DOI 10.7343/as-2022-574

ACQUE SOTTERRANEE
Italian Journal of Groundwater
journal homepage: https://www.acquesotterranee.net/

2022-AS41-574: 19 - 28

Groundwater-surface water interaction revealed by meteorological trends and groundwater fluctuations on stream water level

Interazione acque sotterranee-acque superficiali rivelate dalle tendenze meteorologiche e dalle fluttuazioni delle acque sotterranee sul livello di un corso d'acqua

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ARTICLE INFO

Ricevuto/*Received*: 10 May 2022
Accettato/*Accepted*: 20 June 2022
Pubblicato online/*Published online*: 30 June 2022

Handling Editor:
Marco Pola

Publication note:
This contribution has been selected from Flowpath 2021 congress held in Naples 1-3 December 2021

Citation:
Fronzi D, Gaiolini M, Mammoliti E, Colombani N, Palpacelli S, Marcellini M, Tazioli A (2022) Groundwater-surface water interaction revealed by meteorological trends and groundwater fluctuations on stream water level. Acque Sotterranee - *Italian Journal of Groundwater*, 11(2), 19 - 28
https://doi.org/10.7343/as-2022-574

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Keywords: *aquifer-streams interaction; piezometric level; continuous monitoring; hydro-meteorological trends.*

Parole chiave: interazione acquiferi-corsi d'acqua; livello piezometrico; monitoraggio in continuo; trend idro-meteorologici.

Riassunto

L'importanza di considerare acque sotterranee (GW) e superficiali (SW) come due componenti interconnesse della stessa risorsa è aumentata rapidamente negli ultimi decenni. Al fine di studiare l'interazione GW-SW in bacini sfruttati da diversi pozzi a scopo idropotabile, è stato effettuato un monitoraggio continuo integrato delle condizioni idrologiche. Il sottobacino (14 km^2), ubicato nel bacino dell'Aspio (Centro Italia), è drenato da un piccolo corso d'acqua (Betelico) ed è caratterizzato dalla presenza di una falda acquifera ospitata nei depositi alluvionali (non confinata) ed una ospitata nelle formazioni carbonatiche (semi-confinata). Lo scopo di questo studio è valutare i fattori determinanti del prosciugamento del corso d'acqua avvenuto nel corso degli ultimi due anni, applicando un'analisi sulla serie temporale di piogge, temperature dell'aria, livello piezometrico e del corso d'acqua e dei tassi di pompaggio dei pozzi. L'andamento delle precipitazioni è stato analizzato su un periodo di 30 anni attraverso il calcolo dello Standard Precipitation Index (SPI) e un'analisi sulla ricorrenza dei fenomeni piovosi intensi, mentre la correlazione tra il livello piezometrico e quello del corso d'acqua è stata analizzata per gli ultimi sei anni. La quota assoluta della falda freatica è stata confrontata con il livello di baseflow del corso d'acqua, evidenziando l'interconnessione tra GW-SW nel corso degli anni. Le analisi condotte sul surplus idrico, insieme alla caratterizzazione degli eventi piovosi, supportano l'ipotesi di un prosciugamento del corso d'acqua dovuto principalmente alla diminuzione della ricarica. Questo caso di studio sottolinea l'importanza di studiare le interazioni GW-SW in un contesto climatico in continua evoluzione caratterizzato da un andamento delle precipitazioni decrescente (con un aumento di fenomeni intensi), accoppiando sia i vantaggi di un metodo statistico robusto come l'analisi delle serie temporali che il monitoraggio continuo sul campo.

Abstract

The importance of considering groundwater (GW) and surface water (SW) as a single resource of two interconnected components has rapidly increased during the last decades. To investigate GW-SW interaction in an aquifer system exploited by several pumping wells, an integrated continuous monitoring of the hydrological conditions was carried out. The sub-catchment (14 km^2), located in the Aspio basin near Ancona (Central Italy), is drained by a small stream named Betelico, and it is characterised by the presence of an unconfined alluvial aquifer and a semi-confined limestone aquifer. The aim of this study is to evaluate the drivers of stream drying up occurred during the last couple of years. This has been achieved by applying a trend analysis on rainfall, air temperatures, piezometric and stream level, and well pumping rates. Precipitation trends were analysed over a 30-years period through the calculation of the Standard Precipitation Index (SPI) and through heavy rainfall events frequency plots, while the correlation between piezometric stream levels and pumping rate was analysed during the last six years. The groundwater level was compared with the stream baseflow level, highlighting the interconnection between GW-SW over the years. The analysis on the water surplus (WS) trend, together with the rainfall events characterisation, supports the hypothesis of the decrease in recharge rate as the main driver of the stream drying up. This case study stresses the importance of studying GW-SW interactions in a continuously changing climatic context characterised by a decreasing precipitation trend, coupling both the advantages of a robust method like trend analysis on time series and the field continuous monitoring.

Introduction

A large majority of climate models have long projected drier summers over much of southern and western Europe under future climate scenarios (Rowell and Jones 2006; Seager et al. 2014; Brogli et al. 2019; Grillakis 2019) resulting in intense surface warming and widespread decrease in precipitation, most intense between 40° and 50°N (Tuel and Eltahir 2021). Such trends threaten to put significant stress on human health, water resources, and agriculture (Samaniego et al. 2018; Lentini et al. 2021).

Sudden changes in the regime of hydro-meteorological events are the main causes of natural extreme events like droughts (Turco et al. 2017), fires (Busico et al. 2019; Turco et al., 2019), and floods (Kourgialas and Karatzas 2011; Toosi et al. 2019) that could affect many regions of the world.

Understanding the complex behavior of the integrated surface water (SW) – ground water (GW) system is crucial to the regional water resources management (Rassam et al. 2013), especially in those regions stressed by climate change-related issues (Aryal et al. 2019; Bhatta et al. 2019; Pranzini et al. 2020). The interaction between SW and GW plays an important role in the eco-hydrological system (Sophocleous 2002; Gilfedder et al. 2012). Surface water diversion, groundwater pumping, and irrigation due to agricultural activities could significantly alter the flow regime of both SW and GW (Barlow et al. 2000; McCallum et al. 2013; Shah 2014; Siebert et al. 2010).

Moreover, GW–SW interactions cover a broad range of hydrogeological and biological processes that are controlled by natural and anthropogenic factors at various spatial-temporal scales. Indeed, a better knowledge of these processes is vital in the protection of groundwater-dependent ecosystems, increasingly required in water resources legislation across the world (Bertrand et al. 2014).

During the last years, the Betelico stream, draining the small sub-catchment located in the Aspio basin (Central Italy), has completely dried up. Considering the agricultural and climatic stresses to the basin (Mussi et al. 2017; Pellegrini 2020), this study aims to identify the drivers of the drying up. An investigation of the interaction between the stream and the aquifers of the sub-catchment has been conducted, exploiting both the advantages of a trend analysis on climatic time series (i.e., rainfall and air temperature) and the field continuous monitoring of stream and groundwater levels.

Data and methods

Characterisation of the study area

The study area comprises a sub-catchment (5 km^2) of the Aspio watershed, located in the Marche Region (central Italy), in the proximity of the Conero Mt. regional park (Fig. 1). This sub-catchment is drained by the Betelico stream, a tributary on the left side of the Aspio river.

From a geological standpoint the watershed belongs to the Umbria-Marche stratigraphic succession, consisting of

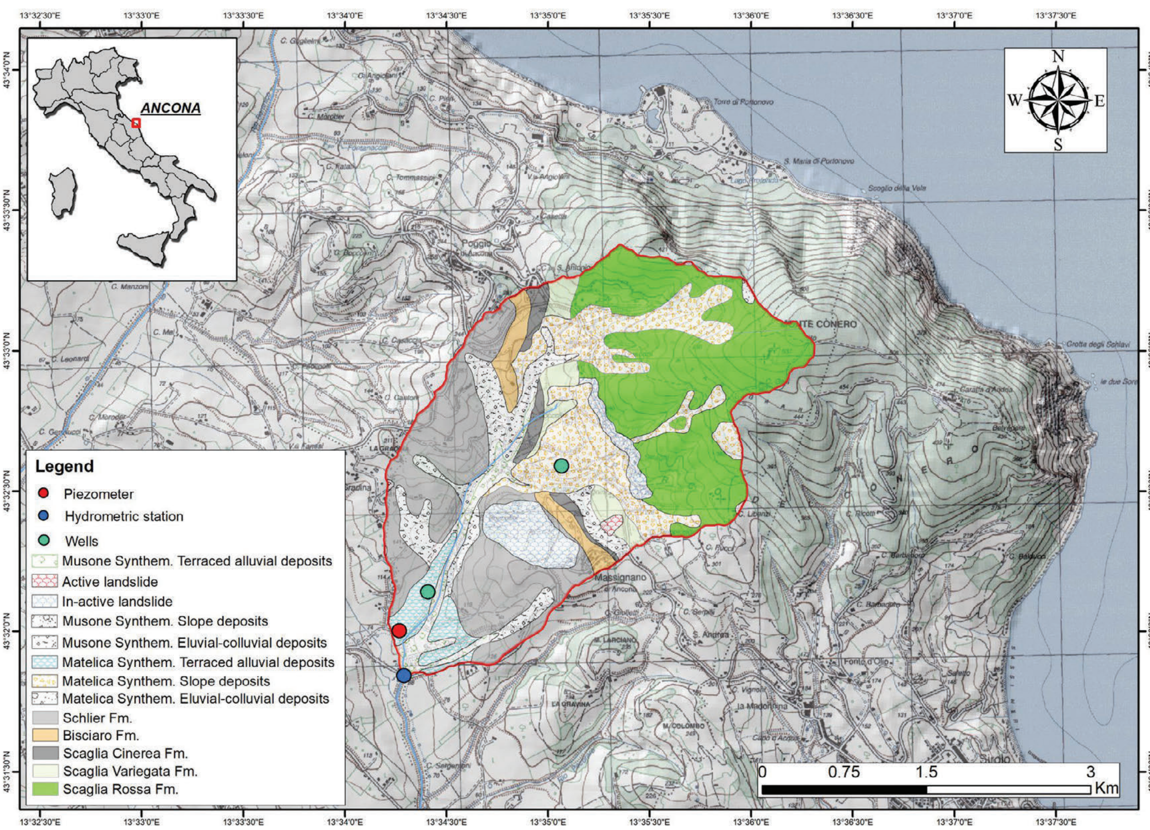

Fig. 1 - Simplified geological map of the study basin with location of the monitoring system.

Fig. 1 - Carta geologica semplificata del bacino di studio con ubicazione dei punti di monitoraggio.

the Mesozoic-Cenozoic limestone sequence, the Miocene-Pleistocene clastic sedimentary formations (Tazioli et al. 2015).

In particular, the oldest geological formation outcropping in the catchment is the Scaglia Rossa Fm. (Upper Cretaceous-Middle Eocene). This formation is constituted by stratified mycritic limestones and limestones, marly, flinty limestones (Mussi et al. 2017). The Scaglia Rossa Fm. gradually increases of clayey-marly lithotypes passing to the Scaglia Variegata Fm. followed by the Scaglia Cinerea Fm. During the Miocene, the sedimentation continued with the deposition of the Bisciaro Fm. and the Schlier Fm. These formations (composed of marly and siliceous marly limestone and clayey marls, calcareous marls, and clays with rare arenaceous intercalations outcrop extensively on the western side of the Conero Mt. in which the Betelico catchment extends. The continental deposition is marked by the presence of terraced alluvial deposits, stratified slope debris deposits and landslide deposits. The Holocene is characterised by the deposition of the alluvial and the eluvial-colluvial deposits in the flattering areas near the watercourse. From a geo-structural point of view, the Conero Mt. ridge is an asymmetric anticline with NW-SE axis direction and NE vergence (Nanni et al. 1997; Scisciani 2009; Cello and Tonti 2014; Sarti and Coltorti 2014). The anticline is characterised by almost vertical strata on the eastern side (Adriatic Sea side), while on the western side (in which the Betelico catchment extends) the strata display an inclination of less than 25°.

The hydrogeological setting of the basin consists of two main aquifers (Fig.2): the first one is hosted in the Scaglia Rossa Fm., and the second one is hosted in the continental Quaternary deposits. The main aquifer is represented by the Scaglia Rossa Fm., and it is confined on the bottom by the marly units of the Marne a Fucoidi Fm., (not outcropping in the sub-basin). Moving westward from the top of Conero Mt., the Scaglia Rossa Fm. is semi-confined by the hydrogeological complex composed by the Scaglia Variegata, Scaglia Cinerea, Bisciaro and Schlier formations, which constitute a single aquiclude at the top. This hydrogeological complex, together with Pliocene and Pleistocene clay layers, hydraulically separates the Scaglia Rossa aquifer from the shallow Quaternary aquifer.

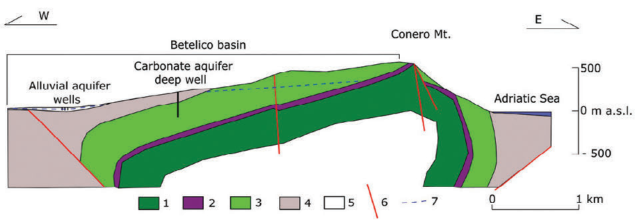

Fig. 2 - Schematic hydrogeological section of the study area. Legend: 1- Maiolica geological formation; 2- Marne a Fucoidi aquiclude; 3- Scaglia Rossa aquifer; 4- Scaglia Variegata, Scaglia Cinerea, Bisciaro and Schlier aquiclude; 5- Alluvial aquifer; 6- Fault 7- Piezometric level. Modified from Mussi et al., 2017.

Fig. 2 - Sezione idrogeologica schematica dell'area di studio. Legenda: 1- Formazione della Maiolica; 2- Acquiclude delle Marne a Fucoidi; 3- Acquifero della Scaglia Rossa; 4- Acquiclude della Scaglia Variegata, Scaglia Cinerea, Bisciaro e Schlier; 5- Acquifero Alluvionale; 6- Faglia 7- Livello piezometrico. Modificata a partire da Mussi et al., 2017.

The permeability of the Scaglia Rossa aquifer is regulated by the presence of fissures and microkarst. The shallow aquifer is responsible for the presence of perennial surface water in the stream and feeds the watercourse through a diffuse presence of silty-sands, sandy-silts and gravels with sands layers (Tazioli et al. 2017). Both the aquifers are tapped by the local water supply company with two well fields, providing water in some small towns of the area.

The climate is temperate and sublittoral, with an average precipitation of about 900 mm/y (Mussi et al. 2017) and the recharge is entirely due to meteoric precipitation.

According to the 2016 Corine Land Cover (CLC), forests represent 50% of the entire sub-catchment, 49.5% is occupied by agricultural areas, while only 0.5% of the territory is occupied by urban settlements. Those land-use percentages, if they are compared to the ones determined for the entire Aspio watershed (Busico et al., 2020), underlie a peculiar natural condition of the Betelico catchment with respect to the other sub-basins.

Field monitoring and data analysis

The catchment was monitored over the last six years, and both the piezometric and hydrometric levels were continuously measured (Fig. 1) employing hydrometric pressure transducer (CTD diver Eijkelkamp, accuracy ± 0.5 cmH_2O and resolution 0.2 cmH_2O) compensated by atmospheric pressure and using an acquisition time interval of 10 minutes then grouped at daily scale (mean daily value). Unfortunately, starting from December 2020, the pressure transducer located in the piezometer was vandalised and broken, so throughout the year 2021, the piezometric level was periodically manually measured.

Hourly rainfall and mean monthly temperature data were downloaded from the official hydro-pluviometric database managed by the Regione Marche Civil Protection Agency, available at the SIRMIP-online portal (https://www.regione.marche.it/Regione-Utile/Protezione-Civile/Console-Servizi-Protezione-Civile/SIRMIP-online). The rainfall data have been retrieved for a period >30 years starting from January 1991 to December 2021, while the temperature data have been downloaded from January 2008 to December 2021 (no missing data are present). Both the rainfall and temperature are recorded in a station located 9 km (air-distance) from the Betelico basin, having the catchment mean elevation (~125 m a.s.l.). Starting from the year 2015 until 2020, the mean monthly well pumping rates provided by the water supply company are available. The retrieved data were analysed and processed through "WaterbalANce" (Mammoliti et al. 2021), a WebApp that exploits the "Thornthwaite-Mather" method to compute the water balance (Steenhuis and Molen 1986). The App allows to gain the mean annual water surplus (WS) to be compared to the mean annual well abstraction and establish the percentage of influence of wells abstraction over the total water surplus. To run the app, latitude (LAT), soil moisture storage capacity (SM), snowfall rainfall temperature threshold (SRT), and runoff coefficient (beta) were set based on the geographical, geological, and climatic features of the area (Tazioli et al. 2015; Tazioli et al. 2017; Mussi et al. 2017). Respectively, LAT = 43 degrees, the SM = 200 mm, SRT = −1 °C and beta = 50% were used. The SM value was selected according to the soil moisture reference tables published by Thornthwaite and Mather, (1957), used by (Mammoliti et al. 2021) for similar areas of central Italy. The beta coefficient (50%) is fixed for all the simulation period, hence it represents a conservative situation for the runoff estimation over the entire water surplus.

To determine the occurrence of particularly dry or wet conditions and their relations with the piezometric and hydrometric levels, the Standardized Precipitation Index (SPI) (McKee et al. 1993) was calculated considering the 31 years interval (1991-2021).

The SPI is the number of standard deviations that the observed value would deviate from the long-term mean, for a normally distributed random variable. In the SPI computation, cumulated rainfalls over different time scales (1, 2, 3 … n months) were fitted to a gamma probability distribution and then transformed into a normal distribution. For a given data time series of precipitation x_i as x_1, x_2 …xn, the SPI is defined by the equation:

$$SPI = \frac{x_i - \overline{x}}{\sigma_x}$$

where: $\overline{x}$ is the arithmetic mean of rainfall and σ_x is the standard deviation.

For a defined timescale, SPI equal to 0 implies that there is no deviation from the mean. Positive values of SPI indicate wet periods, while negative values indicate dry periods (Valigi et al. 2020; Fronzi et al. 2020).

The severity of drought events increases when the SPI is continuously negative and reaches an intensity of at least −1; "n" varying from 1 to 24 months is the best statistical range of application (Guttman 1998, 1999). Therefore, the rainfall data were elaborated using a 12-month time scale (SPI-12) since it better represents long-term precipitation patterns (Fiorillo and Guadagno 2010; World Meteorological Organization 2012).

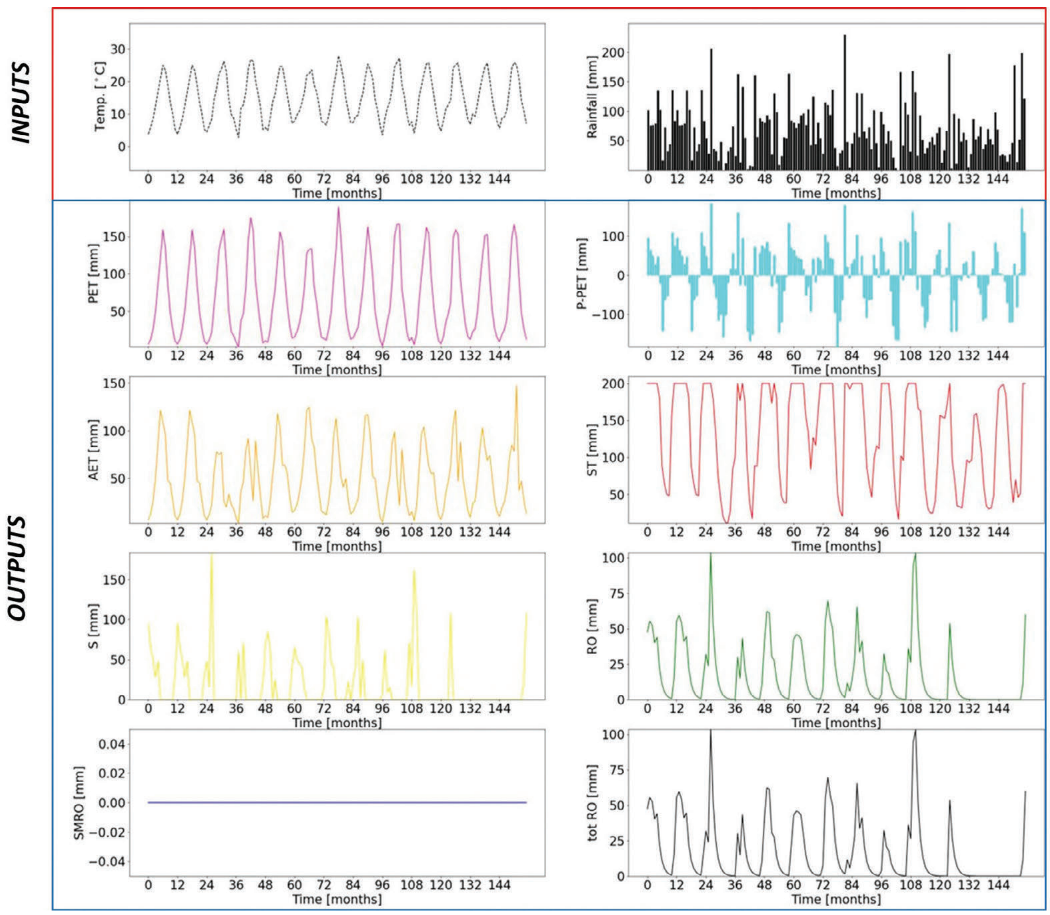

Fig. 3 - Graphical example of WaterbalANce inputs: Temp.= mean monthly temperature (°C), Rainfall = monthly precipitation (mm) and outputs: PET = monthly potential evapotranspiration (mm), delta = P-PET (mm), AET = monthly actual evapotranspiration (mm), ST = monthly soil moisture (mm), S = monthly water surplus (mm), RO = monthly runoff (mm), SMRO = monthly snow melt runoff (mm), TOT RO = monthly total runoff (mm).

Fig. 3 - Esempio grafico degli inputs di WaterbalANce: Temp.= temperatura media mensile (°C), Rainfall = precipitazione mensile (mm) e outputs: PET = evapotraspirazione potenziale mensile (mm), delta = P-PET (mm), AET = evapotraspirazione reale mensile (mm), ST = ritenzione idrica del suolo mensile (mm), S = eccedenza idrica mensile (mm), RO = deflusso superficiale mensile (mm), SMRO = deflusso superficiale mensile dovuto allo scioglimento nivale (mm), TOT RO = deflusso superficiale mensile totale (mm).

Moreover, in order to integrate the SPI results, the precipitation events were classified over the same interval accounting for the number of storm events (i.e., the number of events with a precipitation rate larger than 10 mm/hour) that have occurred every year (Ryu et al. 2021). Such analysis informs about the tendency of rainfall events to foster recharge or runoff and therefore it better exemplifies the WS component. In fact, wetter conditions do not always produce more groundwater recharge (Taylor et al. 2013) that is governed by precipitation characteristics such as duration, magnitude and intensity (Tashie et al. 2016). In particular, heavy-intensity rainfall events over short time periods cause groundwater recharge reduction, while promoting runoff generation (Freeze and Cherry 1979; Dourte et al. 2012; Huang et al. 2012).

Additionally, the linear trend for the meteo-climatic data (i.e., monthly rainfall and temperature data), the hydrometric and piezometric level has been obtained by the linear regression over the analyzed time span and plotted together with the SPI-12 values. Eventually, the mean annual wells pumping rate and WS have been plotted together to identify the key driver of the groundwater level drop and the subsequent drying of the Betelico stream.

Results and discussions

The mean monthly hydrometric level (Fig.4a) and the piezometric level, together with the monthly rainfall (Fig.4b) have been plotted over the six years of observation time (2016-2021).

The monitoring results of the Betelico stream perfectly reflect field observations with the hydrometric level approaching zero centimeters in August 2020 without rising again, except in October 2020, August, November, and December 2021, although remaining below 1 centimeter. The general decreasing trend in the hydrometric level is evidenced by the linear regression (black dotted line in Fig. 4a) with a slight negative angular coefficient.

At the same time, the water table level, even though characterised by sudden fluctuations strictly related to the rainfall events (Fig. 4b), shows a decrease trend during the last six years, reaching the most negative value (-10 m below the ground level) in November 2020.

The rainfall regime of the catchment is outlined by a seasonal oscillation, with the maximum monthly rainfall usually recorded during the spring and autumn seasons (frequently exceeding 100 mm), and the minimum monthly rainfall recorded during the summer and winter periods. The mean annual rainfall value (considering the period 2016-2021) is about 855 mm.

The whole analysed time period is marked by a slight decrease in the precipitation trend, and the year 2020 is characterised by an annual precipitation amount of 508 mm, which is significantly lower than the previous years (Tab. 1). In addition, in the same year, months showing a cumulative rainfall of more than 100 mm have not been observed. Eventually, Table 1 reports the annual rainfall percentage deviation to the mean value recorded for the same period. It can be noticed that the last two years are characterised by

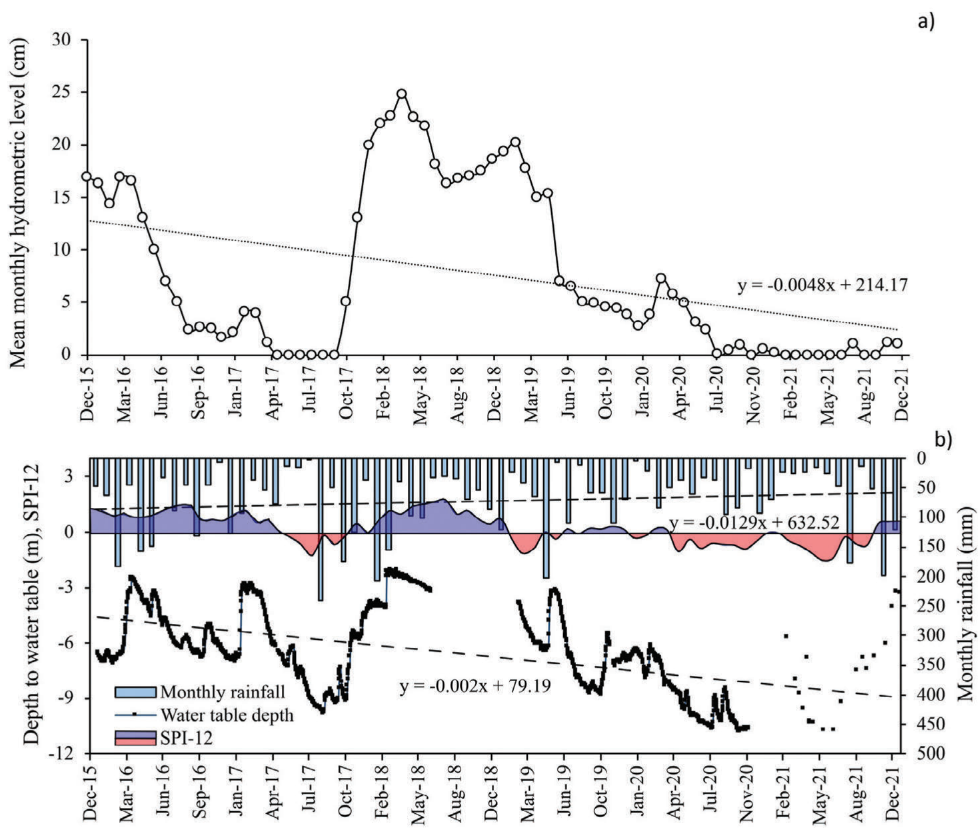

Fig. 4 - (a) Mean monthly hydrometric level for the Betelico stream with the linear trend (black dotted line); (b) Daily piezometric level recorded in the alluvial aquifer together with SPI- 12 values and monthly rainfall over the six years observation time (2016-2021). The linear trends for the piezometric level and the rainfall are represented by the dashed-dotted line and the dashed line respectively.

Fig. 4 - (a) Livello idrometrico medio mensile del Betelico con il suo trend lineare (linea a puntini neri); (b) Livello piezometrico giornaliero registrato nell'acquifero alluvionale, valori di SPI-12 e piogge mensili sul periodo di osservazione (2016-2021). I trend lineari per il livello piezometrico e le piogge sono rispettivamente rappresentati dalla linea a puntini e trattini e dalla linea a trattini.

-41% and -7% respectively of total annual rainfall concerning the mean precipitation amount in the area. Additionally, the year 2021 is characterised by approximately 221 mm out of 797 mm related to storm events (precipitation rate > 10 mm per hour), thus accounting for approximately 28% of the total annual rainfall. In contrast, the year 2020 is marked by a lower percentage of rainfall related to extreme events (5%), however the entire year is significantly less rainy than the annual average rainfall of the whole analysed period.

The mean value of air temperature is about 15°C while the minimum annual values are recorded during December,

Tab. 1 - Annual rainfall from 2016 to 2021 with percentage deviation to the mean annual value and extreme events rainfall amount with percentage over the annual rainfall recorded for the same period.

Tab. 1 - Pioggia annuale dal 2016 al 2021 con deviazione rispetto al valore medio dello stesso periodo espressa in percentuale e cumulata totale di pioggia relativa agli eventi estremi con percentuale rispetto alla pioggia nello stesso anno.

Year	Annual rainfall (mm)	Rainfall deviation to the mean (%)	Extreme events (mm)	Extreme events over the annual rainfall (%)
2016	992.8	+16	40	4
2017	1009.6	+18	50	5
2018	941.2	+10	98	10
2019	878.2	+3	102.4	12
2020	508.2	-41	25.4	5
2021	797	-7	221	28

January and February frequently not exceeding the 25[th] percentile (8.7 °C). The maximum temperatures are recorded during the summer (June, July, and August), exceeding the 75[th] percentile (20.9 °C). The maximum mean monthly temperature (27.9 °C) has been recorded in July 2015, while the minimum mean monthly temperature (2.7 °C) has been recorded in February 2012. Significant changes in the mean monthly temperature trend have not been observed within the analysed time span (Fig. 5).

The SPI computation was conducted for more than 30 years of observations (Fig.6) to obtain a statistical significance dataset (Zuo et al. 2021). However, the comparison with the piezometric and the hydrometric levels can only be performed for the last 6 years (see Fig. 4b). Specifically, in this time span, 14 months are moderately wet (1.0≤SPI<1.5), 11 months are very wet (1.5≤SPI<2.0) and 3 months (September 2014, October 2014, and May 2015, respectively) are extremely wet (SPI>2.0). The year 2016 is characterised by 7 months belonging to a near-normal condition while 5 months denote a moderately wet condition. Then, until May 2017, the area is subjected to a near-normal condition with positive SPI values, while the remaining months of 2017 are characterised by negative SPI values (except for December), with August moderately dry (SPI≈ -1.3). The year 2018 shows positive SPI values ranging from 0.43 (near-normal condition) to 1.75 (very wet condition), with June, July, and August 2018 characterised by very wet conditions. The whole year 2019 denotes a near-normal condition, except in March in which the SPI value is -1.16 (moderately dry). The year 2020 is always characterised by near normal conditions with negative values, except in March and April showing slightly positive SPI values, while May is moderately dry. Eventually, the year 2021 is characterised by 10 months with negative SPI values, three of which (May, June, and July) underline a severely dry condition (-2.0<SPI≤-1.5). The analysis, therefore, shows a consistent number of continuous negative SPI values between the years 2020 and 2021, when the stream desiccation was observed, together with a significant drop in the piezometric level of the alluvial aquifer (Fig. 4). However, since this

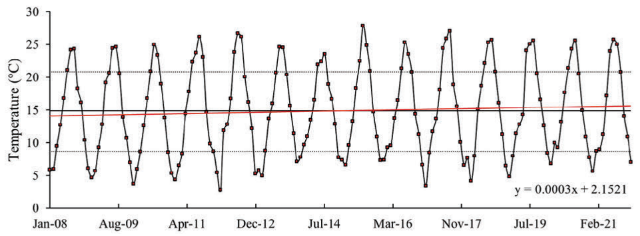

Fig. 5 - Mean monthly air temperature for the study area with its trend (red line), mean value for the whole period (black solid line) with 25[th] and 75[th] percentiles (black dotted lines).

Fig. 5 - Temperatura dell'aria media mensile per l'area di studio con la sua tendenza (linea rossa), temperatura media dell'intero intervallo (linea nera continua) con 25-esimo e 75-esimo percentile (linee nere punteggiate).

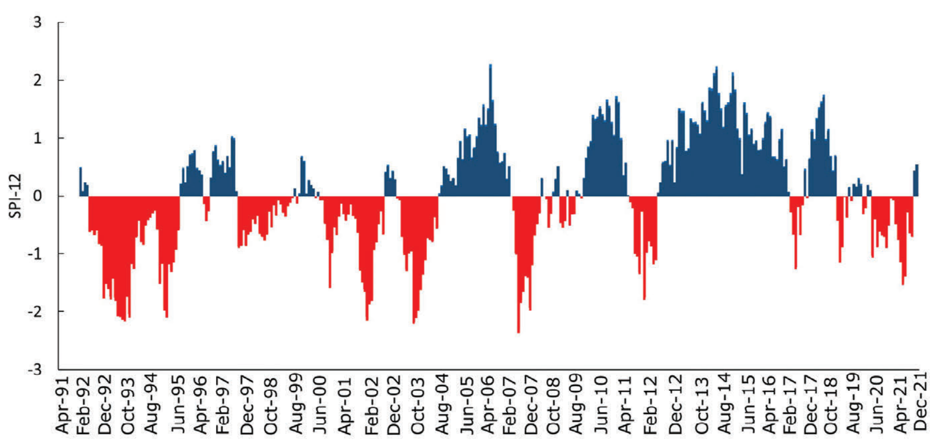

Fig. 6 - SPI-12 values for the analysed rainfall station.

Fig. 6 - Valori di SPI-12 per la stazione pluviometrica analizzata.

DOI 10.7343/as-2022-574

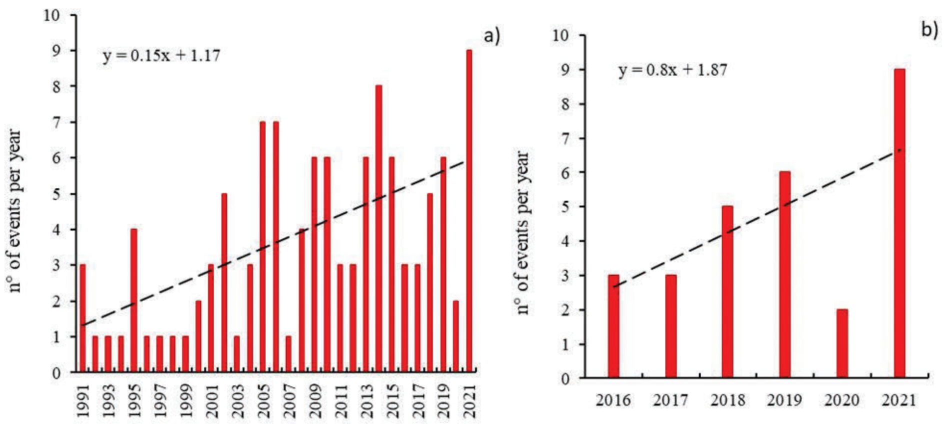

Fig. 7 - Storm rainfall events distribution with linear trend (black dashed line) (a) over the 31 years observation time (1991-2021); (b) magnification for the last six years (2016-2021).

Fig. 7 - Distribuzione degli eventi di pioggia temporaleschi con la sua tendenza (linea nera tratteggiata) (a) sull'intero periodo di analisi (1991-2021); (b) ingrandimento per gli ultimi sei anni (2016-2021).

comparison was only possible in the last few years, the SPI calculation alone doesn't seem to be illustrative concerning the analysed phenomenon.

Because of this, a frequency analysis of rainfall storm events was conducted for the whole period 1991-2021. The analysis of storm events (Fig. 7) clearly shows an increasing trend over the last thirty years, which results to appear even more intense focusing on the last six years observation time (2016-2021). During the '90s most of the years were characterised by a storm event per year with some exceptions (1991, 1995), while it is not unusual to exceed 3 or 4 storm events per year from the early 2000's till today. Specifically, focusing on the magnification for the last six years (Fig. 7b), the increasing trend is sharp with the only exception of the year 2020, which however, was characterised by low precipitation in general as shown in Table 1 (508.2 mm).

The mean annual WS has been plotted together with the mean annual groundwater abstraction from wells over the observation time (Fig. 8), to investigate the most important drivers of the groundwater drawdown and the consequent stream drying-off.

Since figure 8 doesn't show a mean annual wells abstraction increasing trend, the depletion of the groundwater resources

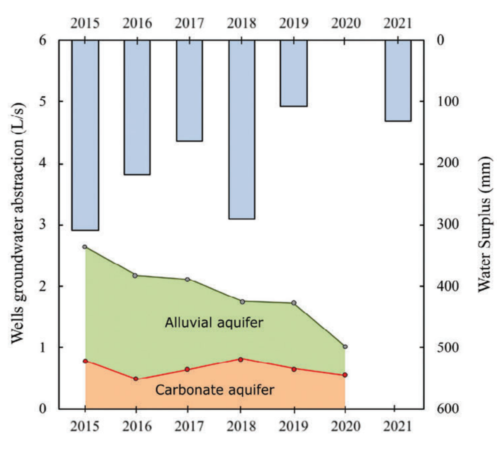

Fig. 8 - Mean annual wells groundwater abstraction and annual water surplus (WS) over the simulation time.

Fig. 8 - Emungimento medio annuale ad opera dei pozzi ed eccedenza idrica annuale (WS) nel periodo di simulazione.

cannot be attributed to the local water supply company. In particular, the mean annual wells groundwater abstraction from the carbonate aquifer didn't show significant variation and remained constant at a value of about 1 L/s; while the abstraction from the alluvial aquifer has even dropped down from a value of almost 3 L/s in 2015 to just over 1 L/s recorded in 2020. Just as example the conversion of the 3 L/s pumping rate into mm/y over the Betelico basin (5 km^2) leads to a value of 3.8 mm/y, which is almost negligible. Despite these simple considerations, the position of the pumping wells (Fig. 1) and their depression cone could have contributed to diminish the Betelico baseflow in 2020, but to quantify such effects a tridimensional numerical flow model should be implemented.

However, analysing the WS it is possible to notice a negative trend over the six years observation time (Fig. 8). The year 2020, during which the Betelico stream completely dried out (Fig. 4a), is characterised by an almost zero WS. This was due to low precipitation during that year with a percentage deviation with respect to the mean value for the observation period of - 41 % (Tab. 1). In 2021 the WS increased to more than 100 mm but was not enough to restore the normal function of the stream, which still nowadays results to be dried. It is likely that the 9 storm events occurred during that year (Fig. 7b), accounting for 28% of the 797 mm total precipitation (Tab. 1) fostered the runoff rather than meteoric recharge. It must be stressed that this hypothesis is not accounted in the WaterbalANce WebApp in which the runoff coefficient (beta) was constantly set for the whole analysed period to 50%. This aspect should be further investigated.

The mean annual groundwater fluctuations strictly related to rainfall events that characterised the basin has always leaded the Betelico stream to periodical dry conditions (summer 2017 in Fig. 4), without persisting over the entire year (Fig. 9). This aspect is also highlighted by the SPI-12 analysis, in which a value of -1.27 was observed in August 2017, followed by an increasing trend that lasted until August 2018 (Fig. 6).

Indeed, the whole year 2018 was characterised by a piezometric level increase, reaching the minimum depth below the ground level, with a consequent surface water recorded in the stream showing a strong GW-SW relationship.

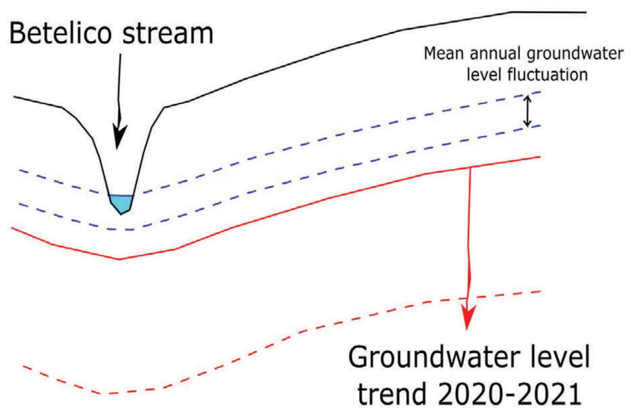

Fig. 9 - Schematic conceptual model of GW-SW interaction for the Betelico stream.

Fig. 9 - Modello concettuale schematico di interazione acque sotterranee-acque superficiali per il Torrente Betelico.

The lack of the meteoric recharge, due to a combined effect of decreasing precipitation trend and increase in storm rainfall events, was identified as the key driver of the groundwater drawdown for the last two years (2020-2021).

The alluvial aquifer piezometric level reached the most negative value in November 2020 (Fig. 4) without intercepting the stream bed anymore and feeding its baseflow. As a consequence, the persisting streams' dry condition results to be stressful for the related ecosystem belonging to the Regional Natural Park of Conero Mt.

Conclusions

According to the results of this research, a hydrological trend which may compromise the groundwater dependent ecosystem in the future years has been highlighted (Hanson et al. 2021).

The drivers that led to the water resource depletion were investigated by analysing the meteo-climatic trends, together with continuous field monitoring of the main hydrogeological parameters. Lack of meteoric recharge was identified as the key factor in the drying up of the watercourse, leading to an excessive groundwater level drop, which has been demonstrated to not be strictly related to the pumping wells present in the area.

Moreover, this case study stresses the importance of studying GW-SW interactions in a continuously changing meteo-climatic context characterised by a decreasing precipitation trend.

As further development the field monitoring system was recently implemented by installing new rain gauges, lysimeters and tensiometers to better investigate the recharge processes occurring in the area by using isotopic hydrology techniques. These new datasets will open a window to the development of numerical hydrogeological models improving the calibration procedure and enhancing detailed hydrogeological balance calculations.

Acknowledgement

The authors thank the editor and the anonymous reviewers. Figures are made with the freely available Inkscape software v.1.1.2 (https://inkscape.org/release/inkscape-1.1.2/), WaterbalANce WebApp (https://thornwaterbalance.com/), and Excel-Microsoft365®.

Competing interest

The authors declare no competing interest.

Author contributions

Collection of data, Fronzi D., Palpacelli S., Marcellini M.; data processing, Fronzi D., Gaiolini M.; interpretation of results, Fronzi D., Gaiolini M., Mammoliti E., Colombani N.; writing-original draft preparation, Fronzi D., Gaiolini M.; writing-review and editing, Fronzi D., Gaiolini M., Mammoliti E., Colombani N, Tazioli A.; visualisation, Fronzi D.; supervision, Tazioli A. All authors have read and agreed to the published version of the manuscript.

Additional information

Supplementary information is available for this paper at https://doi.org/10.7343/as-2022-574

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