

Relationship between seismicity and water level of the Pertusillo reservoir (southern Italy)

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(Received: September 26, 2014; accepted: June 8, 2015)

ABSTRACT The Pertusillo reservoir, located in the High Agri Valley (southern Italy), represents an example of a site affected by continued reservoir-induced seismicity. Although it has been shown that annual fluctuation can be considered the main forcing of the induced seismicity in this area, an investigation of the relationships between the seismicity and some water level parameters of the Pertusillo reservoir carried out in this paper. The aim is to understand, apart from the annual fluctuation, if one or more of these parameters play a dominant role in inducing seismicity year after year SW of the reservoir. The findings of this study suggest that the exceedance of water levels over the previous maxima did not trigger any historical earthquake. In addition, the daily water level rate and the duration for which the maximum water level is maintained do not play any significant role in inducing seismicity. The maximum amplitude of water level change in a hydrological cycle as low as 8 m appears to be large enough to trigger the seismicity SW of the Pertusillo reservoir, whereas higher maximum amplitudes of water level in a hydrological cycle seem not to increase the seismicity rate. Furthermore, it is shown that a long-lasting increase of the water level may lead to induced earthquakes with larger magnitude. Finally, it is demonstrated that the geology of the area SW of the reservoir may provide favourable conditions for the water level fluctuations to induce seismicity in that region, whereas a different geology to the NE of the reservoir is the cause of negligible pore pressure increase.

Key words: induced seismicity, water level, southern Italy.

1. Introduction

It is recognized worldwide that surface-water reservoirs, as well as other energy technologies (National Research Council, 2013), may play a key role in the processes related to the triggering of earthquakes. The basic mechanisms of reservoir-induced seismicity (i.e., the weight of the water and the diffusion of pore pressure) were first investigated by Bell and Nur (1978) by using analytical models. Nevertheless, the interaction between surface-water reservoirs and observed seismicity is still not well understood due to the complexity of the analysed system

(e.g., site geology, characteristics of faults, fluid content) and the lack of a significant statistical population of observations. Demonstrating a clear reservoir perturbation on stress state in the surrounding crust is highly problematic when single or few significant earthquakes occur after the initial impoundment of the reservoir, particularly if an inadequate monitoring of the site has been planned before the actual operation. As an example, the role of the Zipingpu reservoir impoundment in the occurrence of the May 12, 2008 M_w 7.9 earthquake in Wenchuan (China's Sichuan Province) is still debated (e.g., Klose, 2013, and references therein), despite both Deng *et al.* (2010) and Gahalaut and Gahalaut (2010) having presented evidence that the reservoir operation probably did not trigger the earthquake.

When the occurrence of earthquakes near a reservoir site is observed over a longer period, there is the opportunity to understand how the reservoir perturbation may affect the stability of faults over time. This particular phenomenon has been classified in the literature as protracted (Talwani, 1997) or continued (Gupta, 2002) reservoir-induced seismicity. Examples of this type of seismicity can be found near large reservoirs, such as the Koyna-Warna (Gupta and Combs, 1976) or the Nurek Dam (Simpson and Negmatullaev, 1981), as well as small reservoirs, such as the Açú (El Hariri *et al.*, 2010) or the Pertusillo (Stabile *et al.*, 2014a).

The Pertusillo reservoir is located in the High Agri Valley (hereafter HAV), southern Italy, and its impoundment started in October 1963 behind an arc-gravity dam with a height of 95 m from the riverbed. Even if the Pertusillo is a small reservoir, with a maximum volume of about 1.55×10^8 m³, the seasonal annual fluctuation (i.e., the hydrological cycle) of the water level is about 10-15 m and, in a few cases, it has reached higher values up to 50 m (Fig. 1a). This fluctuation produces pressure perturbations of about 0.10-0.15 MPa and up to 0.5 MPa at the bottom of the reservoir. Considering several years of observations, Stabile *et al.* (2014a) and Telesca *et al.* (2014) statistically demonstrated continued reservoir-induced seismicity SW of the Pertusillo that principally occurs between March and July of each year. The time-frequency representation of the water level (Fig. 1b) computed through the S-transform (Stockwell *et al.*, 1996) confirms that the annual fluctuation, which is the main forcing of the induced seismicity (Telesca *et al.*, 2014), is also the dominant period of the water level time series over the 50 years of reservoir operation.

This paper is focused on the analysis of the relationships between the seismicity and several water level parameters of the Pertusillo reservoir with the aim of understanding, apart from the annual fluctuation, if one or more of them play a dominant role in inducing seismicity year after year SW of the reservoir. Following Durá-Gómez and Talwani (2010), we investigated the influence on the observed seismicity of: the exceedance of water levels over the previous maxima, H_{max} ; the water level h ; the daily water level rate, dh/dt ; the maximum amplitude of water level change in a hydrological cycle, $max[dh]$; and the duration for which the maximum water level is maintained $T(h_{max})$.

2. Seismotectonic framework and seismicity data

The HAV is a NW-SE trending intermontane basin formed during the Quaternary age along the axial zone of the southern Apennines thrust belt chain in southern Italy (Fig. 2a). This basin is ~ 30 km long and 12 km wide and is filled by Quaternary continental deposits

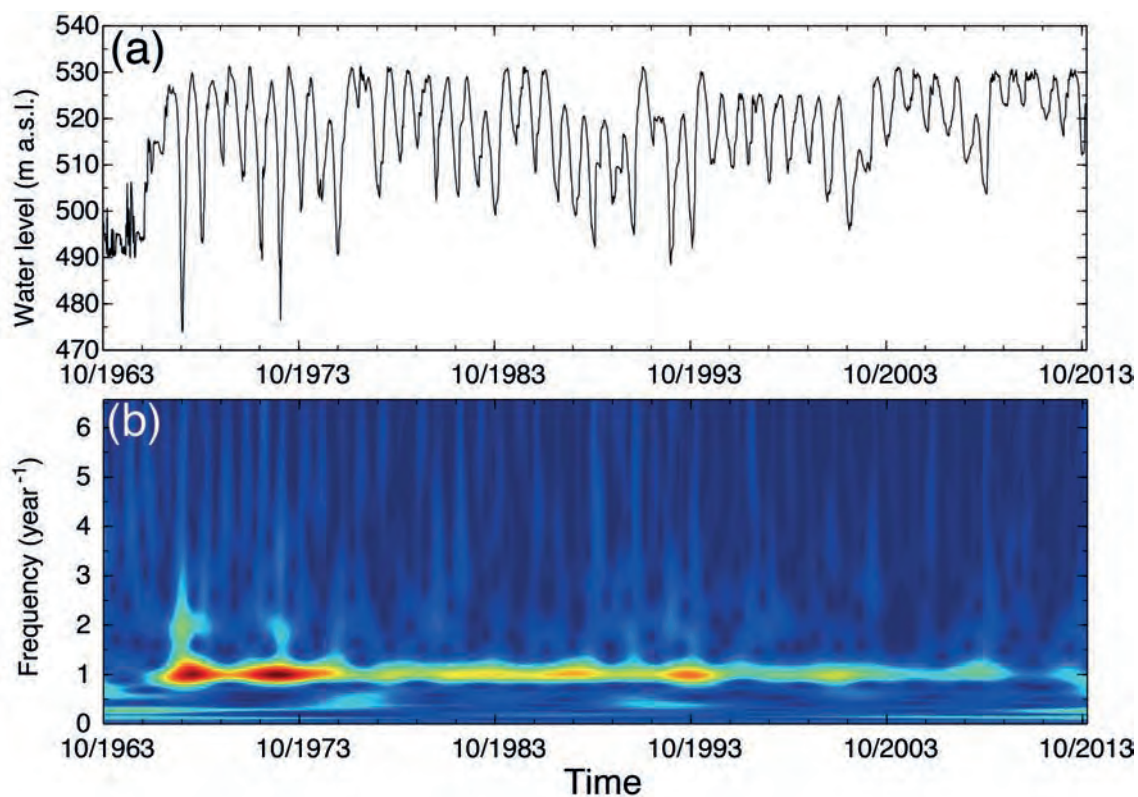


Fig. 1 - Water level of the Pertusillo reservoir from October 1963 to October 2013 (a), and its time-frequency representation (b).

which cover down-thrown pre-Quaternary substratum of the Apennines Chain. According to the Italian seismic classification, the seismic hazard of the HAV is very high, with an expected maximum acceleration for an exceedance probability of 10% in 50 years within 0.25 and 0.275 g. Therefore, it is one of the areas of Italy with the highest seismogenic potential, as confirmed by the occurrence in the valley of one of the most destructive historical earthquakes in Italy, the 1857 M_w 7.0 Basilicata earthquake (Mallet, 1862). The seismogenic fault system capable of producing large events such as the M_w 7.0 Basilicata earthquake is alternatively associated with the following: 1) the Monti della Maddalena Fault System (MMFS) (Maschio *et al.*, 2005), and 2) the Eastern Agri Fault System (EAFS) (Cello *et al.*, 2003).

The Pertusillo reservoir is located in the south-eastern sector of the HAV (Figs. 2a and 2b). The pre-Quaternary substratum of this area is constituted of allochthonous units onto 6-7 km thick Mesozoic-Tertiary carbonate sequence of the Apulia Carbonate Platform, which is stratigraphically overlain by Pliocene terrigenous marine deposits. SW of the Pertusillo reservoir, the allochthonous units are mainly constituted of Mesozoic-Cenozoic shallow-water and slope carbonates (Monti della Maddalena Unit) and by coeval pelagic successions (Lagonegro Units). NE, east and SE of the Pertusillo reservoir, the allochthonous units consist mainly of Tertiary siliciclastic sediments of the Gorgoglione flysch and Albidona Formation (Giocoli *et al.*, 2015). Geophysical investigation and deep-well logs showed that the top of the Apulia Carbonate Platform is between 2 and 4 km below sea level (Stabile *et al.*, 2014a,

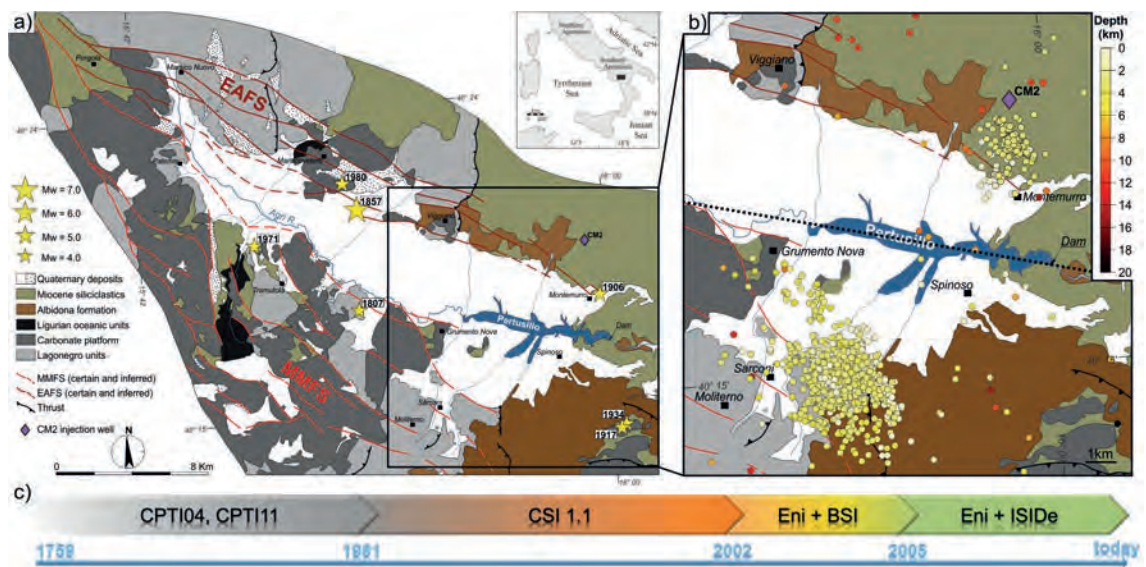


Fig. 2 - Schematic geologic map of the HAV (a) with the indication of the historical seismicity (yellow stars). The black box in panel (a) specifies the area in which is displayed the spatial distribution of the seismicity (b) recorded near the Pertusillo reservoir from 2002 to 2012 [locations from Stabile *et al.* (2014b)]. All the events that occurred in the region SW of the dotted line of panel (b) have been analysed in this study. Timeline of the seismic catalogues and data sets used to build the database of the HAV seismicity since 1759 (c).

and references therein). Effective decoupling between the allochthonous units and the buried Apulia Carbonate Platform is related to the rheological contrast produced by a *mélange* zone, whose thickness is generally several hundreds of metres and locally exceeds 1 km (Stabile *et al.*, 2014a, and references therein).

We have collected data from different catalogues of the historical and recent Italian seismicity since 1759 (Fig. 2c) and populated a database of HAV seismicity. The seismic catalogues and databases used in this study are:

- BSI: Bollettino Sismico Italiano (<http://bollettinosismico.rm.ingv.it>);
- CPTI: Catalogo Parametrico dei Terremoti Italiani [Gasperini *et al.*, 2004 (CPTI04); Rovida *et al.*, 2011 (CPTI11)];
- CSI 1.1: Catalogo della Sismicità Italiana (CSI 1.1, <http://csi.rm.ingv.it>);
- Eni: Database of the microseismic network managed by the Eni company (Stabile *et al.*, 2014a, 2014b);
- ISIDE: Italian Seismological Instrumental and parametric Data-base (<http://iside.rm.ingv.it/iside>).

As shown in Fig. 2c, from 1759 to 1980 only information of the historical seismicity in HAV is available, provided by the CPTI04 catalogue and the next revision of 2011 (CPTI11). Fig. 2a illustrates epicentral location and magnitude of the historical seismicity of the HAV, which includes seven events with $M_w \geq 4.5$. It is worth noting the occurrence in the HAV of only one event with $M_w \geq 5.0$ (the 1857 M_w 7.0 Basilicata earthquake) and of two earthquakes (the 1971 M_w 4.6 earthquake and the 1980 M_w 4.9 earthquake) after October 1963 (impoundment of the Pertusillo reservoir). The two events that occurred after 1963 most likely are natural earthquakes, because their locations are far away the area SW of the Pertusillo reservoir, even considering high location errors of the order of 10 km.

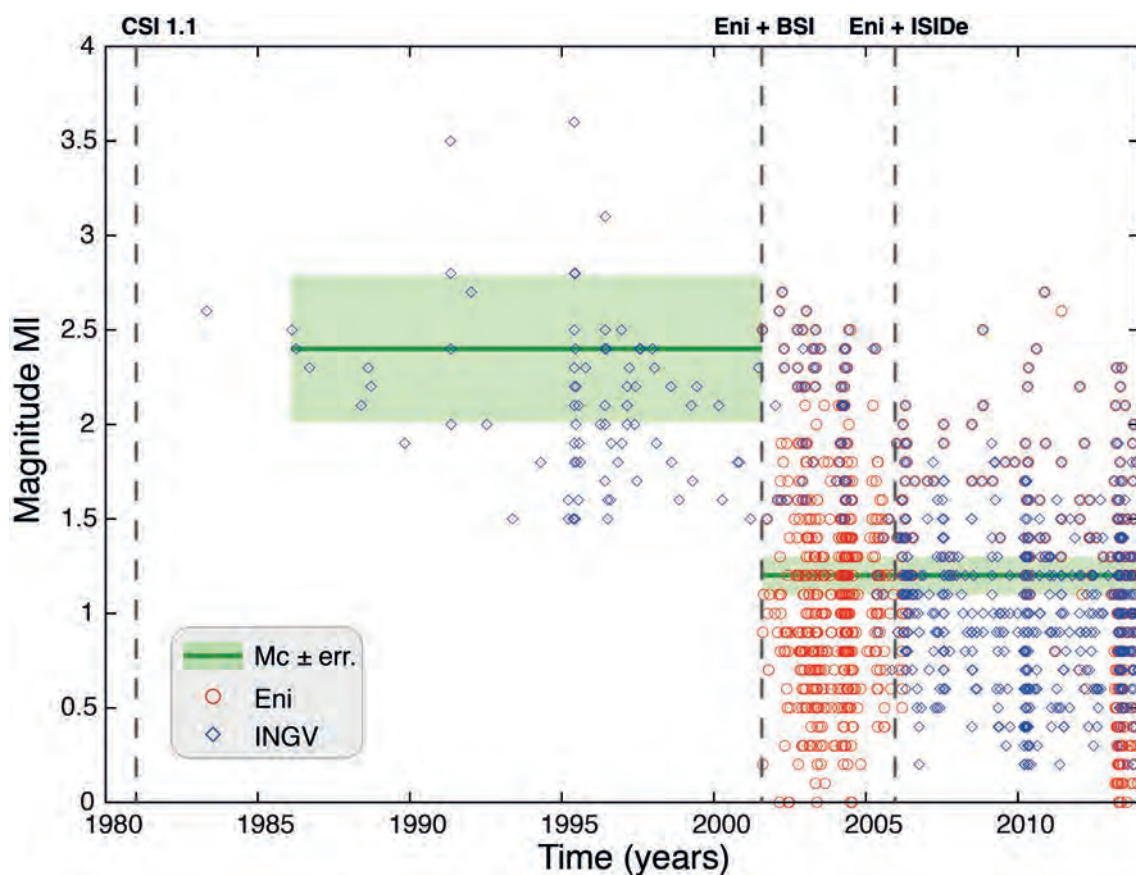


Fig. 3 - The magnitude-time distribution of the analysed seismicity from January 1981 (CSI 1.1 catalogue) to December 2013 (Eni + ISIDE catalogues). Blue diamonds represent data from INGV catalogues (BSI, CSI 1.1, or ISIDE), while red circles represent data from the Eni catalogue. The estimation of the completeness magnitude M_C (green line) with its uncertainty (light green area) is also reported.

The first information about the moderate-to-low seismicity is documented in the CSI 1.1 catalogue starting in 1981. Considering the increased location accuracy of earthquakes included in the CSI 1.1 and the next catalogues, after 1981 we selected only events that occurred in the region below the black dotted straight line in Fig. 2b. The region NE of that line has been excluded from the analyses because it has been demonstrated that the cluster NE of the reservoir (Fig. 2b) is fluid injection-induced seismicity (Stabile *et al.*, 2014b). Fig. 3 shows the magnitude M_L versus the time of occurrence (magnitude-time distribution) of all the selected events. The blue diamond and red circle indicate, respectively, that the source of information is provided by the INGV catalogues (i.e., BSI, CSI 1.1, ISIDE) or by the Eni catalogue. The events included in the INGV and Eni catalogues are represented by both symbols. Furthermore, since a magnitude overestimation of 0.6 has been assessed for the events reported by the Eni catalogue with respect to those reported by the INGV catalogue (Stabile *et al.*, 2014a), we have used the INGV magnitude as default and properly corrected the magnitude of the events included only in the Eni catalogue.

Fig. 3 emphasizes that only events with $M_L \geq 1.5$ were reported before 2002, and just one event (M_L 2.6 earthquake that occurred on April 26, 1983) was included before January 1986.

Using the entire magnitude range method and the maximum curvature method (Woessner and Wiemer, 2005) we obtained a magnitude of completeness $M_c = 2.4 \pm 0.4$ from January 1986 to December 2001 and $M_c = 1.2 \pm 0.1$ from January 2002 to December 2013 (Fig. 3). Clearly evident are a significant drop in the completeness magnitude (green line in Fig. 3) after 2002, together with a reduction of the uncertainty (light green area in Fig. 3).

3. Analysis of the relations between seismicity and water level

Considering the dates reported in Table 1, for each of which is reported the exceedance of water levels over the previous maxima (H_{max}), the last maximum water level was reached on March 16, 1970. This implies that H_{max} did not trigger any earthquake of $M_w \geq 4.5$, whereas influences on low-magnitude seismicity cannot be demonstrated due to the lack of such seismic data in that period (the historical seismicity data records only $M_w \geq 4.5$).

Taking into account the estimations of the completeness magnitude between January 1986 and December 2013, we analysed the relationships between the temporal variation of water level parameters (h , dh/dt , $max[dh]$, $T(h_{max})$) and seismicity by considering: 1) events with $M_L \geq 2.4$ for the investigated period January 1986 to December 2013, and 2) events with $M_L \geq 1.2$ for the investigated period January 2002 to December 2013.

Fig. 4 shows a typical water level fluctuation in a hydrological cycle between the maximum (March-May) and the minimum (September-November). The maximum amplitude of water level change in a cycle $max[dh] = h_{max} - h_{min}$ (where h_{max} and h_{min} are the maximum and the minimum water level in a cycle, respectively) has been evaluated by considering October 1 as the beginning of each cycle. The duration for which the maximum water level is maintained, $T(h_{max})$, has been evaluated through the following equation:

$$T(h_{max}) = \sum_{i=1}^N n_i \tag{1}$$

where N is the total number of days in a cycle (i.e., 365 or 366) and with n_i satisfying the

Table 1 - Dates of exceedance of water levels over the previous maxima and value H_{max} of the new maximum level.

DATE	NEW MAXIMUM LEVEL HMAX (M A.S.L.)	DATE	NEW MAXIMUM LEVEL HMAX (M A.S.L.)
1963-10-01	493.27	1966-01-24	515.70
1963-10-12	497.60	1966-12-06	522.61
1963-12-21	500.67	1967-02-20	527.12
1964-12-27	505.95	1968-04-19	529.83
1965-03-09	506.26	1970-03-16	531.27

Table 2 - Percentage of the number of events that occurred between March and July with respect to the total number of events. Only events with $M_L \geq M_c$ have been counted for each period of investigation.

PERIOD OF INVESTIGATION	N. EVENTS	N. EVENTS MARCH-JULY	PERCENTAGE
1986/01 - 2013/12	42 ($M_L \geq 2.4$)	28 ($M_L \geq 2.4$)	66.7%
2002/01 - 2013/12	517 ($M_L \geq 1.2$)	353 ($M_L \geq 1.2$)	68.3%



Fig. 4 - Typical water levels of the Pertusillo reservoir during the spring (left) and the autumn (right). Photos provided by courtesy of the Ente per lo Sviluppo dell'Irrigazione e la Trasformazione Fondiaria, agency of Potenza, Italy.

condition:

$$n_i = \begin{cases} 1, & \frac{(h_{max} - h_i)}{\max[dh]} \leq 5\% \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

In Eq. 2, h_i is the water level at the i -th day of the hydrological cycle, whereas h_{max} and $\max[dh]$ are the maximum water level and the maximum amplitude of water level change in the considered cycle, respectively. $T(h_{max})$ essentially expresses the number of days for which the water level is close to its maximum. Considering that the maximum amplitude $\max[dh]$ of the seasonal water level fluctuation is about 10-15 m, Eq. 2 allows us to count only the days for which the water level h_i differs from the maximum h_{max} of about 0.50-0.75 m.

Fig. 5 shows the comparison between the seismicity ($M_L \geq 2.4$) located SW of the Pertusillo reservoir from January 1986 to December 2013 and the water level parameters: the water level h (Fig. 5a), the daily water level rate dh/dt (Fig. 5b), the maximum amplitude of water level change in a cycle $\max[dh]$ (Fig. 5c), and the duration for which the maximum water level is maintained $T(h_{max})$ (Fig. 5d). It is well evident that none of these water level parameters played a dominant role in inducing events with largest magnitude ($M_L \geq 2.4$) over the last 30 years. Anyway, we observed that the low-frequency behaviour (periods ≥ 2 years) of the Pertusillo water level (violet dashed line in Fig. 5a) has the same periodicity as the largest magnitude events; therefore, a long period of increased water level may lead to the occurrence of induced earthquakes with larger magnitude.

Fig. 6 shows the comparison between the seismicity ($M_L \geq 1.2$) located SW of the Pertusillo reservoir from January 2002 to December 2013 and the same water level parameters as Fig. 5. Thanks to the lower completeness magnitude, it is possible to observe a periodicity of seismicity that coincides with the annual periodicity of the water level (Fig. 6a), as has already been statistically demonstrated by Telesca *et al.* (2014) for the same period of investigation. The seasonal variation of the seismicity rate is also evidenced by arranging the number of events per month, which indicates that the percentage of the number of events that occurred between March and July is about 67-68% of the total number of events, considering both $M_L \geq 2.4$ and $M_L \geq 1.2$ earthquakes (Table 2). Despite the availability of a high number of seismic events from 2002 to 2013, it is not possible to find (Figs. 6b, 6c, and 6d) any clear relation between the seismicity and the temporal variation of the other three analysed parameters dh/dt , $\max[dh]$, or $T(h_{max})$.

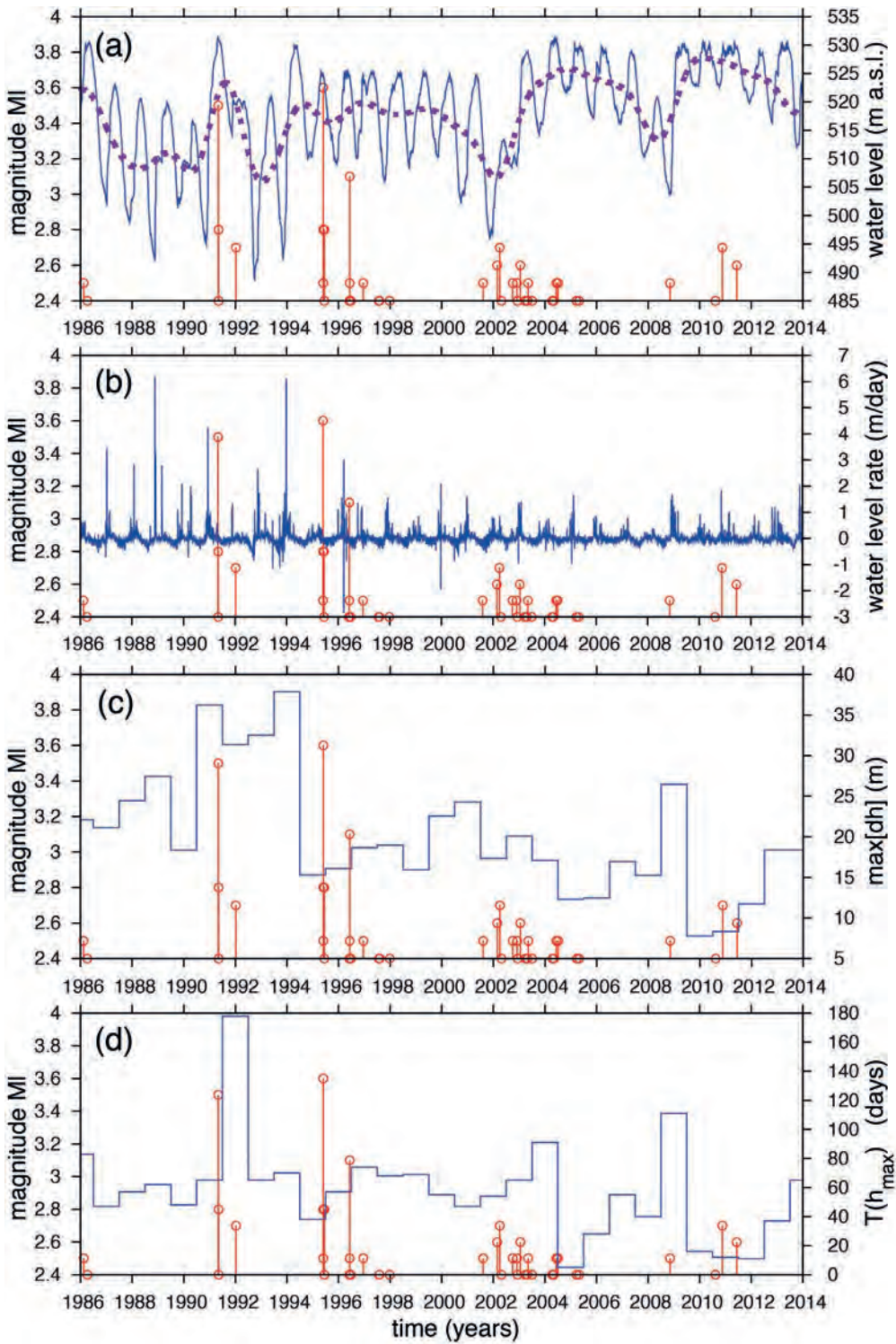


Fig. 5 - Comparison between the seismicity ($M_L \geq 2.4$) located SW of the Pertusillo reservoir from January 1986 to December 2013 and the reservoir water level h (a), the daily water level rate dh/dt (b) the maximum amplitude of water level change in a cycle $max[dh]$ (c), and the duration for which the maximum water level is maintained $T(h_{max})$ (d). The violet dashed line of panel (a) indicates the low-frequency behaviour (periods ≥ 2 years) of the Pertusillo water level.

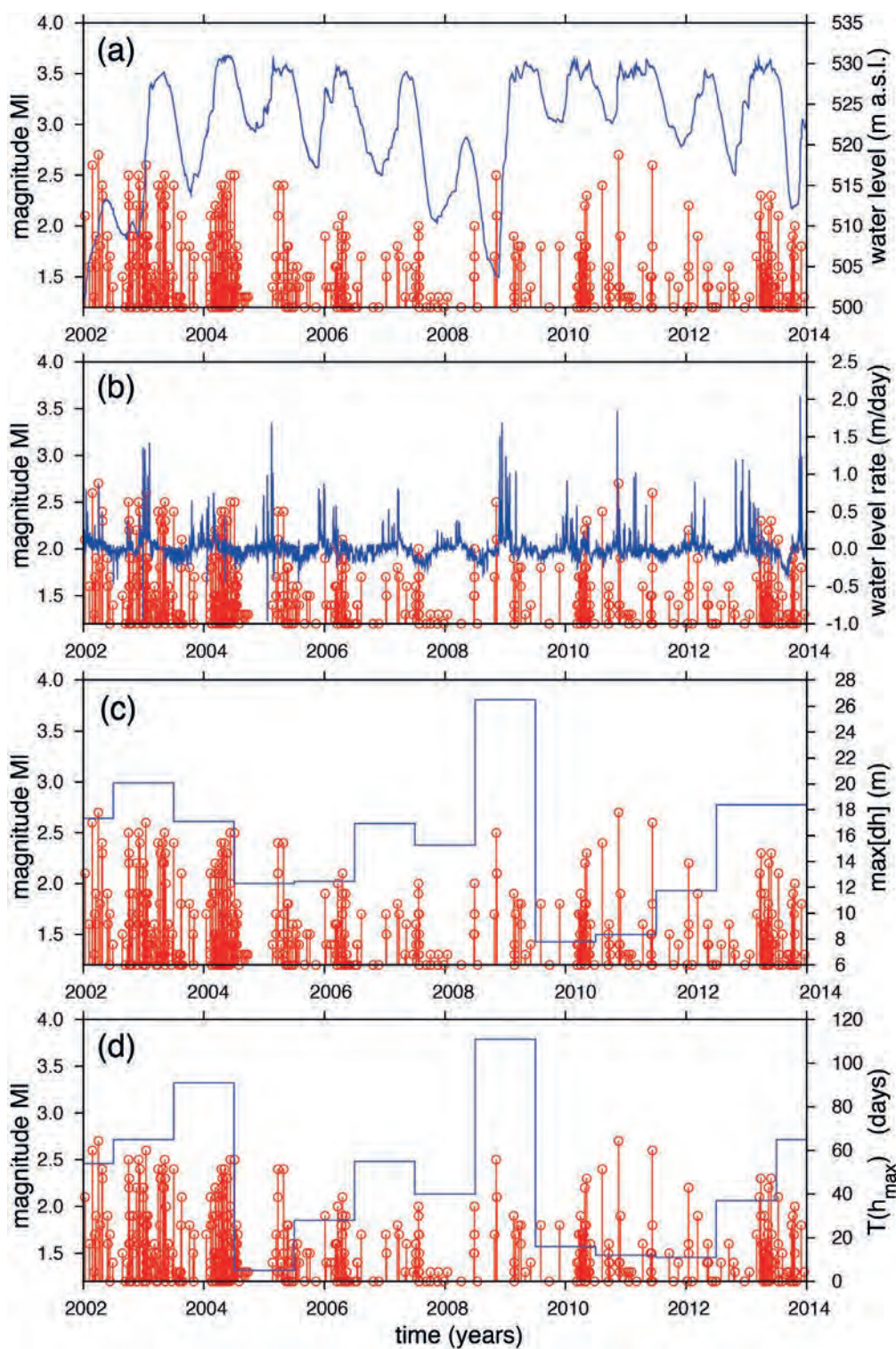


Fig. 6 - The same as Fig. 5 but considering the seismicity with $M_I \geq 1.2$ located SW of the Pertusillo reservoir and for the investigated period between January 2002 and December 2013.

4. Discussion and conclusions

In this paper we investigated the relationship between seismicity and water level of the Pertusillo reservoir by comparing the occurrence of seismic events SW of the reservoir with the temporal variation of different water level parameters: the exceedance of water levels over the previous maxima, H_{max} ; the water level, h ; the daily water level rate, dh/dt ; the maximum amplitude of water level change in a cycle, $max[dh]$; and the duration for which the maximum water level is maintained $T(h_{max})$.

We have analysed the historical seismicity in the HAV, showing all historical earthquakes dating from the impoundment of the reservoir to the last H_{max} value (see Table 1). We argue that influences of H_{max} on lower magnitude seismicity ($M_w < 4.5$) cannot be demonstrated due to the lack of such seismic data for that period. The findings of our study also suggest that the daily water level rate and the duration for which the maximum water level is maintained do not play a dominant role in inducing seismicity with respect to the seasonal water level change (Figs. 5 and 6). Table 2 highlights that the number of events that occurred between March and July is about 67-68% of the total number of events, whether considering $M_L \geq 2.4$ events (from 1986 to 2013) or $M_L \geq 1.2$ events (from 2002 to 2013), hence demonstrating a periodicity of the seismicity rate in agreement with the annual periodicity of the water level (Fig. 1b). Furthermore, we observed that a maximum amplitude in a hydrological cycle as low as 8 m (pressure perturbation of 0.08 MPa at the bottom of the reservoir) appears to be large enough to trigger the seismicity SW of the Pertusillo reservoir ($max[dh]$ parameter in Fig. 6c), whereas higher maximum amplitudes of water level in a hydrological cycle seem not to increase the seismicity rate (Figs. 5c and 6c). Finally, it is worth noting that a long period of increased water level (violet dashed line in Fig. 5a) may lead to the occurrence of induced earthquakes with larger magnitude.

Apart from the publications in the literature that have demonstrated the reservoir-induced seismicity SW of the Pertusillo (Valoroso *et al.*, 2009, 2011; Stabile *et al.*, 2014a; Telesca *et al.*, 2014), there are other two papers that analysed such seismicity without knowing that it was induced by the reservoir. Cucci *et al.* (2004) analysed, among other clusters of southern Apennines, the seismicity that occurred SW of the Pertusillo between April 3, 1996 and June 12, 1996. The authors localized 50 low-magnitude earthquakes ($1.8 \leq M_d \leq 3.4$) and interpreted them as a seismic sequence with a spatial distribution that shows an Apenninic trend along the NW-SE direction and hypocentral depths lower than 7 km. Frepoli *et al.* (2005) analysed the seismicity of the Lucanian Apennines between July 2001 and December 2013, identifying a swarm of 19 earthquakes SW of the Pertusillo occurring in an area of 3×5 km and with shallow hypocentres. The authors observed a slight elongation of the epicentres in a WNW-ESE direction. Apart from demonstrating that the seismicity SW of the Pertusillo is reservoir induced, all the publications in the literature focused on this seismicity agree with the following points:

1. the seismicity has a swarm-type distribution and is characterised by low-magnitude events;
2. the seismicity extends over a volume SW of the Pertusillo reservoir with shallow hypocentres and interests the southern termination of the MMFS at about a 9-km distance from the dam;

3. the seismic deformation is accommodated on different structures highlighted by prevalent normal-faulting kinematics with variability in strike, dip, and rake of focal planes and in the related T-axes directions.

Taking into account the above seismological observations, the geological setting of the area around the Pertusillo reservoir (Fig. 2b) and the results regarding the relationships between the seismicity and the water level parameters of the Pertusillo reservoir, we can argue that there is not an instantaneous undrained elastic response to the variation of the reservoir load. In particular, there is not an immediate seismic response to rapid variations of the water level (daily rates of Figs. 5b and 6b) and the reservoir-induced seismicity (Fig. 2b) is outside the distance of ~ 3.2 km (Stabile *et al.*, 2014a), within which the elastic response to gravitational loading of the reservoir potentially occurs. On the other hand, the presence SW of the Pertusillo reservoir of brittle outcropping allochthonous units, constituted by Monti della Maddalena and Lagonegro Units, and of a network of intersecting fractures between the southern strands of the MMFS and the NE-SW faults, could promote pore fluid pressure diffusion from the reservoir to the SW region. Whether the saturated fault zones near the reservoir are characterized by seismogenic permeability (Talwani *et al.*, 2007), such as demonstrated for the area SW of the Pertusillo reservoir by Valoroso *et al.* (2011) and Stabile *et al.* (2014a), the pore pressure diffuses without significant attenuation and can trigger seismicity along pre-existing faults (i.e., the MMFS). In particular, Valoroso *et al.* (2011) estimated a delayed seismic response of 40 days to the water level fluctuations by analysing the variation of V_p/V_s at different stations, whereas Stabile *et al.* (2014a) estimated a delayed seismic response of one month from the lag of the cross-correlation analysis between the series of the monthly number of earthquakes and the series of the monthly maximum water level. Both the estimations provide values of hydraulic diffusivity in the range 0.1-10.0 m²/s, which corresponds to seismogenic permeability (Talwani *et al.*, 2007).

Since the source of perturbation (the Pertusillo reservoir) of the induced seismicity is at surface, the shallow hypocentres of events suggest that the seismicity is principally confined within the brittle allochthonous units and that the *mélange* zone acts as a seal preventing the migration of fluids. Detailed studies are needed in the future to understand if and how the MMFS promotes fluid flow across the fault system down to the brittle Apulia Carbonate Platform.

Finally, the asymmetrical distribution of the continued reservoir-induced seismicity highlights the geological and structural complexity of the area around the Pertusillo: SW of the reservoir, allochthonous units (Monti della Maddalena and Lagonegro Units) are favourable for reservoir-induced seismicity, whereas NE, the allochthonous units, characterised by Tertiary siliciclastic sediments (e.g., Gorgoglione Flysch and Albidona Formation) with permeability likely below the seismogenic range, offer a great resistance to the flow of water, and the pore pressure increase is negligible. As a consequence, induced seismicity NE of the Pertusillo reservoir can be promoted only by pumping the fluids directly into the Apulia Carbonate Platform, such as happens at the Costa Molina 2 injection well for the disposal of the wastewater produced during the exploitation of the oil and gas field of the HAV (Stabile *et al.*, 2014b).

Acknowledgments. The reservoir data have been provided by the Ente per lo Sviluppo dell'Irrigazione e la Trasformazione Fondiaria, agency of Potenza, Italy. The seismic data of the Eni network were provided by the Basilicata Region through the project "Study of the Local Seismicity" carried out by the CNR-IMAA from April 2012 to December 2014 at the "Osservatorio Ambientale della Val d'Agri" (southern Italy). This study has benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri - Dipartimento della Protezione Civile (DPC), Project S2-2014 (Task 7: Induced seismicity potential in Italy). This paper does not necessarily represent DPC official opinion and policies.

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