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On the variables to be considered in assessing the impact of climate change to alluvial aquifers: a case study in central Italy

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Abstract

Most of the scientific community agrees that global climate change is occurring with a general increase in mean overall temperature (+0.74±0.18°*C* from 1906-2005) and that the precipitation pattern in Europe is trending toward wetter conditions in the northern region and drier conditions in the southern and central-eastern regions. A much larger uncertainty concerns how the changes in precipitations will impact on the water resources, particularly on the groundwater. The goal of this paper is to investigate the variables to be considered in order to estimate the Sustainable Pumping Rate of an aquifer (*SPR*) in a context of climate change. For this goal the case study of the Petrignano d'Assisi porous aquifer has been considered, mainly fed by the inflow from the carbonatic ridges and by the effective infiltration; it is exploited since the 1970s through a well field (about 350 l/s). Changes in the precipitation regime could significantly affect the recharge to the aquifer and the related *SPR*. This study shows the key role played by the interactions of the aquifer with the surface bodies (rivers): in case of a significant decreasing in the effective infiltration, the aquifer system decreases the outflow to the rivers (base flow) leaving almost constant the sustainable pumping rate.

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Keywords: Climate change; alluvial aquifer; stochastic generation model; water resource management.

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1. Introduction

Over the last 50 years, groundwater decreasing storage from direct or indirect effects of climate change has expanded in many countries throughout the world (Green et al. 2011). Climate variability, mainly in precipitation, can largely affect the groundwater levels (Green et al. 2007); moreover, the effects of a decrease of precipitation can result in a significant increase of the abstractions from groundwater, amplifying the depletion of the aquifers. Within this framework, the use of groundwater to modulate the effects of a decreasing of precipitation plays a key role as surface-water storage is becoming more limited. Mathematical groundwater models are also fundamental, both for interpreting and integrating data and for generating general insight to the response of groundwater systems to climate change and other forcing on multiple spatial and temporal scales. In this study, the variables to be considered in order to estimate the Sustainable Pumping Rate (*SPR*) of an aquifer in a context of climate change have been investigated. For this goal the case study of the Umbra Valley porous aquifer has been considered. Starting from the observed and perturbed time series of precipitation and temperature, reliable scenarios of effective infiltration in the next decades have been generated; the impact of such scenarios on the aquifer and the possible consequent variations of the sustainable pumping rate have been explored by means of a numerical model of the groundwater flow, which takes into account possible variations in the interaction surface-ground water.

2. Case study

The case study, the Petrignano d'Assisi aquifer (approximately 75 km^2) is located in the Umbria Region (Central Italy), within the Tiber river basin. It is part of the Umbra Valley aquifer and is located between the Martani western ridges, the Subasio Mount and Foligno-Spoleto eastern ridges. It is a mono-layer, phreatic aquifer consisting of alluvial deposits, that lye on a marly-arenaceous substrate of the Miocene, bordered to the South, West and North-East by lacustrine and fluvio-lacustrine Villafranchian deposits (Figure 1).
In the study area, a dense hydrometeorological monitoring network has provided daily time series at the Tiber basin scale for the period 1952-2008 as well as hourly time series of rainfall and temperature for the period 1989 – 2010. Mean annual precipitation has been estimated about 1020 mm for the period 1924-1930/1935-1992 (data from the Italian National Hydrographic Service); a possible tendency to reduction of both precipitation and river flows in the last years has been underscored by some studies (Palmieri et al., 2008; Romano et al., 2011; Romano and Preziosi, 2012), and a general concern about a negative trend for water availability in the area and in other zones of the Appenine chain in relation to climate changes has arisen (Cambi and Dragoni, 2000; Fiorillo and Guadagno, 2010). Such decrease of the water resources can be observed also in the alluvial aquifer of the area; however, as they are extensively exploited, it is hard to distinguish which part of the observed dewatering is due to a decrease of the recharge and which part to an overexploitation of the aquifer themselves. This is the case of the Petrignano d'Assisi aquifer, that has been exploited for human consumption since the second half of '1970. For this reason a modelistic approach appears the most suitable to evaluate the impact of climate change on this kind of resource. The analysis has been applied considering both the actual climate conditions of the Petrignano basin such as defined by hourly time series of rainfall and temperature observed in the period 1989–2010 and the ones derived by considering the perturbed hydrological time series using the seasonal temperature and precipitation trends assessed on the ground of the observed daily time series at the Tiber basin scale for the period 1952-2008 (Romano and Preziosi, 2012).

3. Petrignano d'Assisi aquifer: MODFLOW calibration for present climate

In order to assess the possible impact to the Petrignano d'Assisi aquifer of the climate change scenarios, a numerical model has been developed and calibrated both under undisturbed conditions (1974) and under exploitation conditions (1998-2010) using the finite-difference code MODFLOW2005 (Harbough, 2005).
The procedure for the calibration of the MODFLOW2005 model for actual conditions is summarized in the following (Romano and Preziosi, 2010):

1. A no-flow condition has been assigned along the southern boundary following an ideal line perpendicular to the equipotential curves (Figure 1).
2. The bottom of the aquifer, reconstructed through well-log and geophyical surveys, is located between -20 m and -80 m with respect to the ground surface (Idrotecneco – R.p.a., 1974).

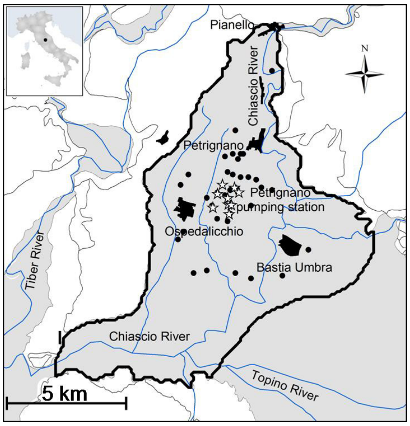

Figure 1. The Petrignano d'Assisi plain. Grey areas: alluvial deposits. White areas: lacustrine and fluvio-lacustrine deposits. White stars: wells belonging to the Petrignano pumping station. Black dots: other wells located within the area. The bold line indicates the boundaries of the model area (from Romano and Preziosi, 2010).

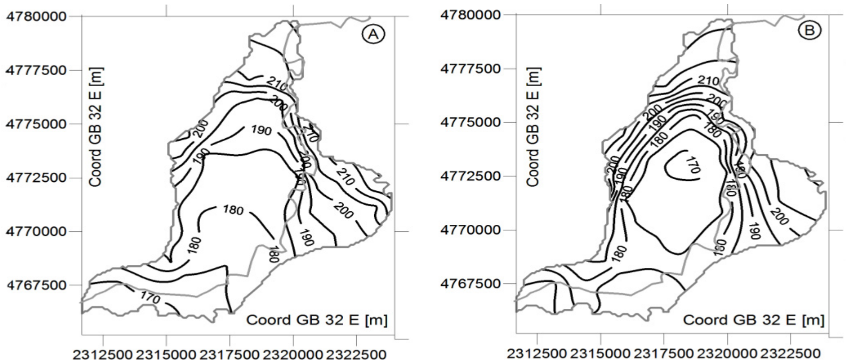

Figure 2 – Piezometric field of 1974 (A) and of 2004 (B).

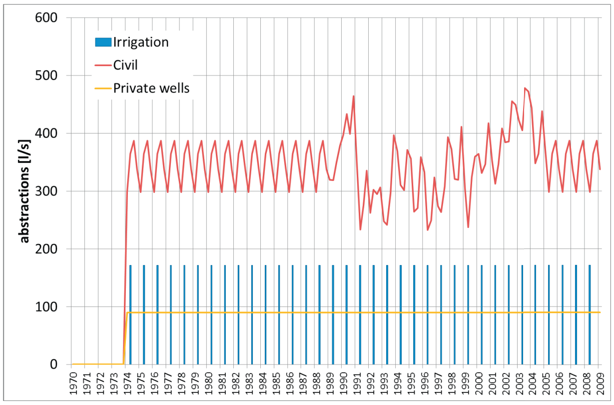

Figure 3 – Estimated withdrawals from the Petrignano plain (1970-2009).

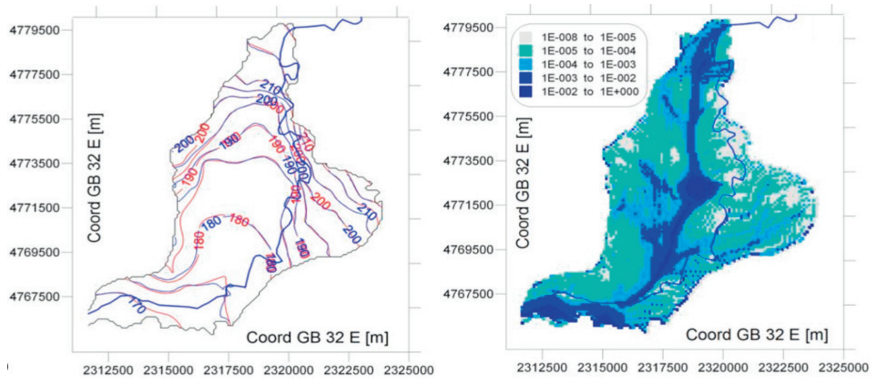

Figure 4 – Results of the calibration under undisturbed conditions.

3. The aquifer is mainly fed by the zenithal infiltration and by a lateral infiltration from the reliefs boarding the aquifer. After calibration (see later), the first term has been estimated equal to about 250 mm/y (550 l/s) and the second to about 100 l/s.

4. The main river crossing the plain, the Chiascio, acts as drain in the lower part of its course, therefore it has been modeled assigning Cauchy boundary conditions.

5. Under undisturbed conditions (before the pumping station was built in the 1970’s) the groundwater flow was approximately directed from North to South, following the Chiascio River course (Figure 2, A). After exploitation a large depression cone became evident (Figure 2, B); piezometric time series show that, starting from 2001, an enlargement of the depression cone that possibly determines a variation of the capture zone and a modification of the river-aquifer interaction regime .

6. Withdrawals in transient conditions (Figure 3) have been estimated as follows: a) withdrawals for the Petrignano d’Assisi well field. The well field of Petrignano d’Assisi started its activity in 1974 and currently its exploitation ranges between 250 l/s and 450 l/s (reference period: 1988-2004); b)withdrawals from private wells. The pumping rate from private rate has been estimated of approximately 90 l/s (Romano and Preziosi, 2010); c)withdrawals for irrigations. This term, assessed on the ground of the extension of the crops over the study area, has been assessed equal to approximately 130 l/s from May to August (Romano and Preziosi, 2010).

7. The hydraulic conductivity has been calibrated in steady state conditions through the numerical code MODAC (Guo and Zhang, 2000). The adopted target was the piezometric field under undisturbed conditions, thus before 1970. A comprehensive description of the adopted calibration procedure can be found in Romano and

Preziosi (2010). In Figure 4 (right) a comparison between the observed and simulated piezometric field is presented; the calibrated hydraulic conductivity pattern is shown on Figure 4 (left).

8. The performed calibration has been finally validated with respect to the observed piezometric heads evolution of the period 1974-2004. A comprehensive description of the adopted calibration and validation procedure can be found in Romano and Preziosi (2010).

4. Generation of future scenarios of effective infiltration

The future scenarios of effective infiltration have been generated through the following procedure: 1) the past temperature and precipitation trends and periodicity have been assessed by analyzing the observed daily time series of temperature and precipitation observed at the basin scale for the period 1952-2008 (Romano and Preziosi, 2012); 2) the observed time series have been perturbed coherently with the most accredited scenarios of climate change (Pachauri and Reisinger, 2007; Bates et al., 2008); 3) future scenarios of effective infiltration have been generated through the Thorntwaite-Mather (model Dingman, 1994) starting from the scenarios of T and P computed at point 2. These effective infiltration scenarios will represent the input data for the numerical flow model, allowing to evaluate the piezometric heads in the study area.

4.1 Assessment of temperature and precipitation trends and periodicity (1952-2010)

An analysis of the rainfall regime has been performed computing the Standardized Precipitation Indices (*SPI*, McKee et al., 1993) of the rainfall time series collected by all the gauges located within the Tiber basin, both at annual and seasonal scale. Following the procedure described in Romano and Preziosi (2012), three more parameters have been studied: the number of rainy days N_{days} (defined by the condition P > 0.1 mm), the mean intensity of precipitation I_{mean} (defined as the ratio between the precipitation cumulated over a given period and the number of rainy days in the same period) and the daily maximum precipitation. Possible trends have been assessed by means of the Mann-Kendall test (Kendall 1975).

Results of the precipitation analysis carried out on daily data for the period 1952-2008 indicate that: 1) there is a cyclic variability of the mean annual precipitation, whose period ranging between 15 and 23 years and amplitude ranging between 15 and 25% with respect to the long-term mean; such variability appears to be related to the variability of the North Atlantic Oscillation Index (Romano and Preziosi, 2012); 2) also the winter and autumn precipitation show a cyclic behavior, whose period ranges between 15 and 23 years and amplitude between 15 and 20% with respect to the long-term mean; 3) any periodicity of the spring and summer precipitation has been observed; 4) a decreasing trend of the annual precipitation equal to -8.4% (1952-2008) and of the winter precipitation equal to -16.2% have been detected. Any trend has been detected for spring, summer and autumn precipitation.

The temperature analysis performed on the time series collected by 15 stations located in the Umbria Region shows an increasing trend both in the minimum and in the maximum daily values: such trend is more evident in summer (approximately + 0.017 °C/y) than in winter and spring (approximately + 0.011 °C/y), whereas in autumn any trend has been detected.

By using trend and periodicity inferred by the observed daily time series, hypothetical future scenarios of seasonal temperature and precipitation anomalies have been defined as shown in ***Table 1***. As it can be noted, for a 60-years period a seasonal positive (negative) trend for temperature (precipitation) is forecast with the highest values for the summer months. Moreover, a constant annual periodicity, with a period of 15 years and amplitude of 15% is forecast for rainfall time series.

Table 1 Seasonal trends for temperature and precipitation extracted by analyzing the observed daily time series at the Tiber basin scale

Season	Temperature		Rainfall		
	Annual increasing (°C/y)	**Increasing for 60 years period (°C)**	**Trend for 60 years period (%)**	**Period (years)**	**Amplitude (variation %)**
Autumn	0	0	-3	15	15
Winter	0.0135	0.81	-8	15	15

Spring	0.0145	0.87	-3	15	15
Summer	0.021	1.26	-10	15	15

4.2 Generation of temperature and precipitation future scenarios

Based on the trends reported in Table 1, the hourly precipitation and temperature time series recorded in study area were perturbed and used as input in the stochastic generation models to obtain long future rainfall and temperature time series. In particular, for the stochastic rainfall and temperature generation, the Neyman-Scott Rectangular Pulses (NSRP, Cowpertwait et al., 1996) model is used for stochastic rainfall generation while the Fractionally Differenced ARIMA (FARIMA, Montanari et al., 1997) model is used for temperature simulations.

The NSRP model is characterized by a flexible structure in which the model parameters broadly relate to underlying physical features observed in rainfall fields. The model has a total of five parameters, estimated through six sampling statistics computed from the observed data (for each month taking the rainfall seasonality into account): hourly mean, hourly and 24 h variances, lag-one autocorrelation of the daily data, and hourly and 24 h skewness. The estimation procedure of such model parameters can be carried out by minimizing an objective function evaluated as a weighted sum of normalised residuals between the statistical properties of the observed time series and their theoretical expression derived from the model. As shown by previous studies (Cowpertwait 1991), the main feature of the model is its ability to preserve statistical properties of a rainfall time series over a range of time scales (Camici et al., 2011). Full details of the NSRP may be found in Cowpertwait (1991). The FARIMA model, unlike classical ARIMA models that are powerful tool for modelling stationary time series, allows reproducing the autocorrelation function of the observed data characterized by a slow decay in the presence of long-term persistence. The procedure for the implementation of the FARIMA model is not straightforward, and it firstly require to remove the seasonal component as the model is only able to simulate deseasonalized time series. Then, the model parameters are identified following the procedure suggested by Montanari et al. (1997).

Both the stochastic generation models allow obtaining stationary time series reproducing the statistical properties of the observed time series in the calibration period. In order to achieve synthetic non-stationary rainfall and temperature time series the following procedure was applied. As concerns the rainfall, the observed local hourly precipitation time series was perturbed by varying the mean rainfall value in accordance with the trend shown in Table1. Therefore, for each year of the period 2010-2070, an hourly time series of length 100 years was generated by the NSRP model for a total of 60 time series each one complies with the trend in Table 1. Let $X_{Y,S}$ the matrix of the generated time series with Y=1, 2,…, 100 rows representing the number of the year of the hourly generated time series and S=1, 2,.., 60 corresponding to the year 2010, 2011,.., 2070, for which the statistical properties are preserved. For example, $X_{10,4}$ represents the 10th year of the 4th generated stationary hourly time series preserving the statistical properties of the year 2014 obtained by the application of the trend till to 2014 itself. Therefore, if all the 10th years are taken out and organized in chronological way from 2010 to 2070, a non-stationary time series of 60 years is obtained. Overall, the outcome of this procedure is synthetized by the transposed matrix $X^T_{S,Y}$, so that the row corresponds to the number of the synthetic non-stationary time series (100 in total), each one this time of length 60 years (from 2010 to 2070; columns). In this case each time series incorporates the trend and periodicity reported in Table 1 as well shown in Figure 5. As regards the temperature time series, the trend given in Table 1 is directly added to the deseasonalized temperature time series generated by the FARIMA model (see Figure 5).

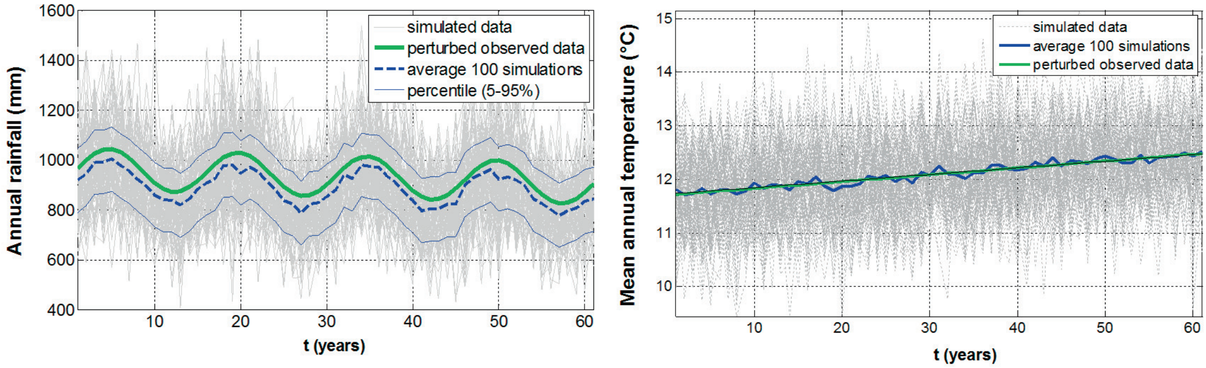

Figure 5 – Annual rainfall (left) and temperature (right) obtained through the stochastic generation models.

4.3 Generation of effective infiltration future scenarios

Starting from the temperature and precipitation scenarios generated through the methodology described in the previous paragraph, scenarios of effective infiltration have been generated by means of the Thorntwaite-Matheron model (Dingman, 1994). This model computes the potential evapotranspiration on the ground of the mean monthly temperature; the actual evapotranspiration is then computed as a fraction of the potential one, where the fraction is given by the actual percentage of the soil moisture, computed at daily scale through a simple soil balance model assuming that no run off takes place. Then data have been aggregated at 4-months time step for the model implementation, neglecting the percolation time. The effective infiltration scenario is shown in Figure 6 for the period 2010-2070, both in case of presence and lack of trend.

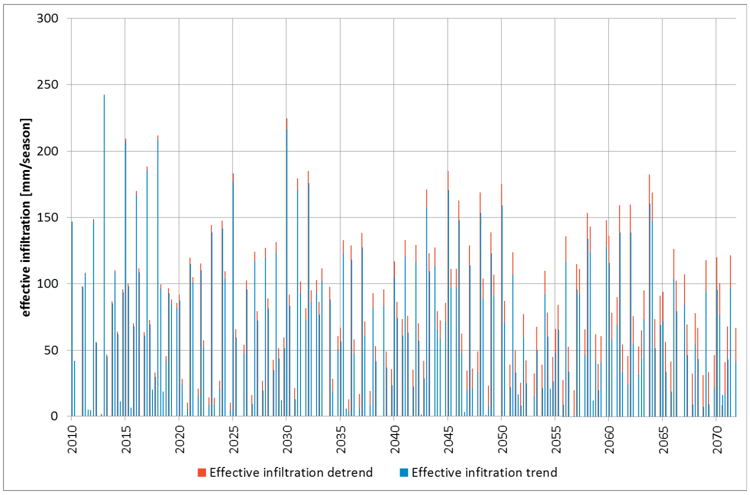

Figure 6– Scenarios of effective infiltration in case both of presence and lack of trend

Table 2. Simulated conditions for the time evolution of the piezometric head in case of absence and presence of climatic trend

SIMULATION	*TREND*	*CIVIL ABSTRACTIONS*	*IRRIGATION ABSTRACTIONS*

NT_0__0	*0*	*0*	*0*
NT_Q_{now}_0	*0*	*Current (Figure3)*	*0*
NT_Q_{now}_I	*0*	*Current (Figure3)*	*Current (Figure 3)*
NT_Q_{prra}_0	*0*	*From PRRA*	*0*
NT_Q_{prra}_I	*0*	*From PRRA*	*Current (Figure 3)*
NT_0_I	*0*	*0*	*Current (Figure 3)*
NT_Qnow_I	*0*	*Current (Figure3)*	*Current (Figure 3)*
T_Qnow_I	*YES (Figure 6)*	*Current (Figure3)*	*Current (Figure 3)*
T_Qprra_0	*YES (Figure 6)*	*From PRRA*	*0*

5. Impact of effective infiltration future scenarios on the piezometric heads and budget evolution

Twelve scenarios of recharge/exploitation of the aquifer have been evaluated through the numerical model. Such scenarios have been obtained through the combination of the following input:

1. Effective infiltration to the aquifer in case of presence or lack of climatic trend for the period 2010-2070.
2. Withdrawals from the Petrignano pumping station equal to the actual ones or equal to those ones forecast in the future (300 l/s only during summer, data from PRRA-Regione Umbria, 2007).
3. Distributed withdrawals for irrigation equal to the actual ones (about 130 l/s) or equal to zero.

The simulated conditions have been summarized in Table 2.

5.1 Impact of the single abstraction terms in case of lack of climatic trend

Figure 7 shows the time evolution of the piezometric head in a point of the plain located in the middle of the Petrignano d'Assisi well field area. The graph in Figure 7 shows that:

a. The influence of the abstractions for irrigation (*NT_0_I*) is extremely limited, since it determines a decrease of about 2 meters with respect to the undisturbed condition.
b. The strongest impact on the aquifer occurs considering the current withdrawals from existing well field (*NT_Q_{now}_I* and *NT_Q_{now}_0*): the induced lowering is about 6 meters taking into account only the pumping from the well fields and about 7-8 meters including also the abstractions for irrigation.
c. In case of the lack of climate trend, the current levels of pumping for civil use and irrigation, both individually and combined, determine a situation of dynamic equilibrium of the aquifer, since the long-term average piezometric heads is almost stationary. In other words, the cone caused by the abstractions stabilizes at the current depth and is not forecast to decrease in the future if a climatic trend does not take place.
d. Pumping scenarios provided by the PRRA (300 l / s in summer) do not cause a significant decrease of the piezometric heads in the area of the well field (both in the case of absence and presence of withdrawals for irrigation), foreshadowing a situation of sustainability in the exploitation of the aquifer. This result is quite obvious, since the forecast civil abstractions are about 1/4 of the current one.

5.2 Impact on the aquifer in case of climatic trend

Figure 8 shows the time evolution of the piezometric head in a point of the plain located in the middle of the Petrignano d'Assisi well field area. The conditions simulated in order to evaluate the impact on the aquifer in case of climatic trend have been summarized in Table 2.

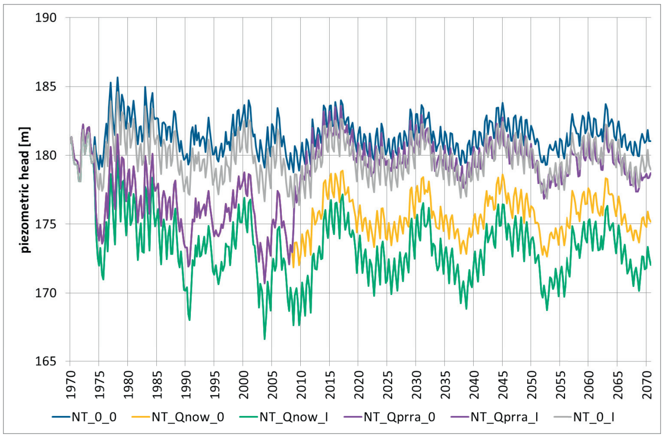

Figure 7 – Impact of the single abstraction terms in case of lack of climatic trend.

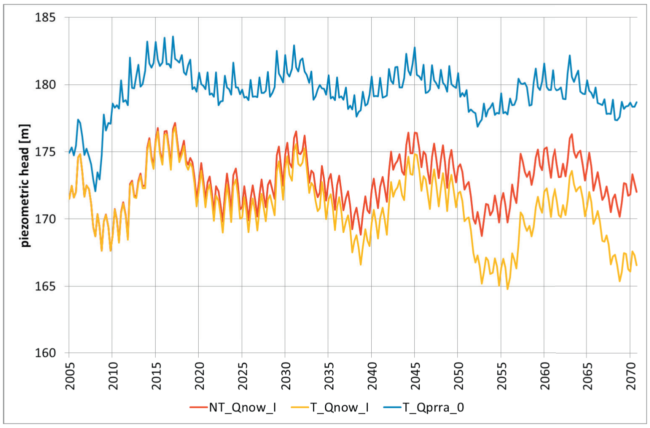

Figure 8 – Piezometric heads computed in a point of the plain located in the middle of the Petrignano d'Assisi well field area in case of climatic trend

a) The combined impact of a decrease of the recharge and the current abstractions, determines a decreasing in the area of the well fields greater of about 5 m with respect to the impact of the only exploitation. In other words, the decrease of recharge determines in the case of abstractions equal to the current ones, a further decrease of almost 5 meters. However, according to the results of the implemented mathematical modeling, the aquifer can sustain the current abstractions also in case of climatic trend, at least for the duration of the simulation.
b) The trend of the piezometric heads computed by the simulation *T_QNOW_I* appears to be related exclusively to the trend of the recharge. It is likely, therefore, that in the event that the negative trend of recharge will continue in the following period, a progressive depletion of the aquifer will take place.
c) Even in case of climatic trend, under the level of exploitation planned by the PRRA, the abstractions appear to be sustainable.
d) During the 70 years of simulation, the current abstractions appear to be sustainable by the aquifer, also for the worst scenario (current level of abstractions and climatic trend), substantially exploiting the volume stored within the aquifer and reducing the flow to the Chiascio river. In fact, the latter decreases during the simulation from approximately 400-600 l/s to about 30-60 l/s at the end of the simulation. In case of absence of climatic trend the outflow to the river ranges between 120 and 220 l/s. This suggests the key

role of the river for assessing future scenarios: in fact, the situation appears to be sustainable considering only the aquifer and its ability to deliver water at the current intensity of exploitation. However, if one widens the analysis considering also the surface waters and the interactions between surface and ground waters, the sustainability could not be verified, particularly when the base flow of the aquifer constitute a significant percentage of the surface body budget. This is not the case, because under the current conditions of exploitation, the inflow to the Chiascio river from the aquifer constitutes approximately 1/8 of its total discharge; nevertheless in other situations the decreasing of the base flow, especially if a contemporary decrease of the surface run off takes place, could lead to potentially dangerous situations from a quantitative and qualitative point of view.

6. Conclusions

In this study, the impact of a possible decrease of precipitation and increase of temperature on the Petrignano d'Assisi aquifer (central Italy) has been investigated through non-stationary hydrological time series stochastically generated and used as input for a numerical model developed with the finite-difference code MODFLOW2005. Results from modeling have been analyzed in terms of sustainability of the current and forecast regime of abstractions with respect both to the possible depletion of the aquifer and to the variation of the surface-groundwater interactions. The performed simulations indicated that during the analyzed 70 years period, the current abstractions appear to be sustainable by the aquifer. However, the reduction of the recharge has been compensated by a decrease of the discharge to the river crossing the plain, resulting in a decrease of the base-flow. The latter result indicates that for the assessment of the impact of climate change to groundwater resources, interactions between aquifers and the connected surface water bodies must be carefully considered.

Acknowledgment

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