

Conceptual and numerical analysis of hydrogeological changes in the Sibillini Mts. due to the M_w 6.5 Norcia earthquake

E. Zullo¹, M. Albano², M. Saroli¹, M. Moro², G. Testa¹, N. Bonora¹, M. Petitta³, T. Reimann⁴, C. Doglioni³

¹ *Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino (FR), Italy*

² *National Institute of Geophysics and Volcanology, Rome, Italy*

³ *Department of Earth Science, University "La Sapienza", Rome, Italy*

⁴ *Institute of Groundwater Management, TUDresden, Dresden, Germany*

Introduction

Earthquakes are widely recognized for inducing variations in hydrogeological systems. Within the field of earthquake hydrogeology, these variations are consistently attributed to changes in crustal permeability, driven by the interplay of multiple mechanisms occurring within the crustal porous medium in response to seismic shaking and pore pressure variation (Manga & Wang, 2007; Wang & Manga, 2010). Such hydrogeological responses are typically observed at springs, along major rivers, and in wells, where they manifest primarily as anomalous variations in discharge rates and fluctuations in piezometric levels.

The M_w 6.5 Norcia earthquake, which occurred on October 30, during the well-known 2016 Central Italy seismic sequence (Chiaraluce *et al.* 2017), profoundly affected the regional hydrogeological system of the Sibillini Mts. Unlike the transient nature of most earthquake-induced hydrogeological changes, the effects of the M_w 6.5 mainshock have proven to be long-lasting, with clear evidence still observable today.

This study aims to analyse the hydrogeological changes induced by the M_w 6.5 Norcia earthquake within the complex hydrogeological system of the Sibillini Mts., by using conceptual models and numerical analysis. Particular attention is given to the role of seismogenic and capable faults in the Sibillini area and how these structures influence the groundwater circulation.

Materials and Methods

The extensive available documentation regarding the Norcia earthquake and the related effects, along with pre- and post-seismic hydrogeological monitoring data, were analysed to define a conceptual model. The data set include information on seismic activity, spring discharge rates and piezometric fluctuations, hydrogeochemical analysis and tracer test results, as well as geological and hydrogeological information of the study area. Although the groundwater circulation of the Sibillini Mts. hydrogeological system is compartmentalized within several hydrogeological

complexes, a single aquifer is assumed for the hydrostructure. The bottom of the aquifer was reconstructed by interpolating data from available hydrogeological cross-sections (Viaroli *et al.* 2021) and 3D geological information (RETRACE-3D Working Group, 2021). Seismogenic faults in the area are considered as relative hydrogeological barriers, influencing the groundwater flow differently in the pre- and post-seismic. A numerical analysis was then performed by using the MODFLOW-OWHM code (Hanson *et al.* 2014). The groundwater flow before and after the Norcia earthquake was simulated by adopting the equivalent porous medium approach to model the aquifer, and the *Horizontal Flow Barrier* package (Hsieh and Freckleton 1993) was used to model the seismogenic faults. A parameters calibration of the pre-seismic groundwater flow model was performed by using the PEST algorithm (Doherty, 2015).

Results and future perspectives

The comprehensive literature analysis enabled the reconstruction of a conceptual hydrogeological model of the Sibillini Mts. hydrostructure at a regional scale, encompassing the whole area where hydrogeological variations were observed. The model extends to shallow crustal depths and is constrained by physical and hydraulic boundaries identified in the study area. A 3D representation of the conceptual model is shown in Figure 1. Both the Vettore-Bove fault system (VBfs) and the Norcia fault system (Nfs) are implemented in the conceptualization as simplified structures.

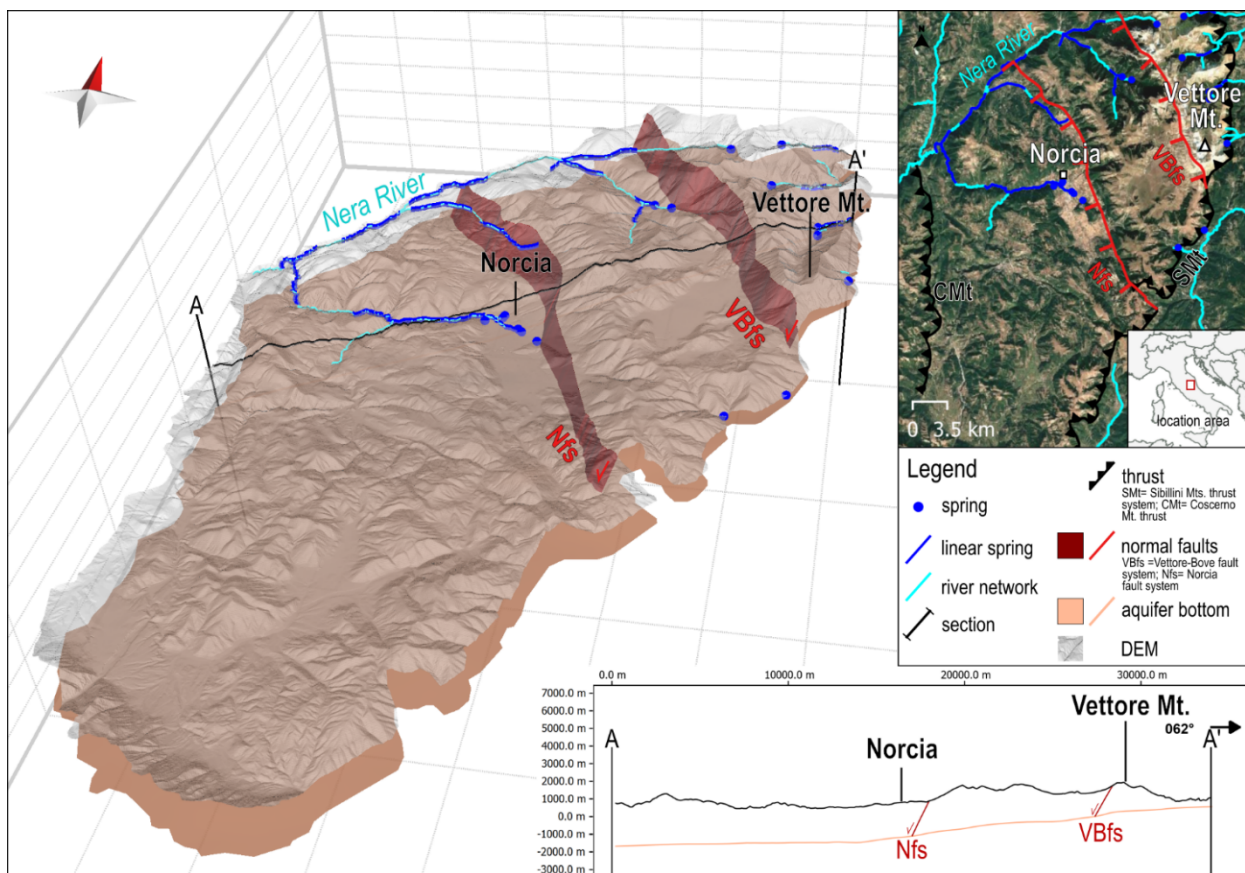


Fig. 1 – Regional hydrogeological conceptual model, 3D geometric representation

Two groundwater flow models were developed based on the defined conceptualization, whose simulation results are shown in Figure 2(a, b). In the pre-seismic groundwater flow, both *VBfs* and *Nfs* act as relative hydrogeological barriers. Their barrier effect leads to a differentiated hydraulic head within the hydrostructure, decreasing from east to west. Calibration of the hydraulic parameters was performed by using measured heads and discharge rates as target observations. The resulting parameterization was then applied to simulate the groundwater flow in the post-seismic scenario (Figure 2b). According to the concept of “*Aquifer Fault Rupture*” (Mastrorillo *et al.* 2020), the Norcia earthquake was simulated by removing the barrier effect of the *VBfs*. This forward simulation results in a redistribution of the hydraulic head in the model, especially to the east of the *VBfs*, and a subsequent change in spring discharge.

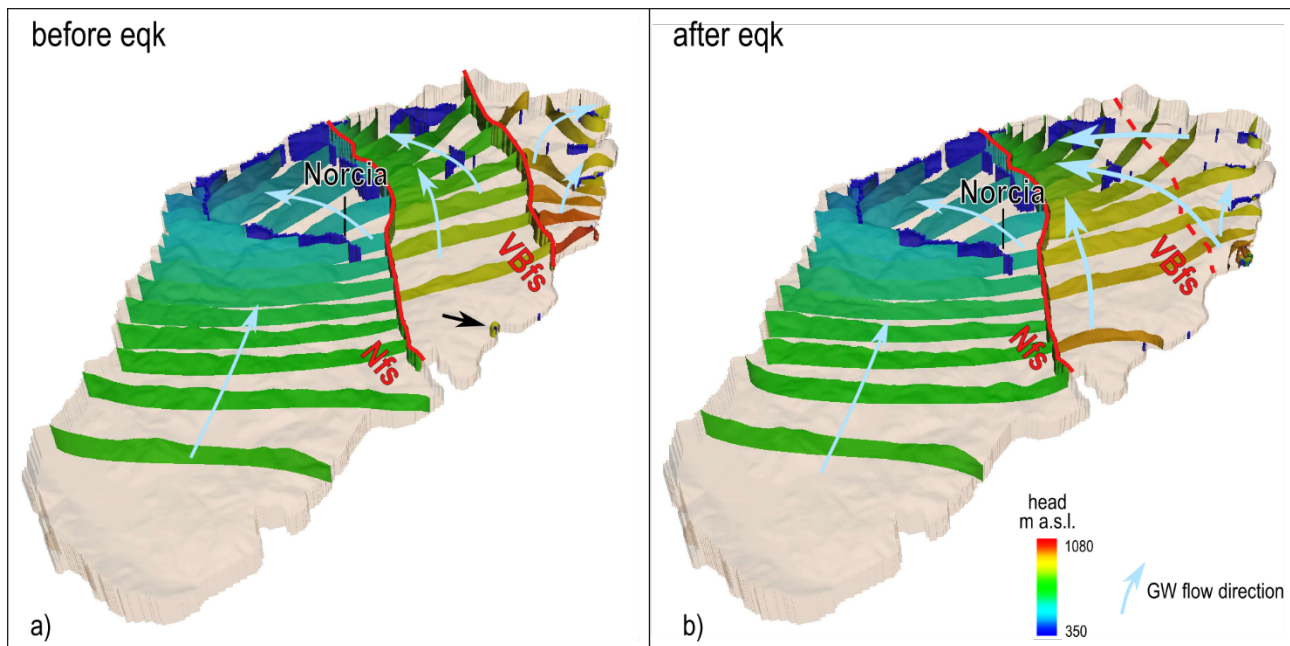


Fig. 2 – Regional groundwater flow numerical models a) before and b) after the earthquake

The results of this study are both qualitative and quantitative. The numerical models and the employed modelling approaches reproduce consistent scenarios, confirming the hypothesis that the faults act as relative hydrogeological barriers. These findings provide valuable insights into the sustained hydrogeological variations induced by the M_w 6.5 Norcia earthquake. Furthermore, the model's ability to simulate both scenarios highlight the importance of a reliable hydrogeological conceptual model.

Future research will focus on further refining the models and analysing groundwater flow in a transient simulation to gain deeper insights into the functioning of such a complex system and the non-transitory nature of the earthquake-induced hydrogeological changes.

References

- Chiaraluce L., Di Stefano R., Tinti E., Scognamiglio L., Michele M., Casarotti E., Cattaneo M., De Gori P., Chiarabba C., Monachesi G., Lombardi A., Valoroso L., Latorre D., Marzorati S.; 2017. The 2016 Central Italy Seismic Sequence: A First Look at the Mainshocks, Aftershocks, and Source Models. *Seismological Research Letters* 88, 757–771. <https://doi.org/10.1785/0220160221>
- Doherty J.; 2015. Calibration and uncertainty analysis for complex environmental models. Watermark Numerical Computing, Brisbane, Australia.
- Hanson R.T., Boyce Scott. E., Schmid W., Hughes J.D., Mehl S.M., Leake S.A., Maddok T.I., Niswonger R.G.; 2014. One-Water Hydrologic Flow Model (MODFLOW-OWHM): U.S. Geological Survey Techniques and Methods 6–A51 (Techniques and Methods), Techniques and Methods.
- Hsieh P.A., Freckleton J.R.; 1993. Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey's modular three-dimensional finite-difference ground-water flow model (USGS Numbered Series), Open-File Report.
- Manga M., Wang C.-Y.; 2007. 4.10 - Earthquake Hydrology, in: *Treatise on Geophysics*. Elsevier, pp. 293–320.
- Mastrorillo L., Saroli M., Viaroli S., Banzato F., Valigi D., Petitta M.; 2020. Sustained post-seismic effects on groundwater flow in fractured carbonate aquifers in Central Italy. *Hydrological Processes* 34, 1167–1181. <https://doi.org/10.1002/hyp.13662>
- RETRACE-3D Working Group; 2021. Progetto RETRACE-3D - centRAL italy EarThquakes integRAted Crustal modEl - Rapporto Finale. Zenodo. <https://doi.org/10.5281/ZENODO.4604940>
- Viaroli S., Mirabella F., Mastrorillo L., Angelini S., Valigi D.; 2021. Fractured carbonate aquifers of Sibillini Mts. (Central Italy). *Journal of Maps* 17, 140–149. <https://doi.org/10.1080/17445647.2021.1894252>
- Wang C., Manga M.; 2010. Hydrologic responses to earthquakes and a general metric. *Geofluids* 10, 206–216. <https://doi.org/10.1111/j.1468-8123.2009.00270.x>

Corresponding author: enrica.zullo@unicas.it