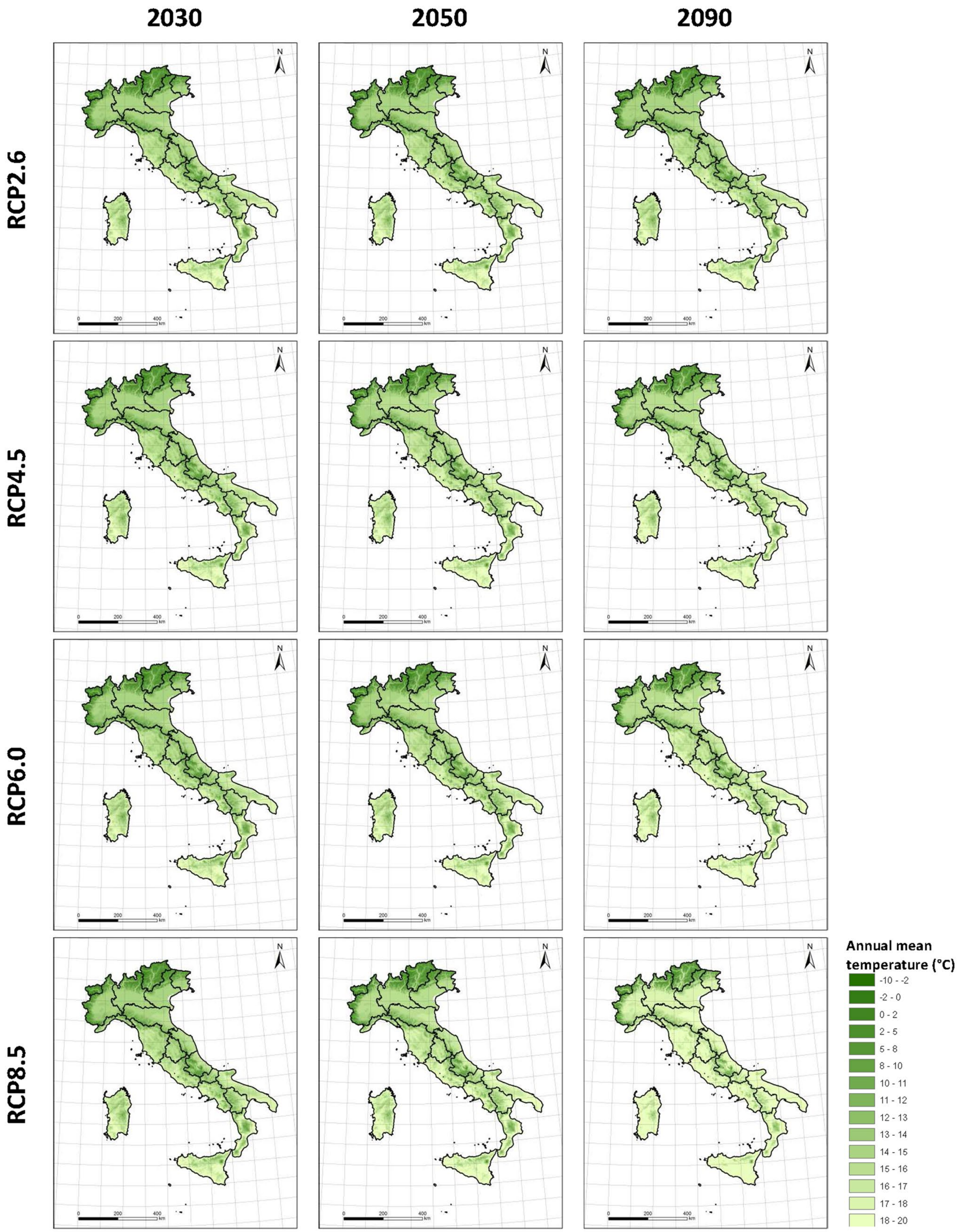

Fig. 7 Projections of 20-year average of annual mean temperature (°C) for four emission scenarios (rows) and three time horizons (columns)

Table 2 20-year average annual mean temperature projections with reference to different time periods and concerning different emission scenarios

Annual mean temperature (°C)					
Emission scenario AR5	Territory	Historical	Short term projection	Medium term projection	Long term projection
		20 year average 1996–2015	20 year average 2020–2039	20 year average 2040–2059	20 year average 2080–2099
RCP2.6	Italy	12.9	13.9	13.9	13.9
RCP4.5	Italy	12.9	13.9	14.3	14.7
RCP6.0	Italy	12.9	13.7	14.1	15.0
RCP8.5	Italy	12.9	13.9	14.8	16.7
RCP2.6	Campania	14.2	15.1	15.2	15.1
RCP4.5	Campania	14.2	15.2	15.5	16.0
RCP6.0	Campania	14.2	15.0	15.4	16.3
RCP8.5	Campania	14.2	15.2	16.1	18.0

Comparison between Italy and Campania region

Table 3 20-year average annual total precipitation projections with reference to different time periods and concerning different emission scenarios

Annual total precipitation (mm)					
Emission scenario AR5	Territory	Historical	Short term projection	Medium term projection	Long term projection
		20 year average 1996–2015	20 year average 2020–2039	20 year average 2040–2059	20 year average 2080–2099
RCP2.6	Italy	960.6	946.6	937.4	956.6
RCP4.5	Italy	960.6	927.7	911.8	921.2
RCP6.0	Italy	960.6	942.9	933.3	935.4
RCP8.5	Italy	960.6	961.8	933.7	835.9
RCP2.6	Campania	1096.7	1050.0	1060.2	1067.5
RCP4.5	Campania	1096.7	1018.4	1021.0	1028.7
RCP6.0	Campania	1096.7	1067.0	1045.5	1057.2
RCP8.5	Campania	1096.7	1084.6	1034.7	911.5

Comparison between Italy and Campania region

Table 4 20-year average groundwater recharge projections with reference to different time periods and concerning different emission scenarios

Groundwater recharge (mm)					
Emission scenario AR5	Territory	Historical	Short term projection	Medium term projection	Long term projection
		20 year average 1996–2015	20 year average 2020–2039	20 year average 2040–2059	20 year average 2080–2099
RCP2.6	Italy	221.7	204.6	199.3	206.9
RCP4.5	Italy	221.7	195.5	183.5	182.8
RCP6.0	Italy	221.7	202.7	194.3	183.0
RCP8.5	Italy	221.7	208.1	185.5	129.1
RCP2.6	Campania	292.8	250.7	254.7	258.4
RCP4.5	Campania	292.8	234.1	228.5	224.2
RCP6.0	Campania	292.8	261.8	243.4	232.3
RCP8.5	Campania	292.8	266.4	224.5	140.5

Comparison between Italy and Campania region

2.5 Results and discussion

The results obtained in terms of temperature, precipitation and groundwater recharge applying the GIS-based procedure BIGBANG at a yearly scale, for the four IPCC AR5 scenarios and for the three future 20 years time periods, are reported in Tables 2, 3 and 4, referring to both Italy and Campania region, in order to compare the impact of climate change on water resources at national and regional level.

Figure 8 shows the maps of 20 year average annual groundwater recharge related to the three time horizons (rows) and the four IPCC emission scenario (columns). Figure 9 shows the ratio of 20 years average annual groundwater recharge between long-term projection (2080–2099) according to RCP8.5 emission scenario and observed period (1996–2015) for Campania region.

The analysis demonstrates that for all scenarios and for all time horizons a significant reduction of availability of groundwater and surface water resources is likely to occur in future.

Nevertheless, as the analysis has been carried out at yearly temporal scale using a simple downscaling procedure, the evaluated reduced availability of groundwater recharge does not take into account the effect of the future expected increase in the inter-annual precipitation variability, truly complex to evaluate. This could produce an additional decrease in groundwater recharge, as more intense precipitation can exceed more frequently soil infiltration capacity.

According to the first emission scenario RCP2.6, the reduction of groundwater recharge is quite constant for all time horizons ranging from 7 to 10% for whole Italy and from 12 to 14% for Campania region (Fig. 10a).

Considering the intermediate scenarios RCP4.5 (Fig. 10b) and RCP6.0 (Fig. 10c), the reduction of groundwater resources increases as time horizon increases, ranging from a minimum of 9% to a maximum of 18% for Italy and from 11 to 23% for Campania region.

The maximum reduction of groundwater resources corresponds to the situation predicted by the RCP8.5 scenario, the worst one in terms of GHG emissions. This scenario provides for the long-term projection 2080–2099, a really critical reduction of groundwater resources in about 52% for Campania region and in 42% for Italy (Fig. 10d).The percentage reduction of groundwater recharge for Campania region is always higher (Table 5) than that observed for whole Italy although the mean potential infiltration rate in Campania is larger than the national one. This means that in Southern Italy, characterized by a Mediterranean climate, the impact of climate change on the groundwater recharge could be higher than that in the Northern Italy, characterized by a more continental climate.

3 Conclusions

This study describes an approach for evaluating the potential impact on water resources, and particularly on the groundwater ones, resulting from probable climate changes predicted by global climate models. BIGBANG evaluations are carried out at yearly scale and they are referred to four emission scenarios and three different time horizons.

Results suggest that, according to the RCP2.6 emission scenario, the reduction of groundwater recharge is quite constant for all time horizons for both Italy and for Campania region. On the other hand, the reduction of groundwater resources corresponding to the worst scenario in terms of GHG emissions (RCP8.5) is really critical, for Campania region and for Italy. Fortunately, there is still enough time to avoid severe situations, as predicted by the worst scenario, by means of the GHGs emissions reduction and of the sustainable management of the water resources.

It has to be highlighted that given the high uncertainty, which characterizes high-resolution climate information obtained using emission scenarios, and downscaling methods, special attention should be payed to the interpretation of the result, especially in decision-making.

In a near future, a monthly projection of water balance components and a more suitable downscaling procedure for climate change scenarios will also allow the evaluation of the seasonal variability of rainfall, temperature and water resources, representing a valuable improvement for the future development of this research.

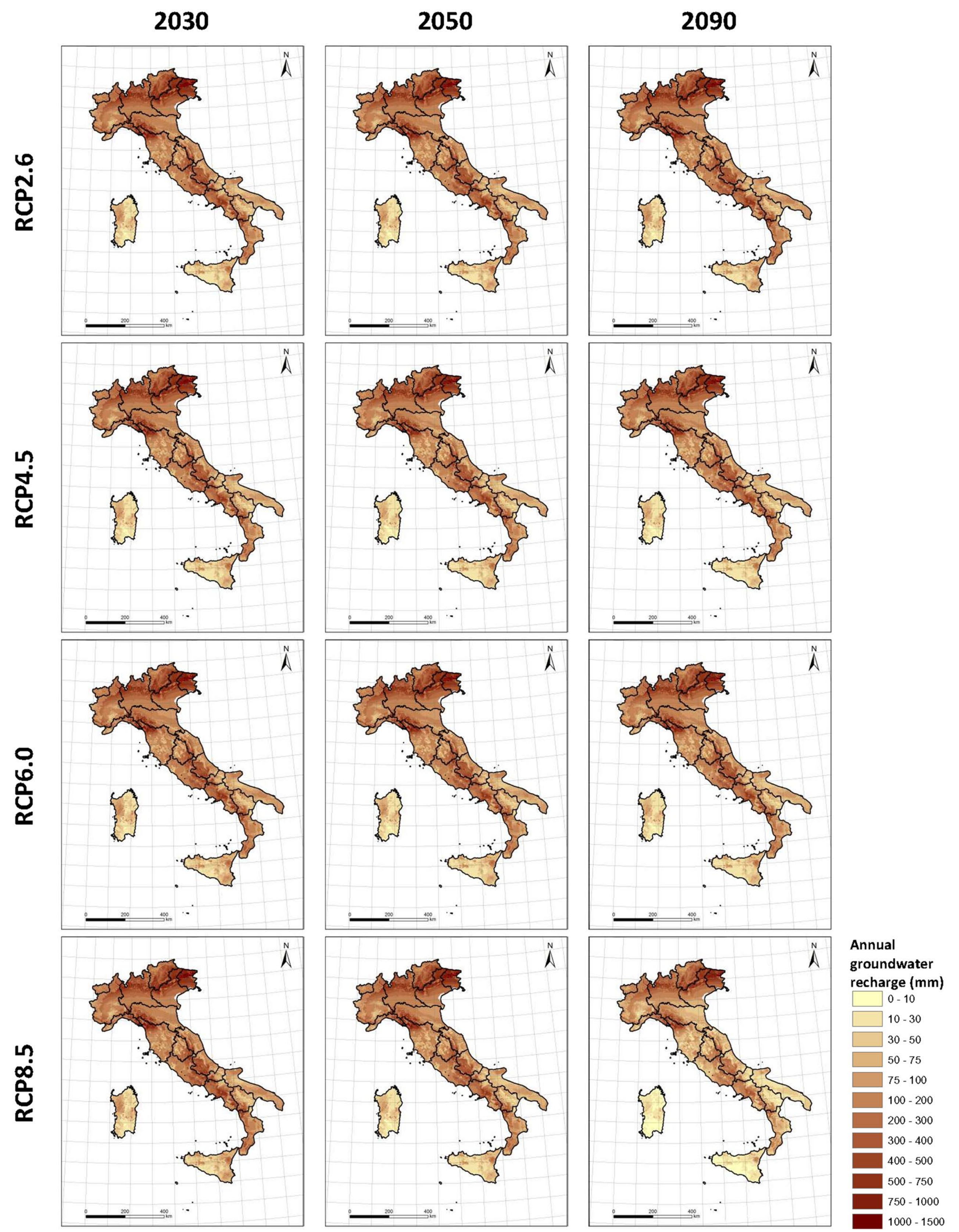

Fig. 8 Projections of 20-year average of annual groundwater recharge (mm) for four emission scenarios (rows) and three time horizons (columns)

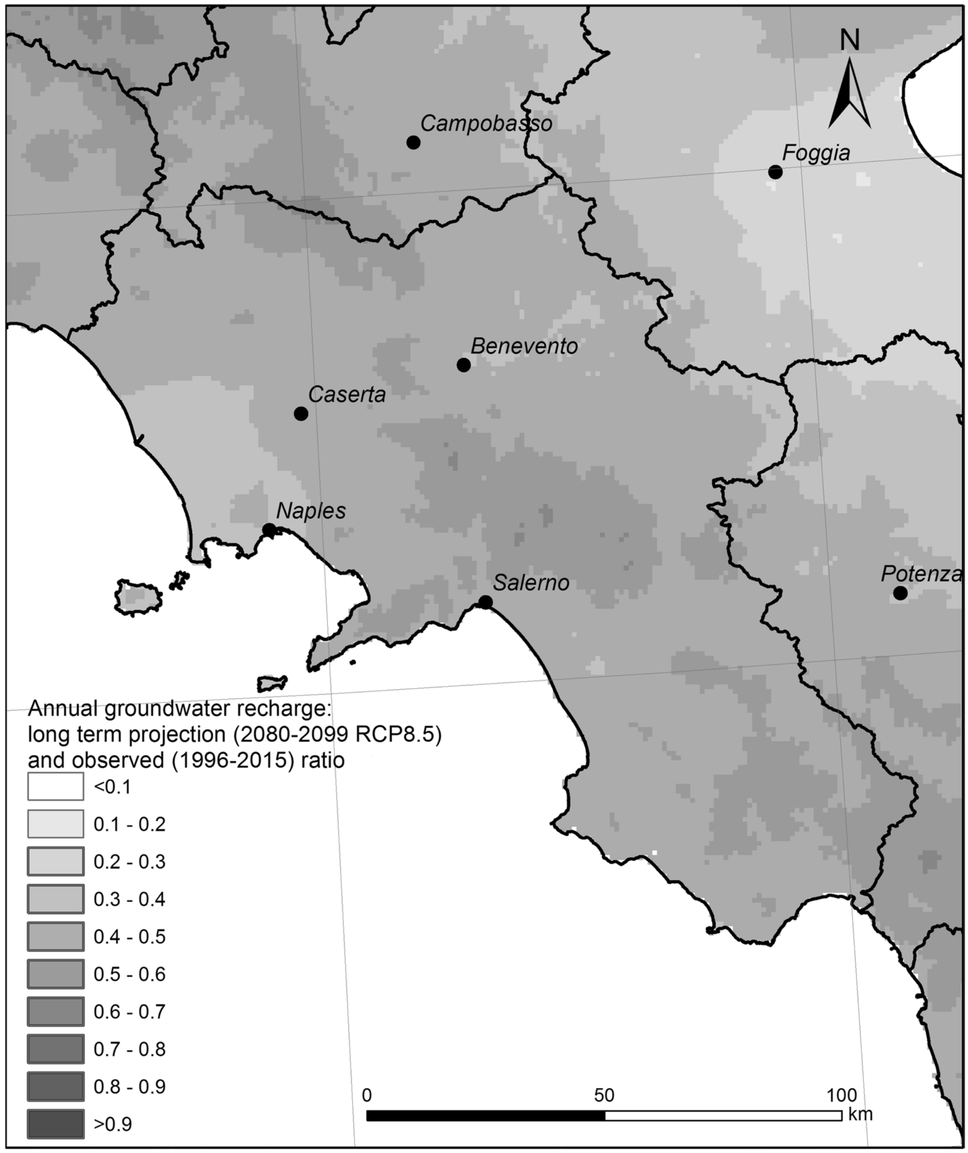

Fig. 9 20-year average annual groundwater recharge: ratio between long term projection (2080–2099) according to RCP8.5 emission scenario and observed (1996–2015)

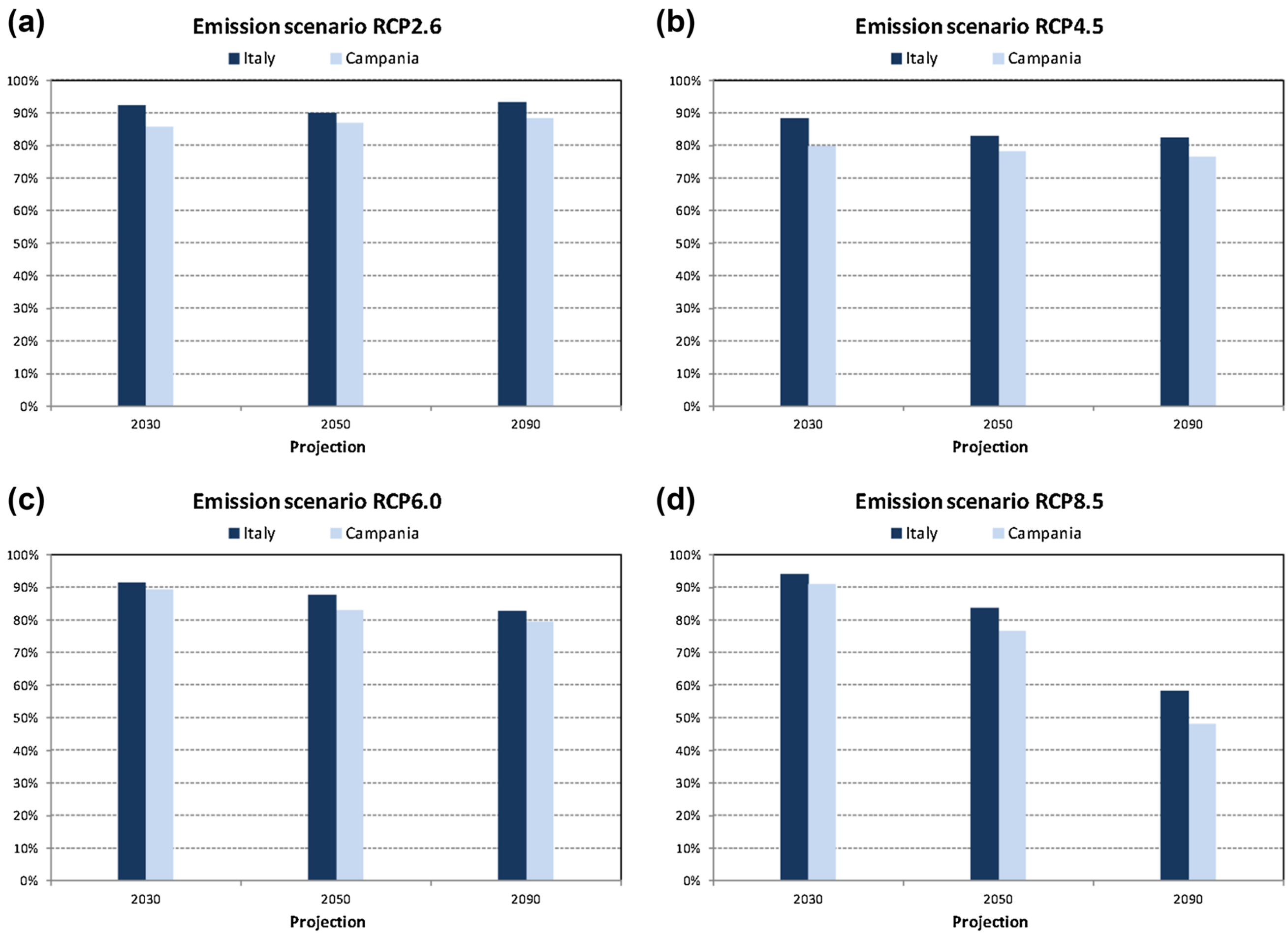

Fig. 10 The percentage variation of 20-year average of groundwater recharge according to the four RCPs emission scenarios: **a** RCP2.6, **b** RCP4.5, **c** RCP6.0, **d** RCP8.5

Table 5 Percentage reduction of groundwater recharge in time horizon projections

Emission scenario AR5	RCP2.6		RCP4.5		RCP6.0		RCP8.5	
Time horizon	Italy (%)	Campania (%)	Italy (%)	Campania (%)	Italy (%)	Campania (%)	Italy (%)	Campania (%)
2030	8	14	12	20	9	11	6	9
2050	10	13	17	22	12	17	16	23
2090	7	12	18	23	17	21	42	52

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