Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

GROUNDWATER FLOW NUMERICAL ANALYSIS OF THE SIBILLINI HYDROSTRUCTURE (CENTRAL ITALY): SYSTEM CHARACTERIZATION AND EVALUATION OF HYDROGEOLOGICAL CHANGES AFTER THE Mw 6.5 NORCIA EARTHQUAKE

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EXTENDED ABSTRACT

In Italia Centrale i Monti Sibillini costituiscono una importante idrostruttura a scala regionale, la cui risorsa idrica alimenta sia il settore adriatico che quello tirrenico. La complessità di questo sistema idrogeologico deriva da una marcata compartimentalizzazione dell'idrostruttura, legata alla presenza di una serie di complessi idrogeologici con proprietà idrauliche differenti, la cui continuità laterale e verticale è spesso interrotta e dislocata dagli elementi tettonici presenti nell'area. Pertanto, ne deriva una condizione di flusso articolato, differenziato in una circolazione superficiale e in una basale, la cui dinamica è localmente variabile. Ciò che accentua questa complessità, infatti, è la presenza di importanti sistemi di faglie, alcune attive e capaci (es.: M. Vettore - M. Bove), la cui dislocazione per effetto di un terremoto può avere un impatto rilevante e in alcuni casi permanente sul deflusso idrico sotterraneo.

La sequenza sismica del 2016 che ha colpito l'Italia Centrale ha provocato effetti idrogeologici molto importanti che non si registravano dal terremoto dell'Irpinia del 1980. In particolare, il terremoto di Norcia del 30 ottobre 2016 ha prodotto fagliazione superficiale lungo il versante occidentale dei Monti Sibillini e alterato l'equilibrio dell'idrostruttura. Le variazioni idrogeologiche indotte, in termini di portata e quote piezometriche, sono state osservate principalmente alle sorgenti e lungo i tratti drenanti dei principali corsi d'acqua. Alcune di queste hanno manifestato un carattere transitorio, altre perdurano ancora oggi.

L'"*Aquifer Fault Rupture*" è il meccanismo proposto per spiegare le variazioni idrogeologiche a lungo termine che non possono essere giustificate da fenomeni transitori, quali variazioni di permeabilità e processi fisici subordinati alla propagazione delle onde sismiche nella crosta. Secondo tale meccanismo, una faglia sismogenetica agisce da barriera idraulica all'interno di un acquifero nei confronti del flusso idrico sotterraneo. La sua rottura, tuttavia, annulla l'effetto barriera, consentendo alla faglia stessa di agire da zona di deflusso preferenziale. La dislocazione prodotta dal terremoto di Norcia che ha raggiunto la superficie, ha tagliato l'acquifero basale dei Sibillini determinando un incremento del flusso idrico sotterraneo con direzione prevalente da est verso ovest, favorendo gli apporti idrici lungo il fiume Nera e il fiume Sordo nella piana di Norcia (ad Ovest). Contemporaneamente, ha ridotto l'alimentazione alle sorgenti disposte in alta quota sul versante adriatico dei Monti Sibillini (ad Est). Quest'ultime, infatti, hanno registrato considerevoli decrementi di portata, con impatti negativi sul sistema di approvvigionamento idrico marchigiano.

Nell'ambito di tali problematiche il presente lavoro si propone di caratterizzare l'idrostruttura carbonatica dei Monti Sibillini e di valutarne le variazioni idrodinamiche indotte dal terremoto di Norcia del 30 Ottobre 2016, adottando un approccio numerico. In primo luogo, è stato elaborato un modello idrogeologico concettuale basato sull'analisi di dati geologici e idrogeologici disponibili in letteratura, al fine di definire i limiti fisici e idraulici del modello. La geometria dell'idrostruttura è stata definita attraverso la ricostruzione, in un modello tridimensionale, del limite inferiore dell'acquifero, utilizzando l'interpolazione di dati idrogeologici e sismici. Successivamente, il modello concettuale così definito è stato implementato numericamente per realizzare un modello idrogeologico di flusso stazionario. In funzione dell'estensione del modello, è stato possibile considerare l'acquifero carbonatico dei Monti Sibillini, eterogeneamente fratturato e carsificato, come un mezzo poroso equivalente, continuo ed omogeneo, permettendo così di assumere valori di permeabilità media rappresentativi. Le faglie sono state implementate nel modello numerico come elementi con permeabilità inferiori rispetto all'Acquifero Basale, al fine di associarne un effetto barriera idraulica rispetto al flusso idrico ortogonale ad esse. Attraverso una proceduta trial-and-error è stato possibile simulare le variazioni di flusso idrico sotterraneo (pre e post terremoto) ottenendo risultati coerenti e confrontabili con le variazioni osservate sia prima che dopo l'evento sismico. Questi risultati sottolineano l'importanza del ruolo delle faglie nell'idrodinamica di un sistema complesso e come tali strutture agiscano da barriere idrauliche relative.

IJEGE, Special Issue 1 (2024): 295-304, DOI: 10.4408/IJEGE.2024-01.S-32
E-ISSN 2035-5688 | ISSN 1825-6635 /

ABSTRACT

The October 30th Norcia earthquake originated from the rupture of different segments of the Vettore-Bove normal fault system. The co-seismic rupture propagated up to the surface, causing important faulting and affecting the hydrodynamics of the Basal Aquifer of the Sibillini Mts. carbonate hydrostructure. Several long-lasting hydrogeological changes occurred at springs over the impacted area. Such changes indicate the disruption of the hydraulic sealing effect of the Vettore fault because of the co-seismic dislocation and the consequent groundwater flow increase through the broken fault. This work aims at characterizing the complex regional hydrogeologic system of the Sibillini Mts. and evaluating the important earthquake-induced hydrogeological changes by means of numerical modelling. A robust conceptual model has been defined according to tectonic and hydrogeological data and based on a 3D reconstruction of the Basal Aquifer. The regional-scale extent of the model allowed us the adoption of a simplified approach treating the carbonate aquifer as a continuous and homogeneous equivalent porous medium, while faults were considered as hydraulic barriers with lower permeability. Simulation results, aligned with the observed variations, highlight the crucial role of faults in influencing the hydrodynamics of carbonate hydrostructures.

Keywords*: carbonate hydrostructure, seismogenic fault, groundwater, basal aquifer, numerical modeling*

INTRODUCTION

The Earth's crust can be considered a biphasic medium, consisting of a solid skeleton and voids filled with fluids (Fyfe, 1978; Albano *et alii*, 2019) with a poroelastic behaviour (Wang, 2000). Consequently, the mechanical stress and strain changes induced by a fault dislocation during an earthquake rupture can alter the hydrologic properties of the crustal rocks, such as rock permeability and porosity, and therefore modify the short- and long-term groundwater circulation in the crust (Manga *et alii*, 2012; Manga & Wang, 2015).

It has been documented that earthquakes can induce various hydrological responses, including changes in streamflow and spring discharge (Muir-Wood & King, 1993; Montgomery & Manga, 2003; Wang & Manga, 2010), variation in groundwater hydraulic heads (Wakita, 1975; Ingebritsen & Manga, 2019), and modification of groundwater hydrochemistry, *e.g.*, observed in springs (Li *et alii*, 2019). Several mechanisms have been proposed to explain these hydrological changes in response to earthquakes: (*i*) regional pore pressure changes by co-seismic static elastic strain (Wakita, 1975; Muir-Wood & King, 1993; Jónsson *et alii*, 2003), (*ii*) regional increase or decrease in permeability caused by static and dynamic stress changes (Rojstaczer *et alii*, 1995; Brodsky *et alii*, 2003; Shi *et alii*, 2019), (*iii*) local coseismic liquefaction or consolidation of loose sediments (Manga, 2001; Wang *et alii*, 2003). Such hydrogeological changes can strongly modify the groundwater setting of local and regional aquifer systems, therefore causing further treats to the population, especially when such groundwater resources are exploited as irrigation, hydropower plants, or water supply.

Fault zones are the features where most of the coseismic hydrological changes happen. They often show a complex hydraulic behaviour as they can act as hydraulic preferred pathways, barriers, or combined conduit-barrier systems, depending on their maturity (*i.e.*, the relative permeability between fault core and damage zone), the direction of groundwater flow, and the stress and strain conditions acting inside the crust (Caine *et alii*, 1996; Bense *et alii,* 2013). The "aquifer fault rupture" concept has been proposed in the literature to explain the aquifer response to earthquakes (Manga *et alii*, 2012; Manga & Wang, 2015; Mastrorillo *et alii*, 2020): the seismogenic fault rupture creates a new flow section which favours the groundwater transfer through the fault. This involves a variation of hydraulic gradients and of groundwater divides in hydrogeological systems as well as changes in the hydraulic properties of the nearby rocks. Because of their complex architecture and in relation to the variability of physical parameters and geological factors, it is notoriously difficult to adequately characterize the hydrologic behaviour of fault zones within the earth's crust. The estimation of the hydraulic properties of fault zones remains a challenge and the lack of data, related to the inability to obtain direct measurements especially at depth, represents an important gap in hydrogeological modelling.

In this work, we analyze the complex interplay between earthquake rupture and groundwater flow at regional scale with the aim to explain the long-term groundwater perturbations that altered the Sibillini Mts. hydrostructure after the 30th of October 2016, Mw 6.5 earthquake (Central Italy), which largely affected the Norcia municipality and the nearby villages.

DATA AND METHODS

We started our study via a collection of all the available literature works and reports about the earthquake sequence and the features of the hydrosturcture (Boni *et alii*, 1986; Valigi *et alii*, 2019; Mastrorillo *et alii*, 2020; Viaroli *et alii*, 2021; Valigi *et alii*, 2020; Petitta *et alii*, 2021a; Petitta *et alii*, 2021b; Petitta *et alii*, 2022). These data allowed us to build a sound hydrogeological conceptual model, supported by available groundwater flow discharge and groundwater head data. Such a conceptual model represents the basis for the implementation of a groundwater numerical model. The numerical approach allows the description of the ground flow system and simulates the groundwater dynamics under different conditions. In our case, we assumed two, endmember, stationary conditions to simulate the groundwater flow before and after the 30th of October 2016 earthquake.

The case study

The 30th of October event is the largest of a long-lasting earthquake sequence, which is spread out over the municipalities of Accumoli, Amatrice, Visso and Norcia (Fig. 1a). The sequence started on 24th of August 2016, when an Mw 6.0 earthquake nucleated between the towns of Accumuli and Amatrice (Chiaraluce *et alii*, 2017; Improta *et alii*, 2019). Hundreds of aftershocks were recorded, which gradually migrated away from the earthquake hypocentre, suggesting the possibility of a transient diffusive process (Chiarabba *et alii*, 2018; Tung & Masterlark, 2018; Albano *et alii*, 2019). On 2016 October 30, the Norcia earthquake (Mw 6.5) struck the town of Norcia and caused further damage. According to seismological and geodetic data, the entire sequence activated along a normal fault system striking approximately NW-SE and dipping 40–55 degrees SW-ward, with a locally listric shape (Cheloni *et alii* (2019) and references therein) and involving a crustal volume of approximately 6000 km^3 (Bignami *et alii*, 2019). These main faults crosscut the ground and outcrop along the Mt. Vettore-Bove fault system, which is characterized by extensional/transtensional kinematics and dissects the Meso-Cenozoic clayey/marly and carbonatic sedimentary layers of the Central Apennines (Galadini & Galli, 2009). A possible local reactivation at depth of an inherited NW-dipping thrust has been also proposed, even if the literature does not consistently agree with this model (Scognamiglio *et alii*, 2018; Bonini *et alii*, 2019; Cheloni et *alii*, 2019; Improta *et alii,* 2019).

Fault rupture produced vertical subsidence of the hangingwall, spreading over more than 300 km^2, reaching values up to 1 m (Fig. 1a), and crosscut the earth's crust to the ground surface, causing important hydrogeological modifications to the carbonate aquifers belonging to the Sibillini Mts. Sustained changes in groundwater flow occurred, especially after the 30 October event which struck the area to the NE of the Norcia town. The main effects of such modifications include (Fig. 1b): *i*) a global increase in discharge at the springs located the western side of the Sibillini Mts. And the Vettore-Bover fault, and along the main drainage system of the Nera River basin; *ii*) the re-emergence of the Torbidone spring in the Norcia plain, dry since 1979 (Petitta *et alii*, 2018; Valigi *et alii*, 2019); *iii*) a strong reduction in discharge, accompanied by a lowering of the groundwater table, at the springs on the eastern flank of the Sibillini Mts., which posed significant challenges to the water supply infrastructure of the Marche region. Mastrorillo *et alii* (2020) proposed that the observed groundwater disturbances, still evident at the time of this writing, could be attributed to an eastward movement of the piezometric divide of Vettore Mt. However, the causes of such a shift of the piezometric divide have not been quantitatively assessed. The purpose of this work is then to assess the hydrodynamic response

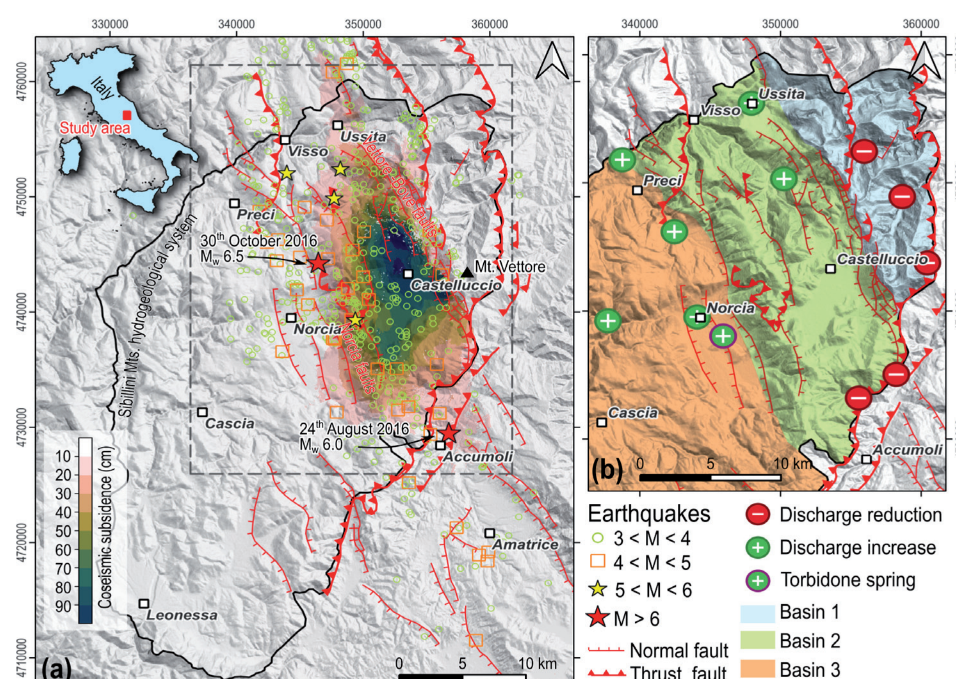

Fig. 1 - (a) Sketch of the 2016 earthquake sequence (Chiaraluce et alii, 2017) with the location of the main events (M >3) and the coseismic ground subsidence caused by the 30th of October earthquake (Bignami et alii, 2019). The black line identifies the boundary of the Sibillini Mts. Hydrogeological system. (b) Detail of the area enclosed in the dashed gray rectangle in panel a, showing the increase and reduction of discharge rates measured at springs and spring groups after the 30th of October event (Valigi et alii, 2020), together with the definition of the three basins constituting the regional hydrostructure

of the fractured carbonate aquifer system of the Sibillini Mts. to the coseismic dislocation of Vettore fault, through the realization of hydrogeological numerical models.

Conceptual Model

To define a conceptual hydrogeological model and to assess the complex behaviour of the Sibillini Mts. hydrogeological system, we identified, based on the available mentioned literature, the hydrogeological features, and the hydraulic physical boundaries in accordance with the relationships with the nearby regional aquifers, the known tectonic elements, and the available hydrogeological data.

The Sibillini Mts. are part of the East-verging fold-and-thrust belt system of the Central Apennines, whose stratigraphy consists of an over 2 km thick Meso-Cenozoic "Umbria-Marche" calcareous sequence, superimposed on the Tortonian clayey sequence as the result of the propagation of folds and thrusts elaborated by strike-slip tectonics. The Mesozoic to Cenozoic carbonate sequence is fractured and karstified and is schematized as a continuous aquifer bounded by less permeable Tortonian to Quaternary units. Quaternary normal faulting fills depressions with continental to volcanic reworked material sequences. The hydrostructure is bordered by discrete permeability limits such as compressive tectonic features. The Sibillini Mts. thrust system (SMt) to the east (Fig. 2a), which separates the carbonate domain from the apulean foreland to the east and outlines the most important regional scale permeability limit along its meridian trend; and the Coscerno Mt. thrust (CMt) to the west, which acts as a local hydraulic limit like the SMt structure (PREZIOSI *et alii*, 2022). Both tectonic features enclose most of the hydrostructure acting as boundaries to the groundwater flow. The remaining boundaries are identified by topographic and lithological limits. The upper-middle Ussita-Nera River system to the northwest collects the groundwater from the several springs located on its left bank and represent the most depressed feature of the area, thus it has been considered as a hydraulic boundary. Finally, the southern boundary of the hydrostructure is bounded by a normal fault system close to the Leonessa municipality. The extent of the hydrostructure is quite large (approximately 1,078 km^2) and includes both the normal faults of Vettore-Bove and Norcia (VBfs and Nfs respectively) and all the spring groups at high and low altitude affected by the 30th of October 2016 earthquake.

Internally, several hydrogeological complexes have been identified (VIAROLI *et alii*, 2021) in relation to the lithologies constituting the "Umbria-Marche" sedimentary layer. The sequence is composed of alternating layers with different permeability that result in a compartmentalization of the hydrostructure. We identify several aquifers, separated by less permeable levels. The *Scaglia Calcarea* and *Scaglia Rossa* formations constitute the shallow aquifer (*Scaglia Calcarea* aquifer), which is strongly fragmented and characterized by minor groundwater flow. This aquifer is separated from the other one by the interposition within the sequence of the Marne a Fucoidi aquiclude. The *Corniola-Calcare Massiccio* complex, which identifies the homonymous fractured and karst geological formation, hosts a huge basal aquifer. The presence of low permeability Jurassic deposits on the top of that complex sustains a separate flow in the above *Maiolica* complex, acting as an aquiclude. When the thickness of the low permeability deposit is reduced and plays the role of aquitard, the basal flow is undifferentiated in the two complexes. At the bottom of the formation, the Triassic Evaporite formation, acts as a regional aquiclude. The shape of such lithology has been reconstructed

Basin	Spring Name	Type	Elevation (m a.s.l.)		Q(m^3/s)	Ref.
			max	Min		
1	Ambro	linear	930	820	0.245	*S19* in VIAROLI *et alii*, 2021
	Tenna	linear	1140	845	0.300	*S15* in VIAROLI *et alii*, 2021
	Aso	linear	940	830	0.690	*S5* in VIAROLI *et alii*, 2021
	Foce di Montemonaco	punctual/tapped	910		0.535	*S9* in VIAROLI *et alii*, 2021
	Sassospaccato	punctual/tapped	1300		0.05	*S35* in VIAROLI *et alii*, 2021
2	San Chiodo	punctual/tapped	760		0.64	*S7* in VIAROLI *et alii*, 2021
	Nera I	linear	760	725	0.820	*S3* in VIAROLI *et alii*, 2021
	Rapegna	linear	800	730	0.360	*S11* in VIAROLI *et alii*, 2021
	Ussita	linear	718	650	0.570	*S8* in VIAROLI *et alii*, 2021
	Capodacqua	punctual/tapped	841		0.34	*S13* in VIAROLI *et alii*, 2021
	Fosso di Capodacqua	linear	830	725	0.130	*S29* in VIAROLI *et alii*, 2021
3	Sordo I	linear	600	530	1.380	MASTRORILLO *et alii*, 2009
	Sordo II	linear	530	463	3.5	MASTRORILLO *et alii*, 2009
	Corno	linear	440	374	0.08	MASTRORILLO *et alii*, 2009
	Nera II	linear	394	370	1.58	MASTRORILLO *et alii*, 2009
	Nera III	linear	370	345	1.975	MASTRORILLO *et alii*, 2009

Tab. 1 - Main springs and spring groups belonging to the three investigated basins, together with their mean discharge rate before the 2016 earthquake sequence (MASTRORILLO et alii, 2009; VIAROLI et alii, 2021) from the analysis of geological and seismic subsurface data (Retrace-3D Working Group, 2021) and hydrogeological sections (Viaroli *et alii*, 2021). This limit is strongly dissected by normal faults and results at different depths, reaching higher altitudes below the Vettore Mt.

The groundwater flow is additionally influenced by the complex fault systems that interrupt the vertical and lateral continuity of the above-described layers by juxtaposing horizons with different hydraulic properties by locally dislocating the sequence. Thus, regional tectonic and structural lineaments govern the preferential direction of flow. Therefore, the whole hydrogeological system can be divided into three basins in series (basin 1, 2 and 3 in Fig. 1b), separated by permeability barriers constituted by the VBfs and Nfs systems, according to the main groundwater flow directions measured with tracer tests (Mastrorillo *et alii*, 2020). The groundwater outflows occur at several springs located at different altitudes and along several segments of the Sordo and Nera rivers, where the riverbed intercept the groundwater saturation level (see Tab. 1). The greatest amount of groundwater is stored in the *Corniola-Calcare Massiccio* geological formations, making the Basal Aquifer the most crucial component in terms of productivity.

Numerical Model

The assumed hydraulic behaviour of the conceptual model of the Sibillini hydrostructure has been verified by means of a steady state numerical analysis with the open-source code MODFLOW-OWHM (Boyce *et alii*, 2020). The hydrogeological domain, covering an area of approximately 1078 km^2, has been discretized with square cells of 200 m × 200 m resolution with a grid rotated with an angle of about 28° counterclockwise to the east direction (Fig. 2b). The model top elevation is imported from a 10 m resolution DEM, while the aquifer bottom elevation is set from the interpolated bottom surface reconstructed by using geological sections and seismic subsurface data (Retrace-3D Working Group, 2021; Viaroli *et alii*, 2021). The VBfs and Nfs faults are modelled as discrete vertical objects with a simplified geometry with the Horizontal Flow Barrier package (HFB, Hsieh & Freckleton, 1993), assuming a lower permeability than that of the aquifer layer, thus representing hydraulic barriers with respect to the horizontal groundwater flow. Springs and segments of riverbeds that are directly fed by the aquifer are implemented in the model as drains (DRN Package) to simulate the amount of groundwater coming out from the system. The average flow rates of springs and streambeds (Table 1) are used as drain observations

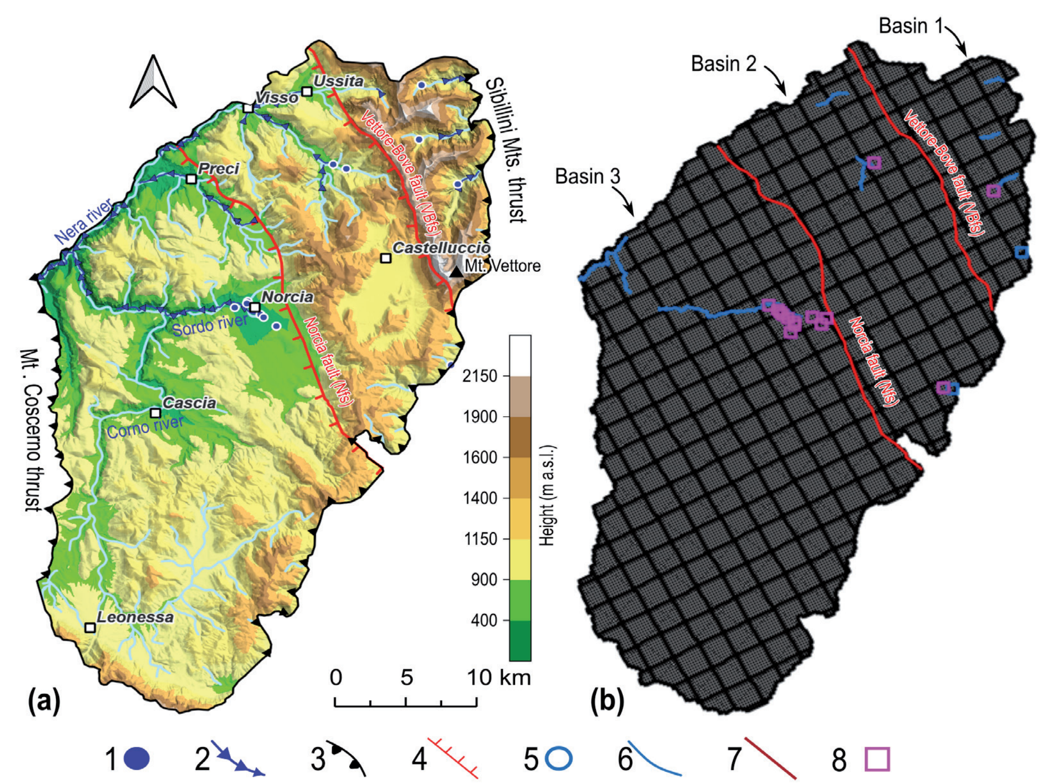

Fig. 2 - Conceptual model (a) and numerical model (b) of the Sibillini Mts. Hydrogeological system. Key to the legend: 1) Springs; 2) Linear springs; 3) main thrusts; 4) main normal faults; 5) Modelled springs (drains); 6) Modelled linear springs (linear drains); 7) Modelled faults (hydraulic barriers); 8) Modelled groundwater level measurement points (observation points)

(DROB package) while available hydraulic head data are used as head observations (HOBS). To simplify the calculation and to avoid the presence of multiple drains in the same cell, some drains have been merged and the contribution in discharge has been added up. In particular, the flow rate of the Foce di Montemonaco tapped spring, in basin 1, has been added to the flow rate of the Aso River linear drain. Also in basin 2, the contribution of the San Chiodo spring has been added to the discharge flow of the Nera I River close to the spring, while in Capodacqua the outflow of the homonymous creek has been added to the punctual drain.

As the model is solved in steady-state conditions, the amount of water feeding the system has been assumed equal to the amount of outgoing water for the three modelled basins. The Recharge (RCH) Package allowed to simulate precipitation/water infiltration in the model and the recharge value has been calculated as the ratio between the sum of the drain's discharges and the total area of the model.

Because of the regional-scale extent of the model, we assumed the Sibillini carbonate aquifer as a homogeneous and continuum equivalent porous medium (Lancia *et alii*, 2020) with a single layer representing the Corniola-Calcare Massiccio basal aquifer with an average permeability value.

We then performed two steady-state forward models with the Newton Solver together with Upstream Weighting of flow (NWT-UPW) configuration to specify properties controlling flow between cells. The first model is intended to simulate the steady state groundwater flow before the earthquake. In this model, both conductance values for the fault and the domain and the conductance values at drains are manually adjusted to best simulate both the spring discharge rates and the groundwater head observations. The second model is intended to simulate the effect of the earthquake on the groundwater flow. To this aim, we assumed the whole configuration and parameters obtained from the first model, but we eliminated the VBfs to simulate a complete disruption of the hydraulic barrier effect exerted by the fault because of the earthquake dislocation.

RESULTS AND DISCUSSION

The steady-state groundwater flow of the basal aquifer before the earthquake has been simulated through a forward trial-and-error procedure. To achieve the best data fitting while keeping all drains active, we attributed different representative permeability to characterize the aquifer in each basin. Specifically, hydraulic conductivity values of 1×10^{-6} m/s, 3×10^{-6} m/s and 8×10^{-6} m/s have been assigned to basins 1, 2 and 3, respectively. The hydraulic properties of faults have also been adjusted, with hydraulic conductivity values set to 1×10^{-11} m/s for the VBfs, with a barrier thickness of 1 m and a value of 1×10^{-10} m/s for the Nfs with a 0.5 m thickness.

This parameterization results in the distribution of the hydraulic head within the aquifer as shown in Fig. 3a. In detail, the basin 1 shows the largest hydraulic head values, with a maximum piezometric level below the Vettore Mt. of about 1480 m a. s. l. This computed head aligns with the hypothesis that the groundwater divide of the hydrostructure is located somewhere in this sector, often corresponding to the VBfs. The assessed hydraulic head distribution produces a groundwater flow directed mainly in the northeast direction, feeding the springs located at higher altitude. The VBfs acts as an hydraulic barrier and facilitates groundwater storage in basin 1, thus generating an evident gap in hydraulic head with respect to the adjacent basin 2.

In basin 2 the maximum hydraulic head is attained at the Castelluccio plain. In this central sector, the predominant groundwater flow is directed in the northwest direction, almost parallel to the Nfs and VBfs tectonic elements, feeding the northern Nera River, where the groundwater head difference with basin 1 is enhanced.

Moving to the basin 3, here the computed mean groundwater head is the lowest of the three sectors, with values ranging from 700 to 550 m a.s.l. in the Norcia plain. In this basin, the drains are in the northwestern part, thus the groundwater flows in the northwest direction and feeds the Sordo and Nera rivers, which account as the main basal outflows of the whole hydrostructure.

The observed strong difference in groundwater head among the three basins suggests a hydraulic separation due to the barrier effect associated with both VBfs and Nfs. This appears to be supported by the main groundwater flow directions, parallel to the tectonic lineaments as observed in the literature (Cambi *et alii*, 2022). Nevertheless, even though the isopiezometric curves are orthogonal to faults, a small amount of groundwater transfer between basins exists. This exchange is ensured by the non-impermeability of barriers and the existence of a hydraulic gradient between sectors. In this perspective, at the pre-seismic state both faults (VBfs and NFs) act as relative, low-permeable, hydraulic elements.

Figure 3b shows the result of a further analysis, performed to simulate the post-seismic groundwater flow model. The steady-state groundwater flow model after the earthquake has been modelled by keeping the parametrization from the model before the earthquake and removing the VBfs in the model. Such an approach removes the hydraulic barrier exerted by the VBfs in the model before the event and simulates in a simplified way the seismogenic fault rupture.

This new set-up resulted in a redistribution of the groundwater flow among the three basins (Fig. 3b), with a new distribution of groundwater head and flow in the first and second basin. A strong groundwater head loss in observed in basin 1, otherwise an increment is observed in basin 2. As a result of these changes, the basal aquifer continues to feed all the drains but some differences in outflows arise: a global reduction in flow rate occurs at drains located at high elevations, especially those in basin 1, with respect to the pre-seismic condition. In contrast, springs discharge rate at the western side of the VBfs have globally increased as the piezometric level raised too. This can be attributed to a significant groundwater transfer from the first basin to the second and third basins. This mechanism can be explained with the Aquifer Fault

Rupture mechanism: during the earthquake, the Vettore fault rupture reached the topographic surface, involving the aquifer and "cutting" the piezometric line. The rupture inside the saturated zone of the aquifer allowed the groundwater to flow through the broken fault zone, due to the existing hydraulic head difference.

This new drainage condition caused a progressive depletion of basin 1, with a consequent lowering of the water-table and decreasing in water supply to high altitude springs. Such a condition is highlighted in Fig. 3c, where a SW-NE oriented cross section (A-A' in Fig. 3a and 3b) shows the significant differences in groundwater table before and after the earthquakes especially at basins 1 and 2. Steep increases in hydraulic gradient close to both faults characterize the water-table in the pre-earthquake condition. The presence of such hydraulic steps arises from the minor permeability assigned to the tectonic features with respect to the aquifer and, therefore, to the barrier effect. This results in a progressive piezometric decrease in the three basins from east to west. In the post-earthquake scenario only the Norcia fault still acts as a barrier, thus the water-table shows only one hydraulic jump between the second and third basin. The head jump between the basins 1 and 2 is drastically reduced due to the disruption of the hydraulic barrier exerted by the VBfs, which has been switched-off in the post-earthquake scenario.

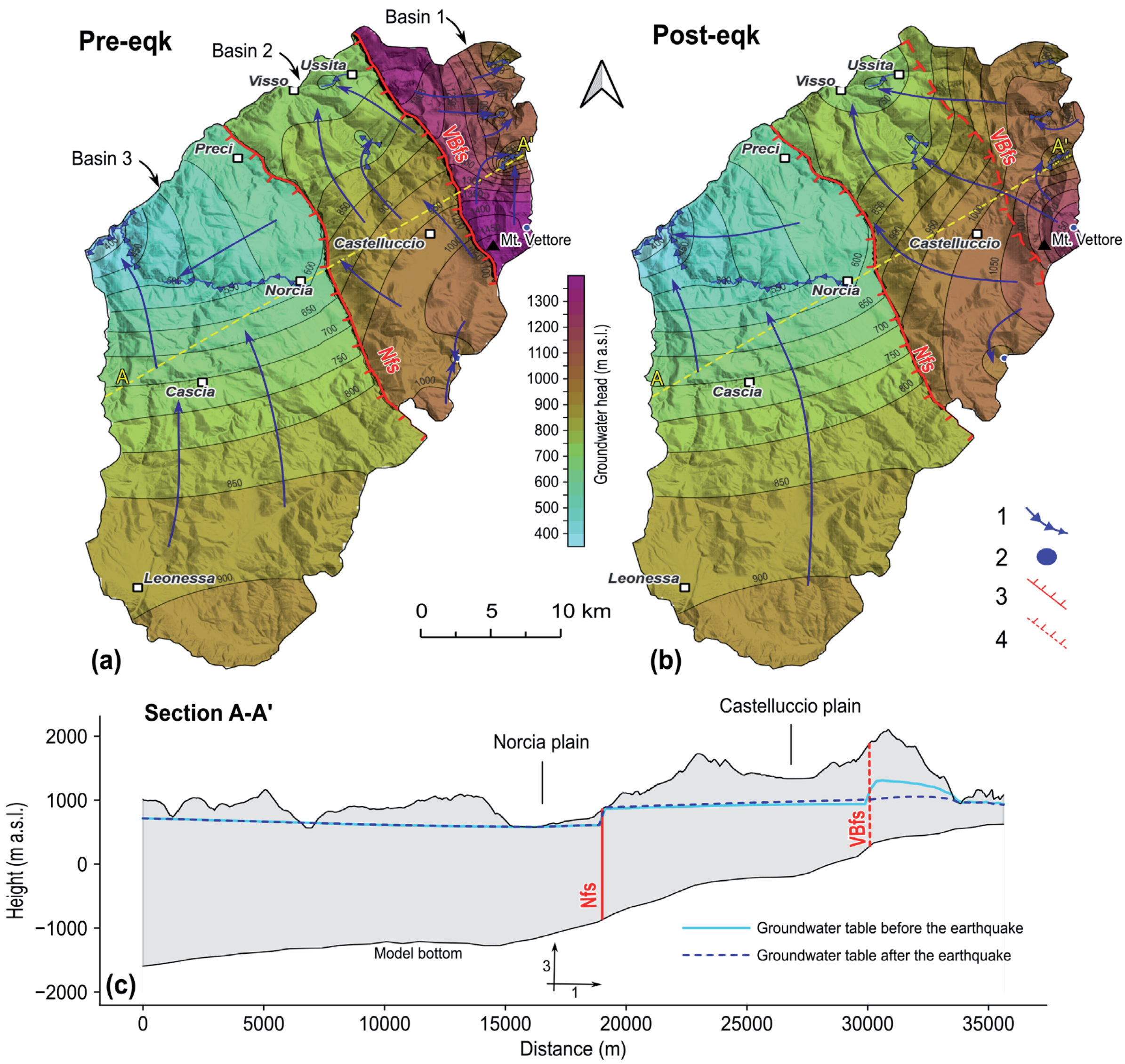

Fig. 3 - Results of the steady-state groundwater flow model of the Sibillini Mts. hydrostrutcture before (a) and after (b) the 30th of October 2016 earthquake. Key to the legend: 1) Linear springs; 2) Springs; 3) Fault acting as a hydraulic barrier; 4) Fault not acting as a hydraulic barrier. Panel c shows the groundwater table computed before and after the earthquake along the A-A' cross section in panels a and b

While in basin 1 the water-table has significantly lowered with a considerable decrease in the discharge contribution at Adriatic springs, by contrast, an increase in water-table is clearly visible in the middle sector (basin 2). At basin 3, there is a negligible change in groundwater head and flow, as our model does not consider any changes in hydraulic conditions of the Nfs and nearby areas. Shutting down the Vettore fault within the model is the simplest way to simulate the breaking of the barrier. This choice serves as an exemplification since it attributes all the hydrodynamic changes caused by the earthquake dislocation exclusively due to the rupture of the entire fault segment.

Earthquake-related hydraulic changes are significantly more complex for at least two specific reasons: (*i*) during the earthquake the VBfs activated, and the rupture affected different segments of the fault with variable slip along the whole length of the fault system. Consequently, the hydraulic barrier consists of a fault zone with variable thickness and varying hydraulic properties. As a result, the expected permeability change along the fault plane after rupture should be spatially heterogeneous. (*ii*) Because of coseseismic ground displacements, the crust (and the associated aquifer) experiences volumetric deformation. Thus, the effects of an earthquake are not confined exclusively to the seismogenic fault but are volumetrically distributed throughout the hypocentral area (Albano *et alii*, 2021a; Albano *et alii*, 2021b). This results in a much more complex reality in which a variety of factors and variables are involved, some of which however remain challenging to determine.

CONCLUSIONS AND FUTURE DEVELOPEMENTS

In this work, a forward numerical analysis provided a sketch of the hydraulic behavior of a complex hydrogeological system, distinguished by notable seismogenic fault systems. The modeling reveals that tectonic features play a crucial role in controlling the hydrodynamics of the Sibillini Mts. hydrostructure, especially the VBfs which has long acted as a low-permeability hydraulic barrier, leading to a significant groundwater storage in the easternmost sector of the regional reservoir.

Despite the exemplifications adopted in the modeling process, the computed distributions of the hydraulic head and outflows are consistent with the observed aquifer's hydrodynamic behavior, confirming the initial conceptual hypothesis and the employed methodology. According to Mastrorillo *et alii* (2020), only the "Aquifer Fault Rupture" can explain the anomalous and long-lasting hydrological changes. Indeed, springs behaviors are a clear indication that the nowadays broken Vettore fault needs time to re-establish its barrier effect as well as time is required for basin 1 to re-storage the depleted groundwater resource.

Future steps will focus on further detailed analysis of the coseismic volumetric deformations of the aquifer related to the 30th of October earthquake. A geomechanical numerical analysis will lead to identify areas and volumes that will undergo contraction or dilation due to the Vettore fault normal displacement. The expected deformation will be translated in a distribution of permeability variation, valuable for future modeling purposes.

In addition, considering the complexities revealed by the model and those expected from future investigations, the adoption of the idea of parsimony, which involves by "starting simple and building complexity slowly" (Hill & Tiedeman, 2007), encourages a revisiting of the hydrogeological model with the hypothesis that an even simpler parameterization could be useful in characterizing the investigated hydrogeological system and enhancing the understanding of its behavior. In this perspective, a new, parsimonious, groundwater flow model will be carried out, which could adequately represent the Sibillini Mts. complex hydrogeological system, also valuable for predictive analysis.

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Received January 2024 - Accepted April 2024