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Groundwater supply and climate change management by means of global atmospheric datasets. Preliminary results

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Abstract

Climate change influences hydrological cycle with a direct effect on groundwater resources, one of the most important supply sources for human consumption and irrigation. In a scenario where General Circulation Models do not represent yet a usual tool for water industry managers, potentially the use of global atmospheric datasets is of great interest for evaluating groundwater resources. In this paper data from the European Centre for Medium-Range Weather Forecasts (ECMWF) are compared to local water table measurements. With particular regard to unconfined aquifers, the good correlation between the trend of soil moisture and local water table data is pointed out. Such a promising result authorizes further insights in order to refine reliable tools for evaluating available groundwater resources in a climate change scenario.

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Keywords: Water balance; soil moisture; ECMWF dataset; water table

1. Introduction

Nowadays one of the greatest concerns of the water industry managers is the potential decrease and quality of groundwater supplies, as it is the main available potable water supply source for human consumption and irrigation. In fact there are strong links between climate change and the hydrologic cycle: precipitation, evapotranspiration, and

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soil moisture depend on temperature regime [1]. In the framework of assessing the water balance, water industry managers have to address the following question [2]: how do groundwater level trends correlate with precipitation and climate behaviour? In other words, what is the influence of climate change on the volume of water that can be extracted from groundwater? Moreover, since the energy cost due to pumping stations is one of the largest components of the total system management costs [3], the analysis of the water table behaviour has also important economical implications. To solve such a paramount importance problem, a multi-disciplinary approach is needed. General Circulation Models (GCMs), which consider all relevant physical factors, must be used for understanding the aquifer response to climate change as a basis for water use policies. That said, this question arises: is the refining of a reliable GCM within the reach of any water supply company? In other words, which water company is so important that it can include all the needed capabilities in its staff? On the economical side of the problem, a further tie rises: does the dynamics of funding – in many cases resulting from a hand-to-mouth policy – allow preparing reliable management tools on time? In a world where water resources were managed according to cross-regional or, better, cross-borders criteria – some cases have been explored but for transnational river basins (e.g., [4, 5]) – a unique GCM could be used by several water companies accordingly. In the real world, water resources are not managed by means of shared criteria and each single water company has to solve its problems separately. In such a case, even if CGMs provided by research centres were used, to obtain realistic results statistical downscaling techniques should be employed to bridge the local- and synoptic-scale process by considering a number of factors including precipitation intensity and timing, topography, vegetation, and soil properties [2, 6]. In a word, a quite complex procedure which also needs an interdisciplinary approach. Moreover things are made more complicated by the fact that in many cases the water table behaviour and its links with the users – i.e., the effects of groundwater extraction and pumping criteria – is not known at a regional scale. In most cases only some local water table measurements and extracted volumes are available, often close to the most important well-fields. Situation is more critical for minor groundwater resources (i.e., those with a small withdrawn discharge) for which also the delineation of the protection areas is often a hard task [7, 8].

In the above scenario, where climate change plays a more and more critical role and, in some sense, exalts management problems, the importance of the global atmospheric datasets has to be pointed out. Particularly, for monitoring climate change, ECMWF (European Centre for Medium-Range Weather Forecasts) – as well as other global research centres – periodically uses its forecast models and data assimilation systems to reanalyse archived observations, creating global data sets describing the recent history of the atmosphere, land surface, and oceans. It is worthy of noting that such climate observations range from early in-situ surface observations made by meteorological observers to modern high-resolution satellite data sets. In this paper data from ERA-Interim – a reanalysis of meteorological observations made by ECMWF – are used for exploring if a link exists between the trend of soil moisture and local water table data. With particular regard to unconfined aquifers, such a link would represent the first stone on which a simplified – but physically based – model could be built to predict the behaviour in time of groundwater resources with the aim of refining a reliable water balance and the related investments for water supply and distribution systems in line with climate change.

2. Data source and description

Two kinds of data have been used for evaluating the behaviour of groundwater: soil moisture content provided by the ERA-INTERIM re-analysis dataset of ECMWF and water table elevation given by the monitoring network managed by the Regional Agency for Environmental Protection of the Umbria Region (ARPA Umbria, Italy).

2.1. ECMWF soil moisture data

ERA-Interim is one of the few global atmospheric datasets produced by the national agencies with the aim of monitoring climate and for research purposes. ERA-Interim is a reanalysis of meteorological observations from January 1979 to present with products gridded at T255 spectral resolution (Triangular spectral truncation at 255, about 80 km) by the ECMWF in collaboration with many institutions [9]. Gridded data products include a large variety of surface and atmospheric parameters, produced by the daily reanalysis of tens of millions of observations assimilated twice a day with a prior estimate of the atmospheric state of the ECMWF global forecast model in a statistical optimal manner. Reanalysis of data was built initially to make better use of the observations to initialize numerical weather forecasts but since the data assimilations system of the observations is constant, the result is a consistent, spatially complete and coherent record of the global atmospheric fields. One of the goals of the reanalysis of the observations was to better represent the hydrological cycle, and then the soil moisture fields are constrained – as the other fields – by the data assimilation performed in the ERA-Interim dataset, to stay close to the fist-guess fields produced by IFS (Integrated Forecast System) and the observations. The land surface scheme TESSEL (H-Tessel for ERA-Interim/land [10]) is producing the land surface forecast for soil moisture at four levels (0-7,7-28,28-100 and 100-289 cm from the ground level, respectively).

In the ERA-Interim dataset moisture is of high quality in the 0-12 hrs forecast range since one consequence of the reanalysis is to represent available observations with a physical coherence. This last requirement translates in the use of a physical model that assimilates and compares observations of different type for each variable according to an optimal analysis. Moreover, information can be extrapolated from locally observed parameters to unobserved parameters at nearby locations and propagate them forward in time. For soil moisture the H-Tessel scheme of the global model provides the model forecast for land surface analysis, with a systematic improvement of the quality of ERA-Interim near surface fields due to satellite data and the assimilation of in situ soil moisture observations [11, 12]. The principal observing network systems providing data assimilated for land surface is constituted by satellites and rain gauge data from GPCP (Global Precipitation Climatology Project v2.1) for precipitation data; the FLUXNET land surface energy fluxes observation network for energy and CO2 flux; the GTS-SYNOP (Global Telecommunication System surface SYNOPtic observation) maintained by the WMO (World Meteorological Organization) to collect daily ground-based observations of the main weather parameters and selected surface quantities. WMO provides through the Global Runoff Data Centre (GRDC) data for checking atmospheric and hydrologic models. In addition, different components of the surface parameterization of the Tessel scheme were revised and used to update the soil moisture estimates of various layers; the formulation of the soil hydrological conductivity and diffusivity was revised to be spatially variable according to a global soil texture map (FAO/UNESCO Digital Soil Map of the World, DSMW, FAO; http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/it/).

The observing network collecting and homogenizing soil moisture data is the International Soil Moisture Network (ISMN, http://www.ipf.tuwien.ac.at/insitu/ [13]) that makes soil moisture data freely available for some periods and locations. In Italy, where this study has been conducted, partial data collected from 3 regions, included the Umbria region, have been assimilated. For further details regarding the observing network and production of the ERA-Interim reanalysis the reader is referred to [9, 14].

Soil moisture content definition used here is the amount of water contained in the unsaturated soil zone in a given soil volume [15]. Given this definition, soil moisture can be measured in a few cubic centimetres as well as several cubic kilometres, depending on the measurement method. The measurement methods provide estimates of the soil moisture content only in the top few centimetres of the soil (e.g. microwave remote sensing) or in a small volume at a given depth (e.g., Time Domain Reflectometry measurements, TDRM) or together with other parts of water terrestrial storage such as the water table elevation (e.g. Gravity Recovery and Climate Experiment, GRACE satellite mission). Then the volume where the amount of water is estimated may be a function of space and time depending on the plants rooting depth or the water table depth.

Our goal is to show that the dataset used provides a reliable estimate of soil moisture volumetric content from the resolution given at continental scale to the point measurements of water table depth at a regional scale. The fields of the volumetric soil water content that have been used are synoptic monthly means over Europe at each of the four main synoptic hours (00, 06, 12, and 18 UTC), where 6 hours is the period of time needed to resolve a wave travelling at synoptic scale (about 1000 km). One must remember here that moisture inside soil and then water table, is the result of precipitation over all meteorological space-time scales. As mentioned above, the ERA-Interim dataset is obtained by using the same procedure that is used in the daily analysis-forecast cycle. Data are assimilated inside the model in different steps that correspond to the analysis-forecast cycle: quality control, objective analysis, initialization and an initial guess from a short-term forecast.

The synoptic monthly means for soil moisture volumetric content are produced from the respective analyses at the appropriate synoptic hour for every day in the month. The synoptic monthly means for soil moisture water content are produced from the set of the appropriate 6 and 12-hour forecasts, initiated at either 00 or 12 UTC, that verify at a particular synoptic hour for every day within the month. The data retrieved from the MARS archive at ECMWF are spanning the soil moisture data from January 1979 up to December 2015 and cover Europe where latitude spans [73.5-33.] degrees north and longitude [-27.-45.] degrees east with a grid of 0.125x0.125 degrees. Given this dataset at four levels, a monthly mean or climatology over the whole period has been calculated as averaged values over the synoptic hours for the first and fourth level (0-7 and 100-289 cm below the ground level). The difference between the actual data from the climatology – the anomaly – is shown in Fig. 1 for January, April, July and October. These maps show a distinct seasonal trend of wet and dry soil moisture content over the whole averaged period (1979-2015).

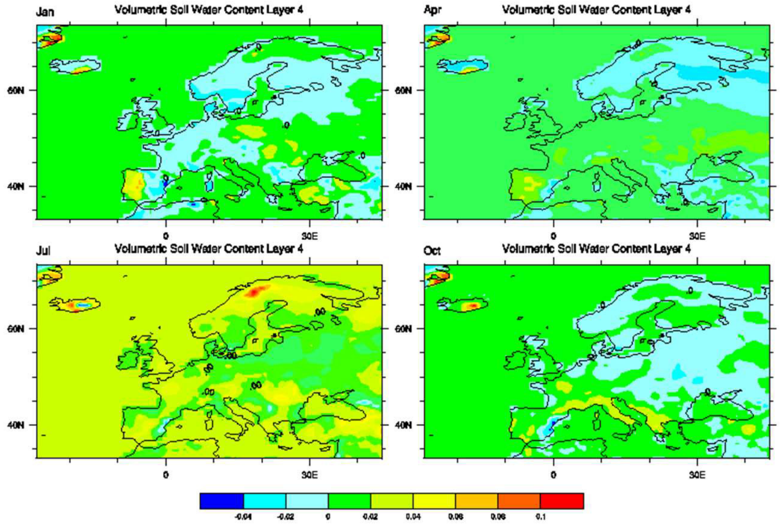

Fig. 1. Anomaly of the volumetric soil water content at layer 4 in Europe in different months.

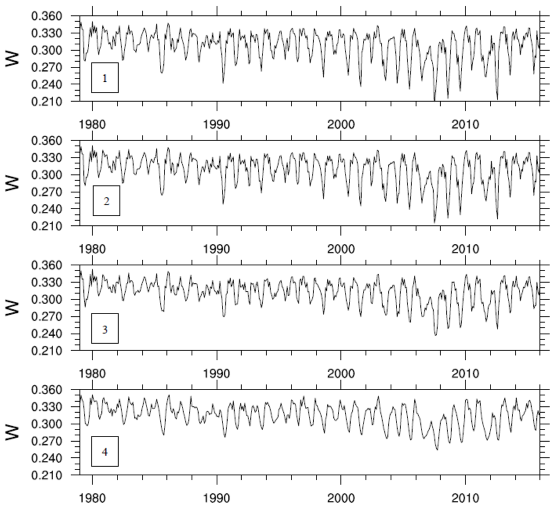

Fig. 2. Time series of the volumetric soil water content at layers1:4.

From a modelling prospective, this is equivalent to say that the balance between precipitation and evaporation as well as runoff is positive for both layers. In Fig. 2 these data are then plotted as time series of the volumetric water content, *w*, from January 1979 to December 2015 for all the available layers. The chosen coordinate points give similar time series for all the latitude and longitude points corresponding to the stations where water table data were analysed (not shown). This means that the soil moisture water content as seen by the ERA-Interim reanalysis is representative of an area that covers Central Italy where Umbria is positioned. A distinct yearly oscillation in time is displayed by all layers, with different water content depending on the year. As an example, the 2003-year, a very dry and anomalous year for all water variables, can be noticed as very dry for all soil moisture layers [16]. Time series of layer 4 will be evaluated in the following as a reference for monthly mean values of soil water content in the unsaturated zone.

2.2. ARPA Umbria water table data

ARPA Umbria collects water table data at 52 sites in the region (Fig. 3). For each of these sites, the water table elevation is provided as the median daily value [17]. Each three months, the measured value is checked by using further equipment. The observation period is not constant; for most of sites monitoring started in early 2000s.

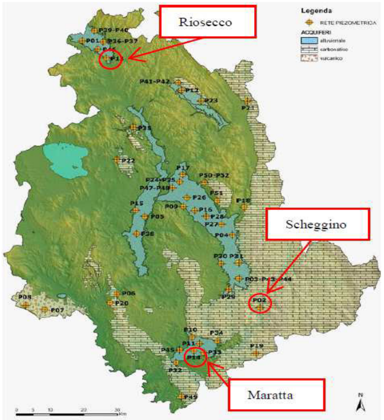

Fig. 3. Water table monitoring network managed by ARPA Umbria (in red the sites considered in this study).

In this paper data from three sites have been considered (Table 1); in Fig. 4 the relevant time-history of the water table elevation, *h*, is reported, with *h* being referred to the ground level. It is worthy of noting that they are spread throughout the Umbria region.

Table 1. Selected water table monitoring sites in the Umbria region, Italy.

Site	No.	Monitored since
Scheggino	P02	20 June 2001
Riosecco	P13	8 Nov 2001
Maratta	P14	8 May 2001

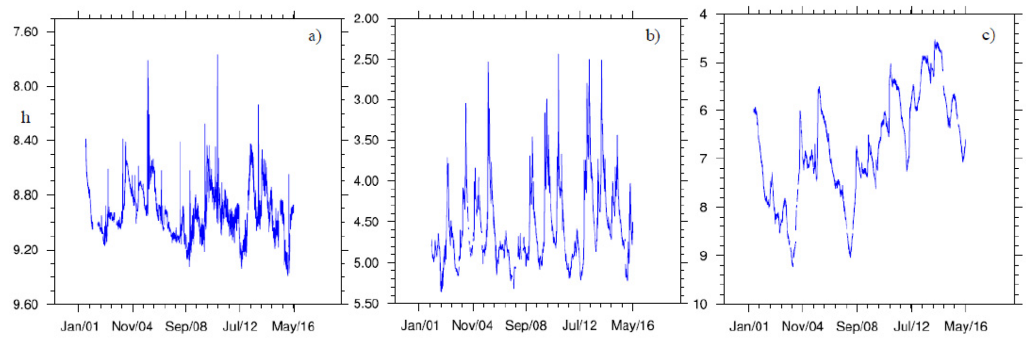

Fig. 4. Water table monitoring (daily data) at the three selected sites (Table 1): a) Scheggino; b) Riosecco; c) Maratta.

3. Soil moisture and water table data analysis

To homogenize the available data, monthly mean values of the selected water table measurements sites have been considered. In Figs. 5 to 7 such datasets have been compared with the time series of the volumetric soil water content at layer 4, the closest to the water table. The analysis of these figures shows a clear correspondence between the extreme values of soil moisture and water table elevation. It is worthy of noting that such a good agreement – in terms of time matching of the peaks – between the time-history of the water content in the vadose zone and the water table elevation happens for all the three sites irrespectively from their location in the Umbria region.

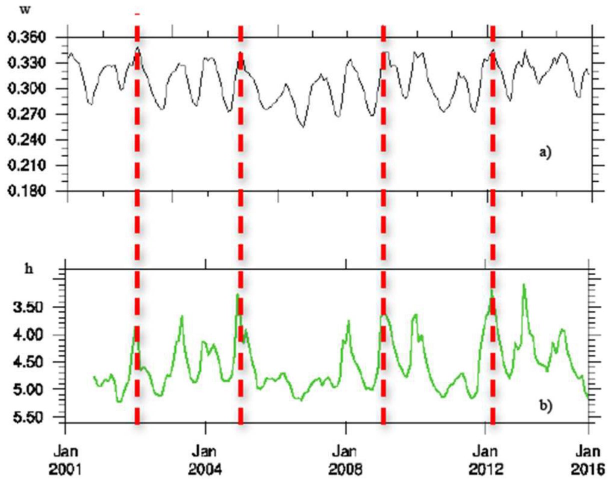

Fig. 5. Riosecco site: mean monthly time series of the: a) volumetric soil water content at layer 4, and b) water table elevation. The red lines highlight the good correlation between peaks of *w* and *h*.

In the perspective of using soil moisture data given by ERA-Interim (or any other global dataset) for forecasting the groundwater behaviour and assessing a reliable water balance, the interest of such a result can be legitimated on the basis of the following two important mechanisms. The first concerns the fact that the larger the water content, the larger the volume of water that reaches the water table. The second important mechanism pertains to the water carrying capacity of the unsaturated soil. In fact, for a given soil, the larger *w*, the larger the soil conductivity and then, for a given rain, the larger the infiltration towards the water table.

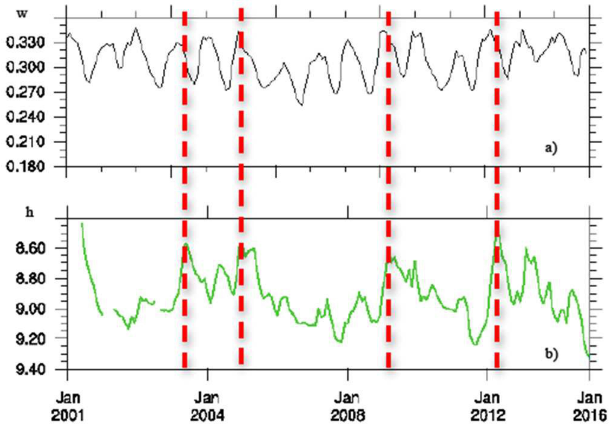

Fig. 6. Scheggino site: mean monthly time series of the: a) volumetric soil water content at layer 4, and b) water table elevation. The red lines highlight the good correlation between peaks of *w* and *h*.

According to such highlighted mechanisms, the match between the extreme values of *w* and *h* indicates a link between the actual water flux and water table elevation. Moreover, the periods of time where the maximum values of *w* happen are characterized by a larger potential in terms of the volume of water that could reach the groundwater in rainy conditions. In other words, the larger values of *w* exalt the connection between the land surface – where the precipitation is "available" – and the groundwater.

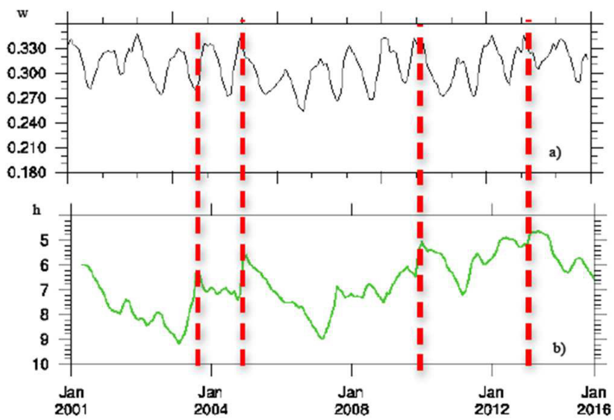

Fig. 7. Maratta site: mean monthly time series of the: a) volumetric soil water content at layer 4, and b) water table elevation. The red lines highlight the good correlation between peaks of *w* and *h*.

4. Conclusions

Climate change influences hydrological cycle with a direct effect on groundwater resources, one of the most important supply source for human consumption and irrigation. In the framework of assessing water balance and the related hydraulic works for water supply and distribution, it is crucial to correlate quantitatively climate trends, precipitation and groundwater behaviour. In a scenario where General Circulation Models do not represent yet a usual tool for water industry managers, potentially the use of global atmospheric datasets is of great interest for evaluating groundwater resources. In such a context, the reanalysis of the meteorological observations may represent a powerful tool for estimating the global atmospheric fields with a physical coherence.

In this paper data from ERA-Interim – a reanalysis of meteorological observations made by the European Centre for Medium-Range Weather Forecasts (ECMWF) – are compared to the local water table measurements given by the monitoring network managed by the Regional Agency for Environmental Protection of the Umbria Region (ARPA Umbria Italy). With particular regard to unconfined aquifers, the good correlation between the trend of soil moisture and local water table data is pointed out. Such a promising result authorizes further insights in order to refine reliable tools for evaluating available groundwater resources in a climate change scenario.

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