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Analysis of fragmented piezometric levels records: the ARTE (Antecedent Recharge Temporal Effectiveness) approach

Analisi di serie piezometriche frammentate: il metodo ARTE (Antecedent Recharge Temporal Effectiveness)

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Riassunto

Rispetto ai parametri climatici, i record piezometrici sono spesso soggetti ad un'alta frammentazione sia spaziale che temporale, ciò a dispetto della loro importanza negli studi di carattere idrogeologico. In questo studio verrà presentata una metodologia per l'analisi di serie di dati piezometrici altamente frammentate, denominata Antecedent Recharge Temporal Effectiveness (ARTE). La metodologia è stata verificata su dati piezometrici di tre piezometri localizzati nella pianura di Lucca (Toscana, Italia) sul periodo 2016-2020. Per ciascun record piezometrico sono stati derivati dei dataset frammentari, estraendo valori ogni 30, 60, 120 giorni ed a intervalli casuali. I principali meccanismi di ricarica della falda acquifera indagata sono stati identificati nell'infiltrazione diretta delle precipitazioni e nell'infiltrazione in alveo del principale corso d'acqua dell'area. Conseguentemente, sono state acquisite le serie di dati per differenti pluviometri ed idrometri automatici presenti nell'area. La metodologia ARTE è stata applicata all'analisi tra i suddetti processi di ricarica e le variazioni del livello piezometrico utilizzando i dataset artificialmente frammentati, permettendo di identificare gli intervalli temporali potenzialmente rappresentativi dei tempi necessari alla propagazione delle variazioni piezometriche indotte dai processi di ricarica. Basandosi sulle relazioni tra livelli piezometrici e processi di ricarica identificati con il metodo ARTE, per ciascun piezometro sono state ricalcolate le serie di dati complete sul periodo considerato e sono state comparate con i dati originari. La serie piezometriche ricalcolate presentano valori di RMSE tra 0.21 m e 0.73 m e di NRMSE tra 0.08 e 0.16, particolarmente soddisfacenti se considerati rispetto a più complesse procedure di ricalcolo delle serie piezometriche basate su insiemi di dati più ampi.

Abstract

In contrast to climatic data, piezometric records are often fragmented both in time and space continuity, despite their crucial importance in groundwater studies. This work presents a new method for analysis of groundwater level vs. recharge processes relation from fragmented piezometric data, called Antecedent Recharge Temporal Effectiveness (ARTE). The ARTE method was tested on 5 year-long (2016-2020) water table level datasets measured by three automatic piezometers located in the Lucca plain (Tuscany, Italy). For each piezometric level time series, measurements were extracted every 30, 60, and 120 days, and randomly, obtaining fragmented records inlcuding less than 3% of the complete time series. As for recharge processes of the monitored aquifer, rainfall and riverbed infiltration were selected. Hence, daily rainfall and daily mean river stage time series were acquired from different automatic raingauges and hydrometers respectively. The relationship between these recharge processes and the variation of the piezometric level from the artificially fragmented datasets were evaluated with the ARTE method. The ARTE method was potentially able to identify maximum correlation time intervals, for which the recharge processes are most likely to influence the groundwater level.

Based on the analysis conducted on the fragmented piezometric datasets, the reconstruction of each piezometric time series was attempted for the study period. The simulated daily groundwater level records have RMSE values between 0.21 m and 0.73 m and NRMSE values between 0.08 and 0.16, which are satisfactory results when compared with other more complex simulation procedures, in which the training datasets are increasingly larger.

Introduction

Most of the freshwater resource on Earth, and even the least vulnerable, is represented by groundwater (Taylor and Alley 2001; UNEP/MAP-Plan Bleu 2009; Abhijit et al. 2020). However, it is a not directly perceptible resource, and therefore its sustainable protection is only possible through knowledge, specific tools, methods, and monitoring programs that make quantitatively and qualitatively perceived what naturally is not.

The knowledge of the main aquifer recharge processes and dynamics is fundamental in groundwater study and management. Many works apply correlation methods to study the hydrogeological relationship between recharge processes and aquifers response (Padilla and Pulido-Bosh 1994; Panagopoulos and Lambrakis 2006; Fiorillo and Doglioni 2010; Caren and Pavlic 2011; Duvert et al. 2015; Stevanovic 2015; Cai and Ofterdinger 2016; Chiaudani et al. 2017; Pavlic and Parlov 2019; Denic-Juki et al. 2020). Most of these applied autocorrelation and cross-correlation functions to determine aquifers recharge time and dynamics in karst areas Padilla and Pulido-Bosh 1994; Panagopoulos and Lambrakis 2006; Fiorillo and Doglioni 2010; Caren and Pavlic 2011; Stevanovic 2015; Pavlic and Parlov 2019; Denic-Juki et al. 2020). While Duvert et al. (2015), Cai and Ofterdinger (2016), and Chiaudani et al. (2017) analyzed the recharge dynamics in fractured and porous aquifers.

However, these studies require long-term and continuous groundwater level records. Unfortunately, their availability is quite rare before the second half of the 20th Century (Taylor and Alley 2001), but lots of fragmented groundwater level data are still produced at present.

In this study, we propose and apply the ARTE (Antecedent Recharge Temporal Effectiveness) to a case study. The method is aimed to analyze the relationships between groundwater levels and their influencing processes (e.g., rainfall, river stage variations, etc.), in the case of highly fragmented piezometric level records. Then, to test the effectiveness of the ARTE method, complete piezometric time series were recalculated based on the ARTE results. The reconstructed time series consistency was evaluated with RMSE (Root Mean Square Error) and NRMSE (Normalized Root Mean Square Error, normalized to the maximum amplitude) values (Moriasi et al. 2015).

Methods

Study area

The Lucca plain is located in an intramountainous basin in northwestern Tuscany (Italy, Fig. 1). The basin represents a tectonic depression, linked to the Serchio River valley graben to the NW and the Val d'Elsa valley graben to the SE (Trevisan et al. 1971; Nardi et al. 1987a). It was involved in different depositional phases, conditioning the hydrogeological structure (Trevisan et al. 1971; Nardi et al. 1987a).

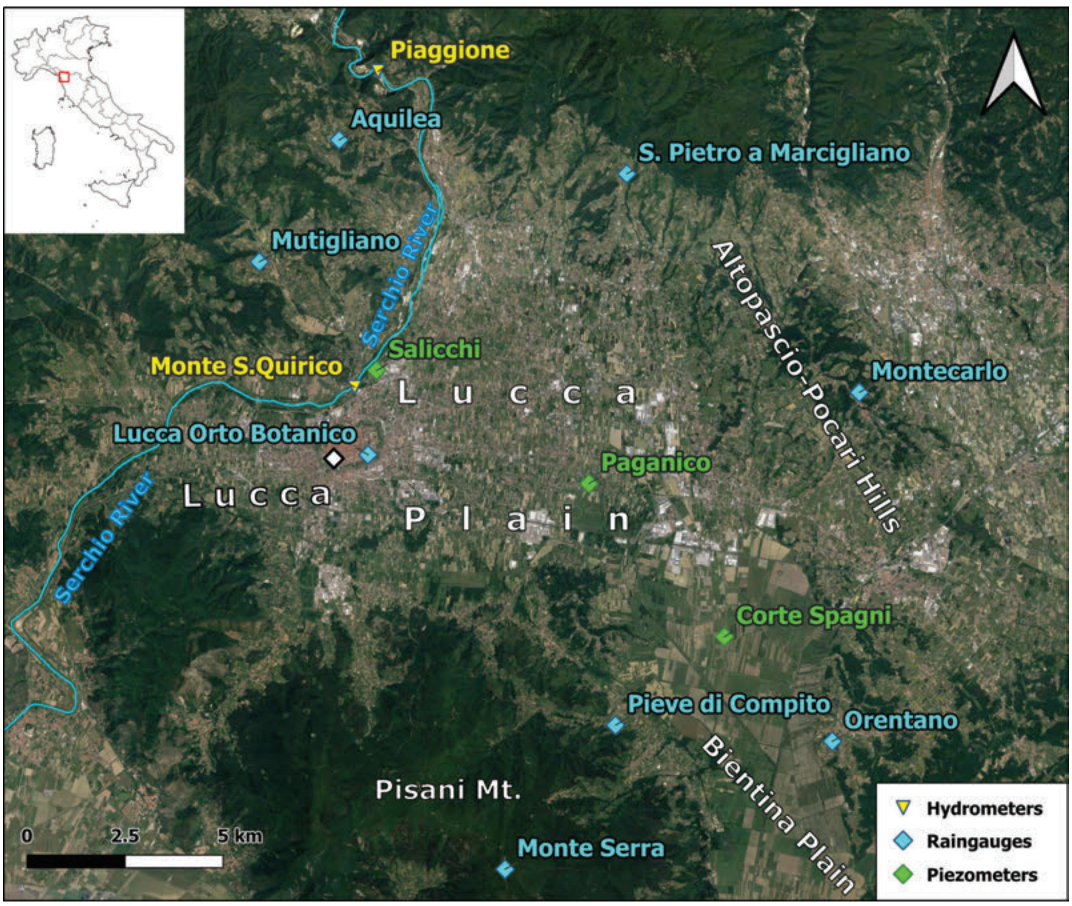

Fig. 1 - Location of the Lucca plain, including the considered raingauges, piezometers and hydrometers.

Fig. 1 - Localizzazione della pianura di Lucca in cui sono riportati pluviometri, piezometri e idrometri utilizzati in questo lavoro.

Different depositional environments occurred in the basin (Trevisan et al. 1971; Nardi et al. 1987a): lacustrine deposits (Upper Villafranchian), consisting of fine clayey sediments and coarse conglomerate, and pebbles and sands closer to the margins of the basin and at the end of this depositional cycle; pebbly and sandy fluvial and delta deposits (middle Pleistocene) overlying the previous lacustrine deposits in the eastern margin of the basin; alluvial deposits and paleo-riverbeds of the Serchio River, mainly oriented from N to SE and SW, referred to the Würm II (Nardi et al. 1987a).

The plain is characterized by a main and very transmissive aquifer composed of gravel, sand, and pebbles, including clay and silty-clayey sand lenses. The main aquifer is unconfined in the northern portion of the plain (Figs. 2 and 3), dipping southwards and resulting confined, being covered by impermeable sediments (Nardi et al. 1987a; Giannecchini et al. 2019). The aquifer thickness varies along the Lucca plain, increasing from Nord to South (from 10-15 m to 40 m), with a reduction near the margin of the Pisani Mt. (Nardi et al. 1987a). Paleo-riverbeds are present inside the main aquifer, representing thicker and more permeable flow paths. From the northern portion of the plain they run in three main directions, SE, S, and then W, SW (Nardi et al. 1987a; Giannecchini et al. 2019 - Fig. 2).

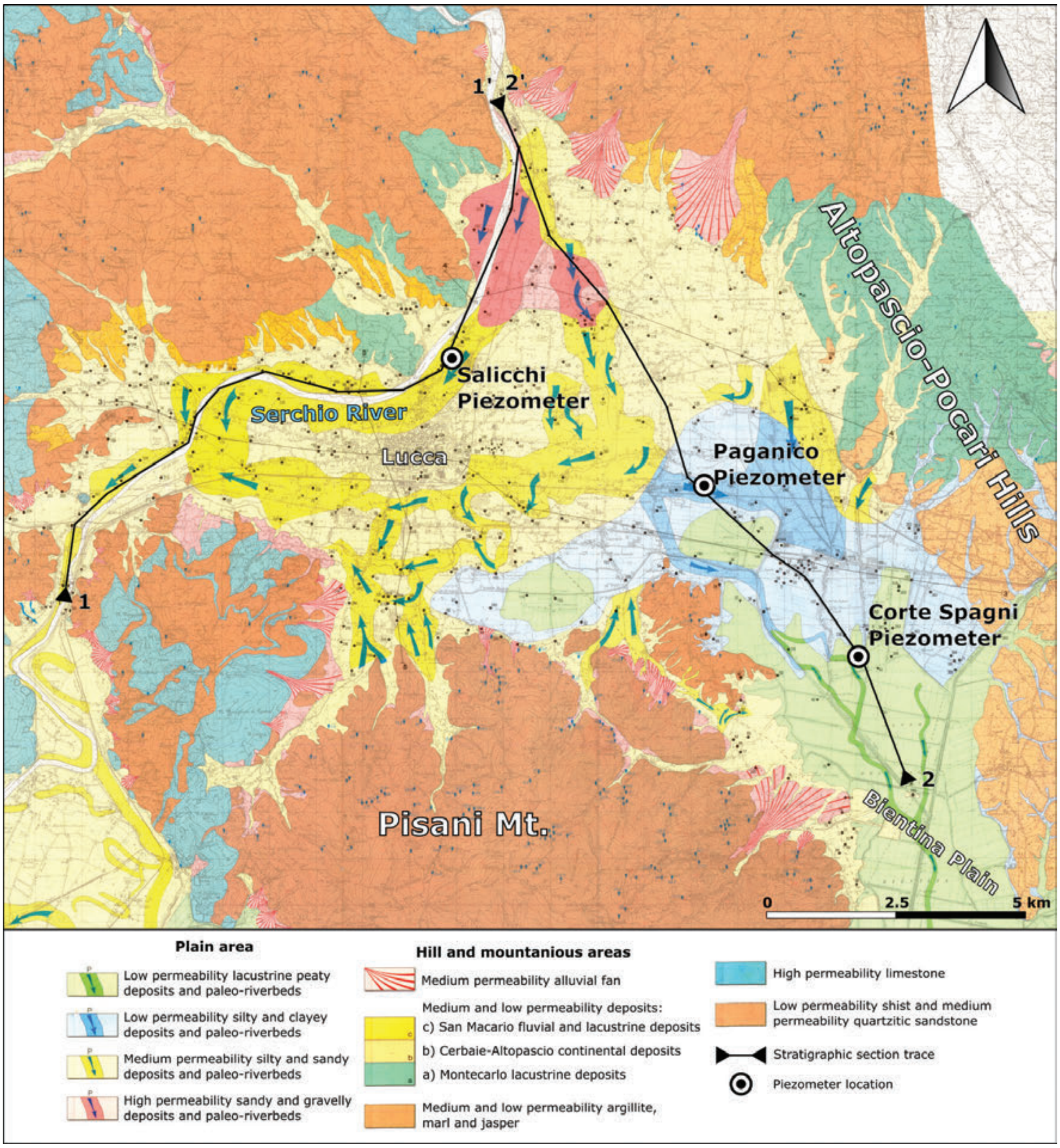

Fig. 2 - Geological map of the Lucca plain (modified after Nardi et al., 1987b).

Fig. 2 - Carta geologica della pianura di Lucca (modificata da Nardi et al. 1987b).

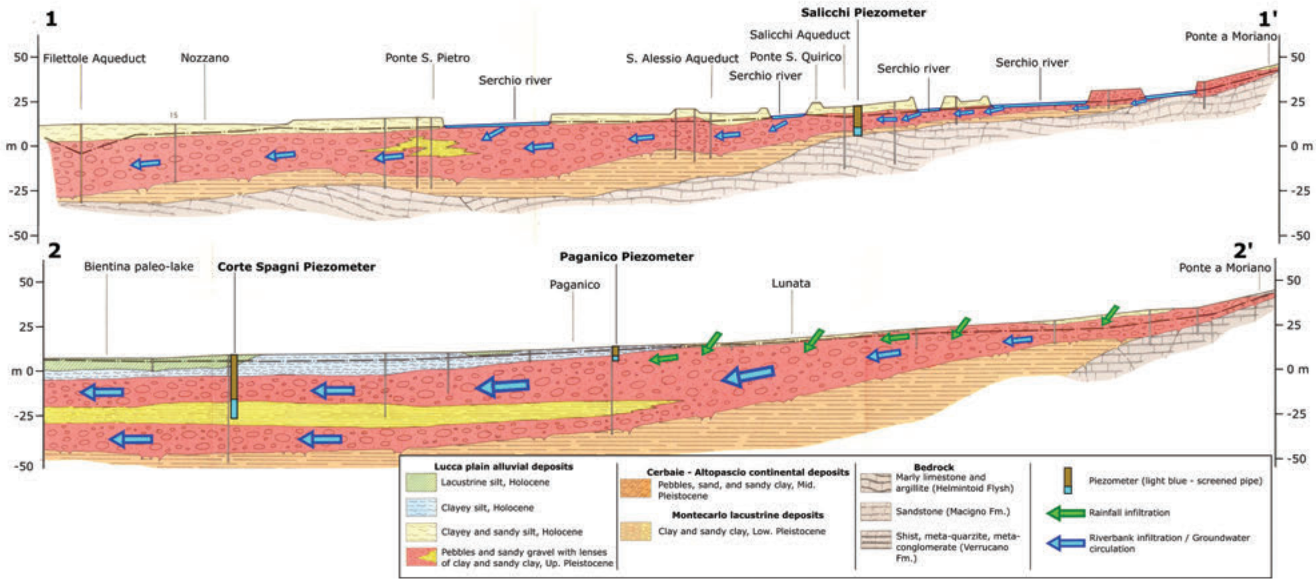

Fig. 3 - Geological cross sections of the Lucca plain. Section traces are drawn in Figure 2 (modified after Nardi et al., 1987b).

Fig. 3 - Sezioni geologiche della pianura di Lucca. Le tracce delle sezioni sono riportate in Figura 2 (modificata da Nardi et al., 1987b)..

The transmissivity of the main aquifer was estimated between 10^{-3} and 10^{-1} m^2/s, with the maximum values along the Serchio River track and the main paleo-riverbeds. Three main aquifer recharge processes were identified: direct rainfall infiltration through the plain surface, Serchio riverbed infiltration (Borsi et al. 2014), and lateral inflow from the surrounding valleys and reliefs (Nardi et al. 1987a; Giannecchini et al. 2019).

Monitoring network and dataset

The datasets were selected from the Tuscany Region Hydrologic Service (SIR, https://www.sir.toscana.it/) and cover the period 2016-2020. The selected stations include three piezometers (Salicchi, Paganico, Corte Spagni), eight raingauges (Lucca Orto Botanico, Aquilea, Mutigliano, Montecarlo, Orentano, Pieve di Compito, Monte Serra, S. Piero a Marcigliano) and two hydrometers (Monte S. Quirico, Piaggione) (Fig. 1). All data were available with a daily frequency.

The average annual rainfall in the 2016-20 period is approximately 1400 mm for the selected raingauges, with two rainfalls maximum in autumn (the main one) and spring (Fig. 4). Two hydrometers were selected along the Serchio River (Figs. 1 and 4), given the important contribution of the river itself to the main aquifer recharge (Nardi et al. 1987a).

The selected piezometers are located along an NW-SE axis through the plain in different stratigraphic contexts (Figs. 1 and 2). The Salicchi piezometer is 200 m SE from the Serchio River. It is 19 m deep, screened from 14 m from ground level (f.g.l.) to bottom, and set inside the main gravelly aquifer (Fig. 3 section 1-1'). The piezometric level (Fig. 4) shows an irregular behavior with an amplitude of about 2 m.

The Paganico piezometer is placed in the SE part of the plain (Figs. 1 and 2). It is 8 m deep and screened from 5.5 m f.g.l. to the bottom and positioned in the upper portion of the gravelly aquifer, inside one of the main paleo-riverbeds. The piezometer is located less than 1 km SE from the outcropping area of the main aquifer. The piezometric level shows a spiked behavior and an absolute amplitude of around 3-3.5 m (Fig. 4).

The Corte Spagni piezometer is located in the SE margin of the plain (Figs. 1 and 2). The piezometer is 37 m deep, screened from 25 m f.g.l. to the bottom, and intercepts the main gravelly aquifer. In this area, the main aquifer shows the thickest impermeable cover and is surrounded by the Pisani Mountains and the Altopascio-Porcari hills, recognized as the origin of the lateral recharge flow paths (Nardi et al. 1987a; Giannecchini et al. 2019). The piezometric level shows a more continuous level fluctuation and is characterized by the higher amplitude of level oscillation (about 4 m - Fig. 4).

The three selected piezometric level time series were sampled to simulate a timely scattered data record. Four samplings, three every 30, 60, and 120 days and one random, were performed.

The ARTE method

ARTE (Antecedent Recharge Temporal Effectiveness) is based on the linear correlation coefficients between two processes supposed to be one dependent on the cumulative/mean values of the other. This method is intended to be applied in cases of the dependent variable's fragmented and timely irregular data.

The method is structured as follows. Different time intervals [k] to compute the cumulative/mean values of the original independent process [$X_{(t)}=x_1, x_2......x_n$] are chosen. Cumulative [$S_{k(t)}$] and mean independent [$M_{k(t)}$] time series are calculated for each selected time interval [k], as follows:

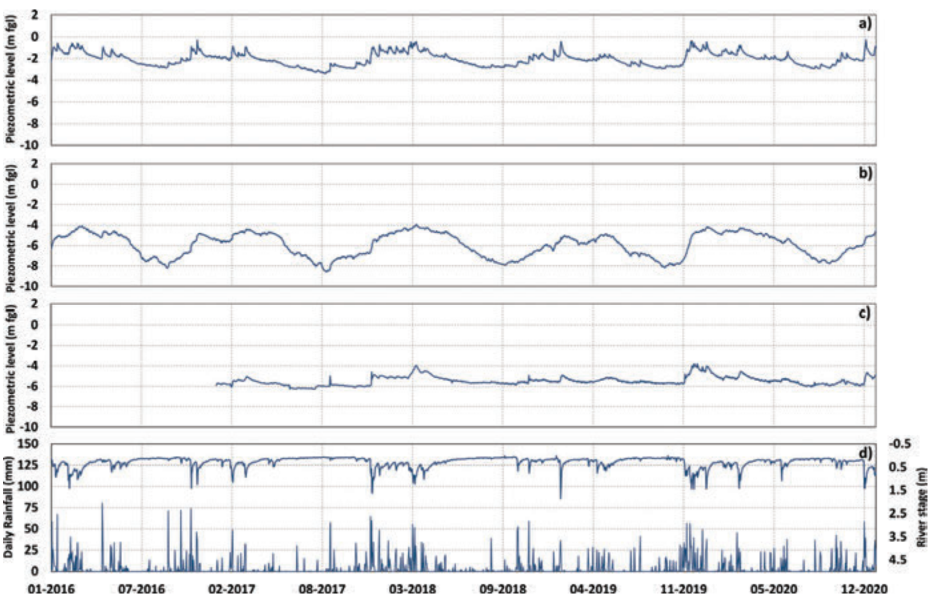

Fig. 4 - Groundwater depth (from ground level) of Corte Paganico (a), Corte Spagni (b) and Salicchi (c) (2016-2020) compared with the mean daily rainfall resulting from the eight raingauges (d), and the river stage trend at the Monte San Quirico hydrometer (d).

Fig. 4 - Livelli piezometrici (da piano campagna) dei piezometri di Corte Sapgni (a), Paganico (b) e Salicchi (c) (2016-2020), comparati con la pioggia giornaliera media degli otto pluviometri selezionati (d) e con i livelli idrometrici di Monte S. Quirico (d). (fgl: from ground level).

$$\text{with } i \geq k \;\; \mu_{ki} = \frac{\sum_{i-k}^{i} x_i}{k} \qquad \mathrm{M}_{k(t)} = (\mu_{k1}, \mu_{k2}, \ldots \mu_{k\;n-k})$$

$$\text{with } i \geq k \;\; S_{ki} = \sum_{i-k}^{i} x_i \qquad S_{k(t)} = (S_{k1}, S_{k2}, \ldots S_{k\;n-k})$$

Given a fragmented dependent process {$Y_{(t)}$} with few known ith values, its linear coefficient of determination {$r^2_{(k)}$} vs. each selected $S_{k(t)}$ and $M_{k(t)}$ corresponding ith values are computed. The $r^2_{(k)}$ values are plotted vs the k intervals. Peak of $r^2_{(k)}$ values vs. k intervals indicate for which k the $S_{k(t)}$ and $M_{k(t)}$ are more linearly explanatory of the fragmented $Y_{(t)}$.

Based on the hydrogeological setting of the area, rainfall and river infiltration (Borsi et al. 2014) were identified as the main cause of the groundwater level oscillation (Nardi et al. 1987a; Giannecchini et al. 2019). Rainfall was computed as $S_{k(t)}$ and river stage as $M_{k(t)}$. For different sites, other known processes affecting groundwater levels should be tested as $X_{(t)}$. Hence, the method was applied to the artificially fragmented piezometric level data ($Y_{(t)}$) and rainfall and hydrometric time series ($X_{(t)}$). The k values corresponding to the peak of $r^2_{(k)}$ were considered as the propagation time of the recharge impulse through the aquifer to the monitored piezometers. The selected k intervals were: 3, 7, 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180, 195, 210, 225, 240, 255, 270, 285, 300, 315, 330, 345, and 360 days.

The ARTE method was also applied to the complete piezometric records. Hence, a comparison between $r^2_{(k)}$ and k from fragmented and complete piezometric series was performed.

To test the effectiveness of the ARTE method results, complete piezometric time series were derived from rainfall and hydrometric data. Linear equation of $Y_{(t)}$ vs $S_{k(t)}$ and $M_{k(t)}$ with higher $r^2_{(k)}$ were selected. The piezometric time series were computed by applying the such equations to the relative $S_{k(t)}$ and $M_{k(t)}$. Then, the ARTE groundwater level reconstruction quality was estimated using RMSE (Root Mean Square Error) and NRMSE (Normalized root mean squared error) (Moriasi et al. 2015), as follows:

$$RMSE = \sqrt{\sum \left(\frac{\left(\hat{h}_i - h_i\right)^2}{N} \right)}$$

$$NRMSE = \frac{\sqrt{\sum \left(\frac{\left(\hat{h}_i - h_i\right)^2}{N} \right)}}{A}$$

where: $\hat{h}_i$, h_i - predicted and observed groundwater level at time i; N - number of groundwater level observations; A - maximum amplitude of the groundwater level computed as difference between the maximum and minimum levels recorded in the studied period.

The ARTE analysis and the simulation were executed by Visual Basic for Application (VBA) language coded on Microsoft Excel (2018).

Results

Figure 5 shows the results of the ARTE method for the Corte Spagni piezometer. In the graphs related to sampled piezometric level vs. rainfall (as $S_{k(t)}$) interval relationship, the $r^2_{(k)}$ vs. k values appear similar to those of the complete relationship between piezometric level and rainfall. Only the $r^2_{(k)}$ values with the Montecarlo rainfall diverges from the complete piezometric level vs. rainfall interval relationship, probably due to the lower extension of the Montecarlo rainfall time series. The $r^2_{(k)}$ peak values are set between 120 and 180 k, with $r^2_{(k)}$ between 0.4 and 0.7.

In the two graphs for the sampled Corte Spagni piezometric level vs. river stage (as $M_{k(t)}$) relationship, the $r^2_{(k)}$ vs. k shows a similar trend to the complete piezometric level vs. river stage, except for the randomly sampled piezometric data. The $r^2_{(k)}$ peak values for the selected piezometric level vs. river stage are set between 60 and 100 k, with $r^2_{(k)}$ between 0.8 and 0.5.

For the Paganico piezometer, the distribution of $r^2_{(k)}$ values for sampled piezometric level vs. rainfall (as $S_{k(t)}$) and $r^2_{(k)}$ values for the complete piezometric level vs. rainfall interval show a general similar shape, even if more differences are recognizable (Fig. 6).

Also in this case, the $r^2_{(k)}$ distribution with the Montecarlo rainfall diverges from the complete piezometric level vs. rainfall. The $r^2_{(k)}$ peak values for the selected piezometric level vs. cumulated rainfall relationship are between 80 and 120 k. The $r^2_{(k)}$ peak values are set between 0.5 and 0.9. Moreover, for the Monte Serra, Orentano, and Lucca Orto Botanico raingauges there is a secondary $r^2_{(k)}$ peak between the 20 and 40 k.

In the two graphs for sampled Paganico piezometric level vs. river stage (as $M_{k(t)}$), the distribution of the $r^2_{(k)}$ vs k shows different shapes and absolute values between Monte San Quirico and Piaggione hydrometers. In the Monte San Quirico graph, the piezometric level sampled every 30, 60 and 120 days shows $r^2_{(k)}$ peak values for the 3 and 30-75 k river stage average, respectively. Only, the $r^2_{(k)}$ vs k values for randomly sampled piezometric level have a shape comparable to the complete piezometric level vs. river stage.

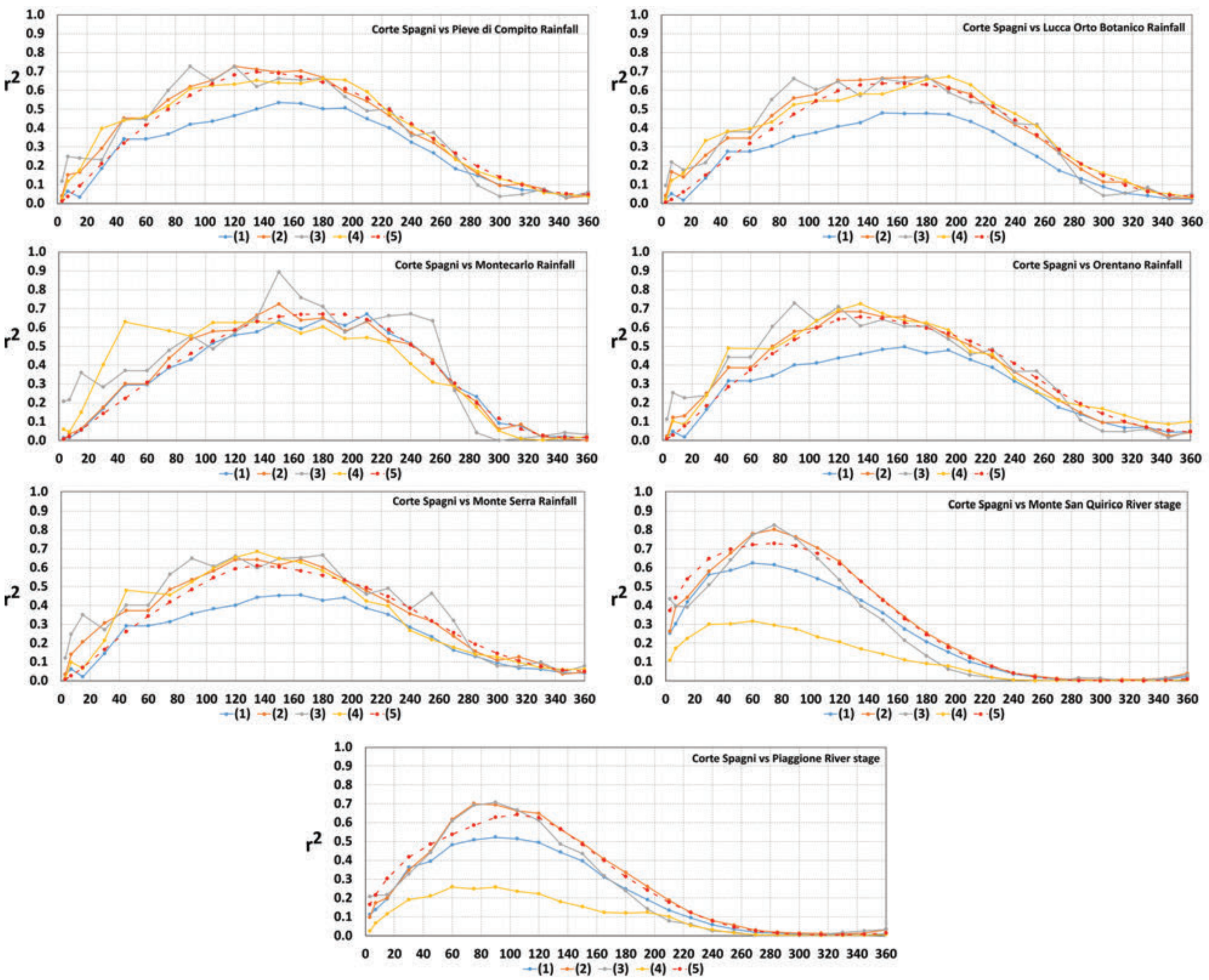

Fig. 5 - $r^2_{(k)}$ vs. k for Corte Spagni piezometric level sampled every (1) 30 days, (2) 60 days, (3) 120 days, (4) randomly and (5) for all the piezometric level time series vs. the cumulated rainfall/river stage mean of the selected k intervals.

Fig. 5 - Valori di $r^2_{(k)}$ per i livelli piezometrici di Corte Spagni campionati ogni (1) 30, (2) 60, (3) 120 giorni, (4) casualmente e (5) per la serie di livelli piezometrici completa rispetto alla pioggia cumulata ed al livello idrometrico medio degli intervalli *k* selezionati.

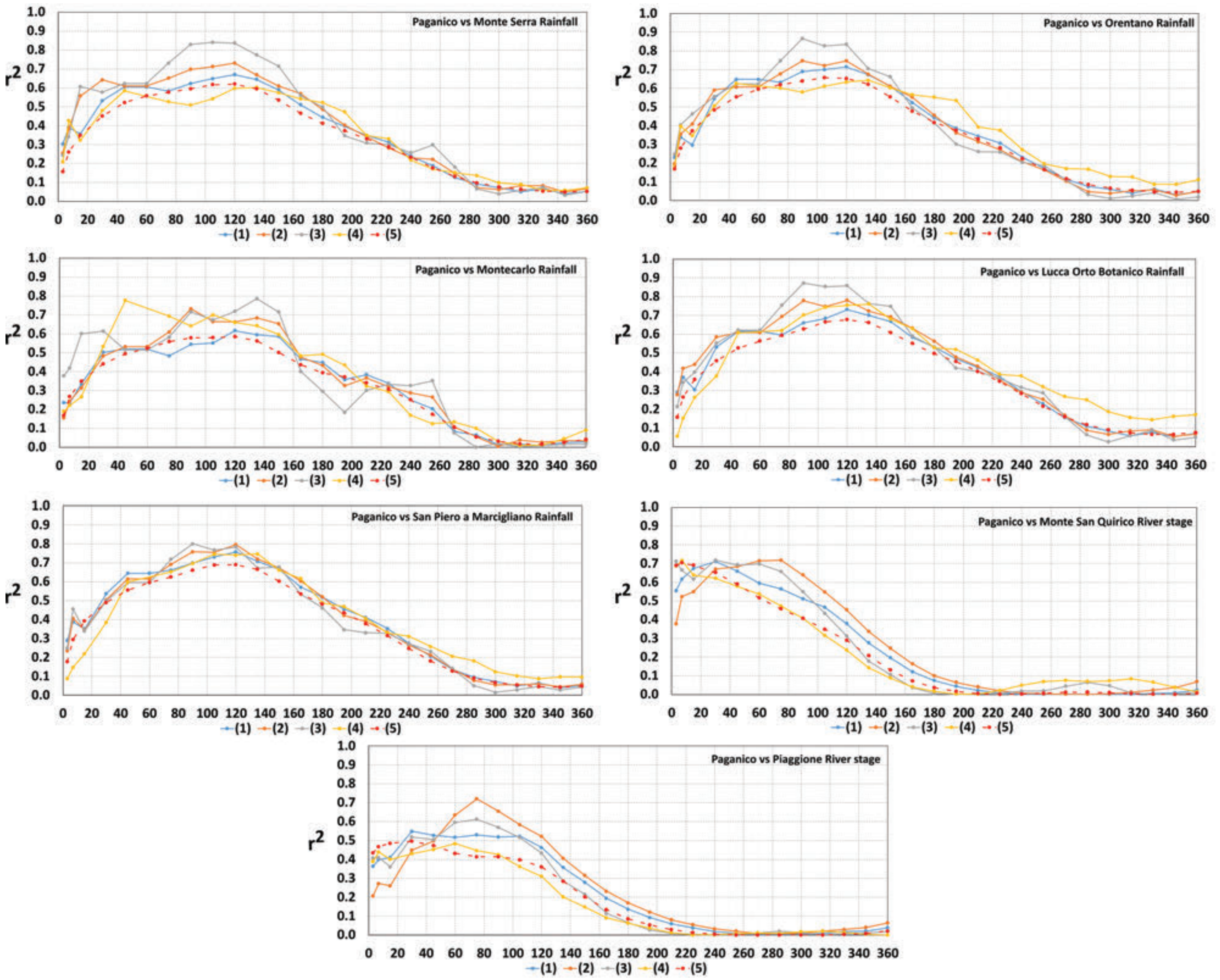

Fig. 6 - $r^2_{(k)}$ vs. k for the Paganico piezometric level sampled (1) every 30 days, (2) every 60 days, (3) every 120 days, (4) randomly and for (5) all the piezometric level time series vs. the cumulated rainfall/river stage mean of the selected k intervals.

Fig. 6 - Valori di $r^2_{(k)}$ per i livelli piezometrici di Paganico campionati ogni (1) 30, (2) 60, (3) 120 giorni, (4) casualmente e (5) per la serie di livelli piezometrici completa rispetto alla pioggia cumulata ed al livello idrometrico medio degli intervalli *k* selezionati.

Figure 7 shows the results of the ARTE method applied to the Salicchi piezometer. The distribution of $r^2_{(k)}$ values for sampled piezometric level vs. rainfall (as $S_{k(t)}$) relationship and the $r^2_{(k)}$ values for the complete piezometric level vs. rainfall interval relationship are quite similar. The Salicchi piezometric level was analyzed with respect to the Mutigliano, Lucca Orto Botanico, and Aquilea raingauges due to the geographical proximity. For all the three raingauges the $r^2_{(k)}$ maximum values fall in the interval between 30 and 165 k. In this interval some details can be highlighted: a first peak between 45 and 60 k is observable, followed by a slight decrease of the $r^2_{(k)}$ values for the k equal to 75; another maximum of $r^2_{(k)}$ values is present at 120-150 k, followed by a slow decrease. The maximum $r^2_{(k)}$ values are between 0.5 and 0.85.

Moreover, for the Salicchi piezometer, the two graphs for sampled piezometric level vs. river stage (as $M_{k(t)}$) relationship show different $r^2_{(k)}$ distribution shapes and absolute values between the Monte San Quirico and Piaggione hydrometers. In the Piaggione graph, the piezometric level sampled every 30, 60 and 120 days shows $r^2_{(k)}$ maximum values at 30 and 105, 45-60, 30-60 k, respectively. The piezometric level randomly sampled does not show a clear maximum value. In the Monte San Quirico graph, the $r^2_{(k)}$ distribution for sampled piezometric level vs. river stage and the $r^2_{(k)}$ values for the complete piezometric level vs. river stage have similar shapes. The $r^2_{(k)}$ values show a peak for 15 and 30 previous days river stage average, respectively.

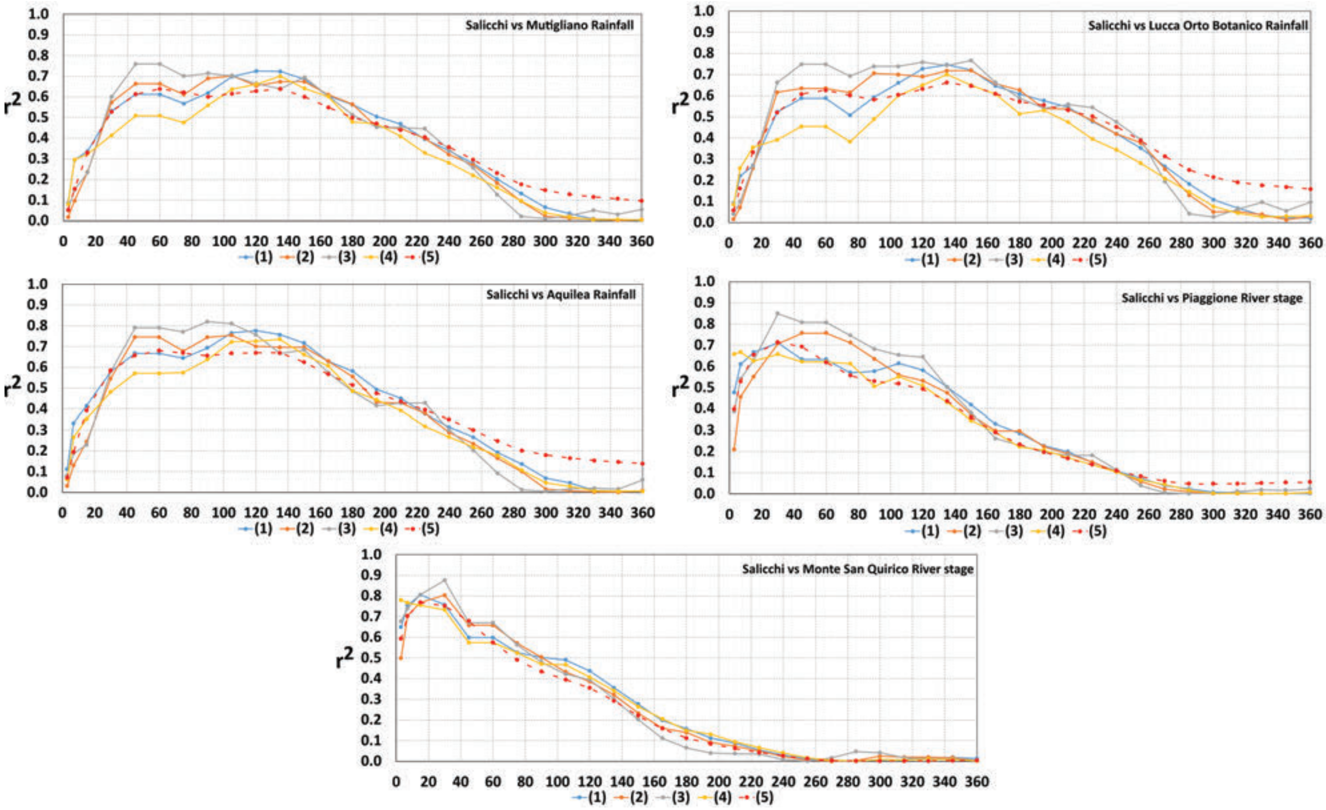

Fig. 7 - $r^2_{(k)}$ values for Salicchi piezometric level sampled (1) every 30 days, (2) every 60 days, (3) every 120 days, (4) randomly and for (5) all the piezometric level time series vs. the rainfall sum/river stage mean of the selected k intervals.

Fig. 7 - Valori di $r^2_{(k)}$ per i livelli piezometrici di Salicchi campionati ogni (1) 30, (2) 60, (3) 120 giorni, (4) casualmente e (5) per la serie di livelli piezometrici completa rispetto alla pioggia cumulata ed al livello idrometrico medio degli intervalli *k* selezionati.

Modeling of piezometric level time series from ARTE analysis

The best-correlated rainfall $S_{k(t)}$ and river stage $M_{k(t)}$ were selected. The three piezometric level time series were recalculated by applying the higher $r^2_{(k)}$ values correlation equation to the rainfall $S_{k(t)}$ and river stage $M_{k(t)}$. For the rainfall $S_{k(t)}$, 150, 105, and 135 k were selected for Corte Spagni, Paganico, and Salicchi piezometers, respectively. For the river stage $M_{k(t)}$, the 75, 45, and 15 *k* were selected for Corte Spagni, Paganico, and Salicchi piezometers, respectively. The Lucca Orto Botanico raingauge and the Monte San Quirico hydrometer time series were selected for the piezometer level reconstruction.

Given the hydrogeological settings, the Corte Spagni piezometer recalculated time series is obtained as the mean of the recalculated time series from rainfall and river stage (Fig. 8), the Paganico piezometer recalculated time series is derived only from rainfall data (Fig. 9), and the Salicchi piezometer recalculated time series is derived only from river stage data (Fig. 10). Figures 8, 9, and 10 show the differences between original and recalculated data.

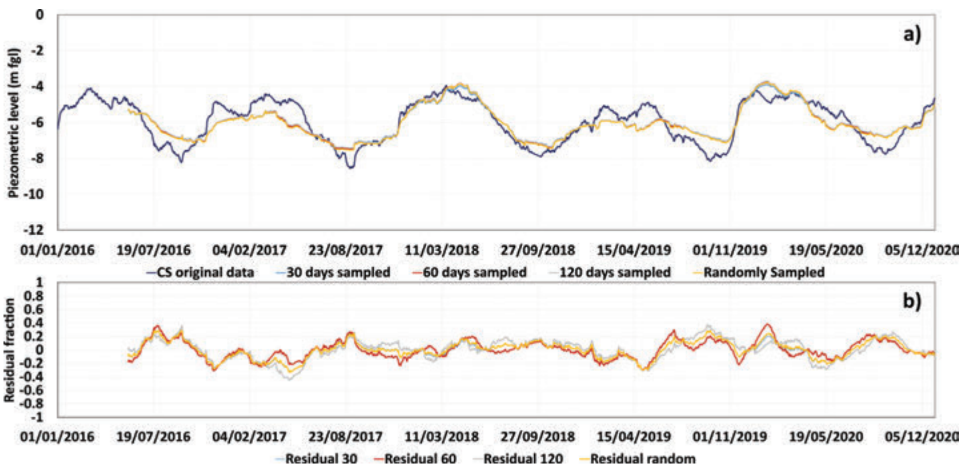

Fig. 8 - a) original and recalculated data for the Corte Spagni piezometer. b) Deviation of recalculated data from the original ones reported as fraction of the original data amplitude.

Fig. 8 - a) Livelli piezometrici originali e ricalcolati per il piezometro di Corte Spagni. b) deviazione tra dati ricalcolati ed originali espresso come frazione della massima ampiezza reale. (fgl: from ground level).

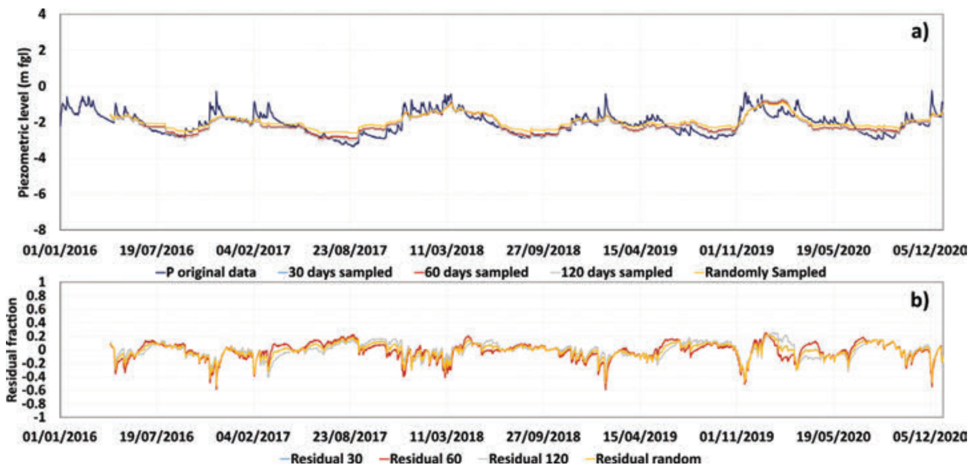

Fig. 9 - a) original and recalculated data for the Paganico piezometer. b) Deviation of recalculated data from the original ones reported as fraction of the original data amplitude.

Fig. 9 - a) Livelli piezometrici originali e ricalcolati per il piezometro di Paganico. b) deviazione tra dati ricalcolati ed originali espresso come frazione della massima ampiezza reale. (fgl: from ground level).

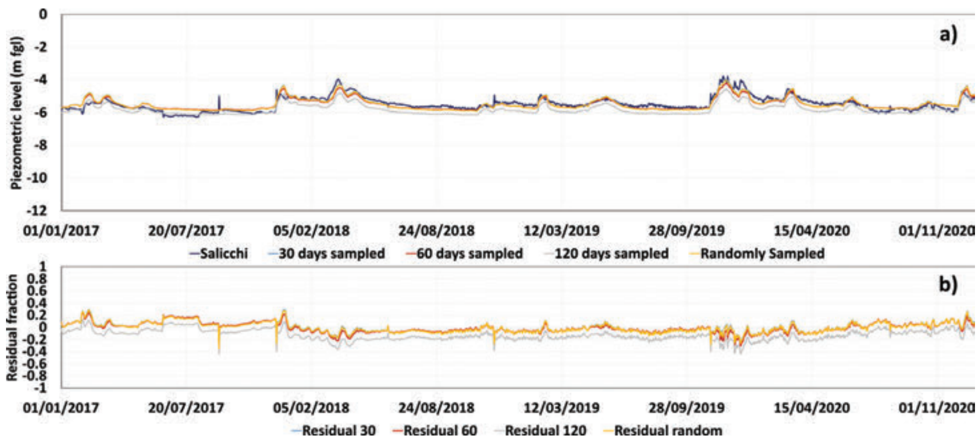

Fig. 10 - a) original and recalculated data for the Salicchi piezometer. b) Deviation of recalculated data from the original ones reported as fraction of the original data amplitude.

Fig. 10 - a) Livelli piezometrici originali e ricalcolati per il piezometro di Salicchi. b) deviazione tra dati ricalcolati ed originali espresso come frazione della massima ampiezza reale. (fgl: from ground level).

Discussion

Given the thicker and lower permeability cover in the area of the Corte Spagni piezometer, direct infiltration of rainfall seems to represent a minor recharge factor of the main aquifer. The lateral continuity of this aquifer towards NW implies a possible effective connection with the Serchio River recharge, as recognized by Nardi et al. (1987a). The slighter variations (Fig. 4) of the groundwater level of the Corte Spagni piezometer seem to agree with its deeper and farther from the river position. From the ARTE analysis, the *k* around 120-180 and 60-100 days correspond to the higher $r^2_{(k)}$ values for rainfall and river stage, respectively. The higher $r^2_{(k)}$ values suggest that the cumulated rainfall and the mean river stage from the antecedent 120-180 and 60-100 days, respectively, are most likely to influence the groundwater level at Corte Spagni.

The Salicchi piezometer is located near the Serchio River and the influence of the river stage variation is probably dominant on the piezometric level. From the ARTE analysis, the k around 120-150 corresponds to the higher $r^2_{(k)}$ values for rainfall. For the river stage relationship, the higher $r^2_{(k)}$ values set around 40-60 and 15-30 k for the Piaggione and Monte San Quirico hydrometers. Based on these results, the Salicchi piezometer shows shorter influence periods from the river. This seems consistent with the river-piezometer proximity.

The Paganico piezometer is located near an area that can be quickly recharged due to rainfall direct infiltration and on the faster path of river infiltration pulses, making it more difficult to distinguish the different recharge processes. The spiked shape of the Paganico piezometric level time series (Fig. 4) suggests a rapid connection between the impulsive recharge mechanism and groundwater level. From the ARTE analysis, the *k* around 80-120 corresponds to the higher $r^2_{(k)}$ values for rainfall. This suggests a faster rainfall to groundwater connection, as supposed from the hydrogeological setting. For the river stage relationship, the $r^2_{(k)}$ values largely differ among the 30, 60, and 120, and randomly sampled piezometric data. These k values are also considered as maximum time lags between the variation of the rainfall/river stage processes and the groundwater level variations.

Figures 5, 6, and 7 highlight that the $r^2_{(k)}$ vs. *k* obtained for the sampling datasets are comparable in shape and values to the $r^2_{(k)}$ vs *k* obtained using the complete piezometric time series. Consequently, the use of incomplete piezometric level data seems to return similar results to the complete piezometric time series with the ARTE method.

Some exceptions regard the Paganico piezometric level vs. both river stage time series (Fig. 6) and the Corte Spagni randomly sampled piezometric data vs. river stages data (Fig. 5). For the Paganico piezometer, the difference between sampled and complete piezometric data vs. river stage $r^2_{(k)}$

values is possibly due to a shorter relationship interval between river stage and piezometric level variations. For the Corte Spagni piezometer, the difference is possibly due to the time distribution of the randomly sampled piezometric data.

Figure 11 shows an example of Corte Spagni piezometric level vs. cumulative rainfall for the previous 120 days and the differences between $r^2_{(k)}$ values for 30, 60, 120 days sampled, randomly sampled, and complete time series. The distribution of the sampled piezometric data over all four seasons allowed to get better information on the complete distribution, whereas data of different seasons are quite separated inside the graph and seem to be representative of the complete distribution. A seasonally complete data sampling becomes necessary to obtain higher $r^2_{(k)}$ values and more representative linear regression of the recharge-piezometric level relationship.

Simulation performance

For the Corte Spagni and Paganico piezometers, the differences between simulated values from 30, 60, and 120 days and randomly sampled piezometric data are not particularly accentuated. In particular, for the Corte Spagni piezometer the RMSE and NRMSE range from 0.62 m to 0.73 m and from 0.13 to 0.16, respectively (Tab.1). The recalculated data related to the Paganico piezometer are not able to describe the spiked variability of the piezometric level. However, the long period fluctuation is well approximated. The RMSE and NRMSE range from 0.33 m to 0.39 m and from 0.11 to 0.12, respectively (Tab. 1). For the Salicchi piezometer, the best-simulated values are obtained for 30, 60 days and randomly sampled piezometric data. Simulated values from 120 days of sampled piezometric data show systematic underestimation since December 2018. For the Salicchi piezometer, the RMSE and NRMSE range from 0.21 m to 0.39 m and from 0.08 to 0.16, respectively (Tab. 1). The Salicchi piezometer simulation, obtained for 30, 60 days and randomly sampled data, has the lower misestimation and NRMSE. The deviation of calculated values from original data is practically always less than 20% of the maximum variability, and often less than 10%. Such good approximation is probably due to the strong relationship between the Serchio River stage and the piezometric level in the Salicchi piezometer area, in agreement with the hydrogeological setting.

Tab. 1 - RMSE (in m) and NRMSE values for simulated groundwater level of Corte Spagni, Paganico and Salicchi piezometers for 30, 60, 120 days and randomly sampled data.

Tab. 1 - Valori di RMSE (in m) e NRMSE per le serie piezometriche simulate per I piezometri Corte Spagni, Paganico e Salicchi relativi ai valori campionati ogni 30, 60, 120 giorni e casualmente.

Sampling interval	Corte Spagni		Paganico		Salicchi	
	RMSE	NRMSE	RMSE	NRMSE	RMSE	NRMSE
30 days	0.63	0.14	0.33	0.11	0.21	0.08
60 days	0.63	0.14	0.39	0.12	0.21	0.09
120 days	0.73	0.16	0.35	0.11	0.39	0.16
Random	0.62	0.13	0.34	0.11	0.21	0.08

Given the training datasets spanning from 1 to 3% of the original data, the obtained NRMSE values, never above 0.16, seem to validate the effectiveness of the ARTE method in identifying recharge mechanisms for groundwater. Moreover, it is worth noting the daily frequency of the reconstructed groundwater records is considerably lower than the annual frequency of the reconstructions by Ferguson and Georges (2003) and Huang et al. (2019).

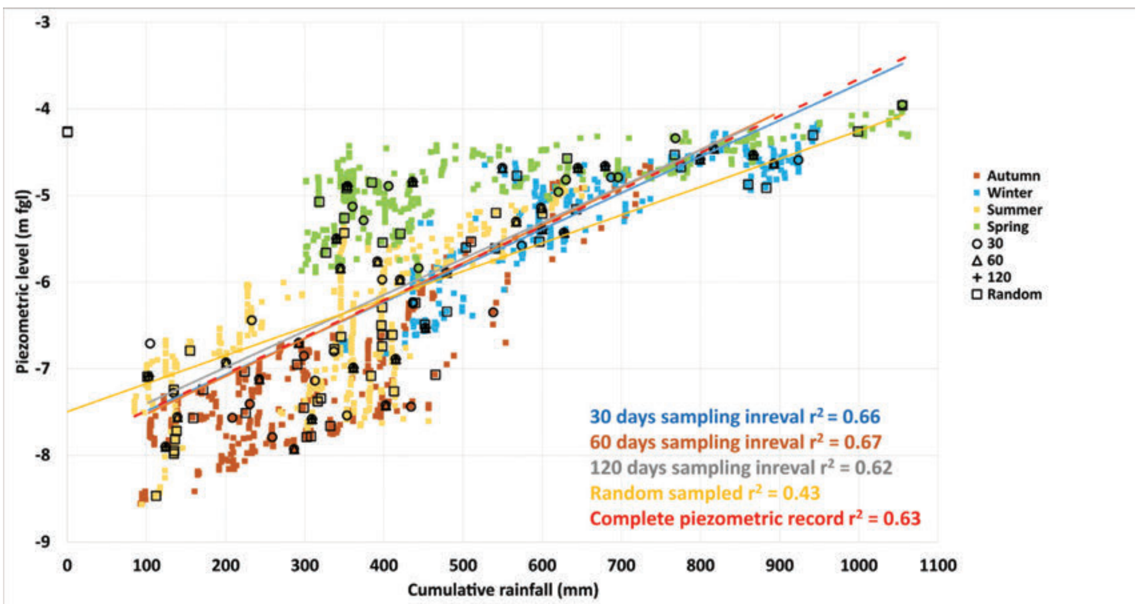

Fig. 11 - Complete piezometric levels for Corte Spagni piezometer vs. cumulative rainfall of the 120 days preceding each piezometric data. Sampled data are highlighted and the corresponding linear regression and $r^2_{(k)}$ are shown.

Fig. 11 - Livelli piezometrici di Corte Spagni rispetto alla pioggia cumulata dei 120 giorni precedenti ad ogni dato piezometrico. Sono evidenziati i dati estratti dalla serie completa e le rispettive rette di regressione sono riportate con il valore di $r^2_{(k)}$ associato. (fgl: from ground level).

Conclusions

In this work, we presented the new ARTE (Antecedent Recharge Temporal Effectiveness) method. The method is intended to evaluate the groundwater vs. recharge processes relationship in cases of highly fragmented piezometric level records. The method was tested on artificially time fragmented groundwater level datasets (the fragmented records represent about the 3% of complete time series).

The ARTE method seems to be able to identify time intervals of higher correlation between the piezometric level and recharge processes, with lower limits of 10-15 days. Such identified intervals were interpreted as recharge processes periods more likely to influence the groundwater level and possibly maximum time of propagation of the recharge process fluctuation. Although the identified time intervals are quite large, it must be noted the reduced datasets (less than 3% of the complete data) from which the information is derived.

The method results subjected to time dispersion of the sampled piezometric data along the years. To obtain a satisfactory representation of the relationship between groundwater and recharge processes, the sampled data should be distributed over all the seasonal variability.

For the proposed test site, the rainfall and river level were assumed as the main drivers of groundwater level fluctuations. Probably, if other processes influencing groundwater level are present (e.g., pumping wells), the $r^2_{(k)}$ vs k values would be lowered or at least affected.

Based on the analysis of fragmented datasets elaborated by the ARTE method, a simulation of the complete piezometric records was attempted. The simulated piezometric level time series are characterized by low values of NRMSE (between 0.08 and 0.16), indicating a reasonably good reconstruction of the piezometric time series in relation to other simulation methods (Culibaly et al. 2001; Tsanis et al. 2008; Taormina et al. 2012; Ghose et al. 2018; Huang et al. 2019). However, the method improvement and validation need to be test in other settings, with different groundwater level influencing processes.

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Competing interest

The authors declare no competing interest.

Author contributions

Matteo Nigro: Conceptualization, Methodology, Formal analysis, Writing, Reviewing. Michele Ambrosio: Conceptualization, Methodology, Work supervision, Writing, Reviewing. Maria Teresa Fagioli: Conceptualization, Methodology, VBA coding, Work supervision, Writing, Reviewing. Chiara Curcio: Conceptualization, Methodology. Roberto Giannecchini: Work supervision, Writing, Reviewing.

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