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Geological and hydrogeological review of the uppermost part of the Emilia-Romagna alluvial plain

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The Po Plain in northern Italy is a rapidly subsiding sedimentary basin characterized by a complex geological history that created an extensive fold and fault system that hosts numerous underground hydrocarbon reservoirs. The evolution of the basin is not only governed by natural factors but also by anthropogenic factors that affect both the shallower and deeper sedimentary layers. The Emilia-Romagna alluvial plain makes up part of the Po Plain and has been the focus of numerous studies related to its geomorphology, land settlement, hydrocarbon exploitation, water production and seismic behavior. The research activity has increased throughout the years due to the concern for its management and conservation, ensuring its upholding against environmental changes and human activity. An essential part for most of these studies is the geological review of the area that provides the necessary base for understanding the basin evolution and connecting results of previous studies with new research outcomes. In the current work, some aspects of the geological framework of the Po Plain are presented, focusing on the characteristics of the uppermost sedimentary deposits of the Emilia-Romagna region and in particular its hydrogeological setting and groundwater bodies. This paper provides an overview of the fundamental geological characteristics of the alluvial subsurface exploited for groundwater production, which constitute the main cause of land subsidence in Emilia-Romagna.
Keywords*: Po plain, subsidence, water production, hydrogeological settings, stratigraphy*

1. Introduction

The Emilia-Romagna alluvial plain makes up the southeastern part of the Po Plain sedimentary basin in northern Italy. The Po Plain is bound between the Southern Alps to the north and the Northern Apennines to the south and represents their foreland basin system during the Paleogene (Turrini *et al.*, 2014, 2015; Rossi *et al.*, 2015). The region of Emilia-Romagna is well known for its historical heritage sites (e.g. Ferrara and Ravenna, included in the *UNESCO World Heritage*), its widespread industrialized areas, its natural environment and its extensive agricultural activities. Over the last century, it has been affected by a drastic subsidence due to natural and anthropogenic factors (Fig. 1). The anthropogenic subsidence was driven by the economic development and increasing demand for the utilization of the natural resources of the basin after World War II. The exploitation mainly includes groundwater from a shallow multi-aquifer system as well as natural gas from onshore and offshore reservoirs (Teatini *et al.*, 2006). The anthropogenic components of subsidence affect and speed-up the natural subsidence processes (Galloway, 2014). In fact, in the Emilia-Romagna plain, an increase in subsidence rates has been recorded from 2-3 mm/yr up to 70 mm/yr (Cenni *et al.*, 2013) with some areas subsiding cumulatively by more than 1 m since the 1950s (Carbognin *et al.*, 1984; Teatini *et al.*, 2005).

Subsidence studies are essential for the preservation and risk assessment of several parts of the Emilia Romagna region. They necessitate a detailed geological-stratigraphic model as an input that accurately describes the characteristics of the uppermost sedimentary layers. In this paper, a geological review of the Emilia-Romagna alluvial plain is presented, focusing on the sedimentary layers affected by the water production used for civil and agricultural use (Teatini *et al.*, 2006).

2. Tectono-stratigraphic setting

The Po Plain rests between the fold-and-thrust belts of the Southern Alps and Northern Apennines and is filled with accumulating thicknesses of Pliocene-Quaternary sediments (Fig. 2a,b). The development of these belts is the result of the collision of the African and European plates that began in the Cretaceous and is still ongoing with rates of 3-8 mm/yr (Bruno *et al.*, 2021). Consequently, the Po Plain lies on the Adria microplate, that is the buried sector of a promontory of the Africa plate.

Before the dominant compressional period of the area, a Mesozoic extensional phase occurred that lasted until the lower Paleogene. The Cenozoic compression was the main cause of the development of the Southern Alps thrust zones due to a N-S tectonic compres-

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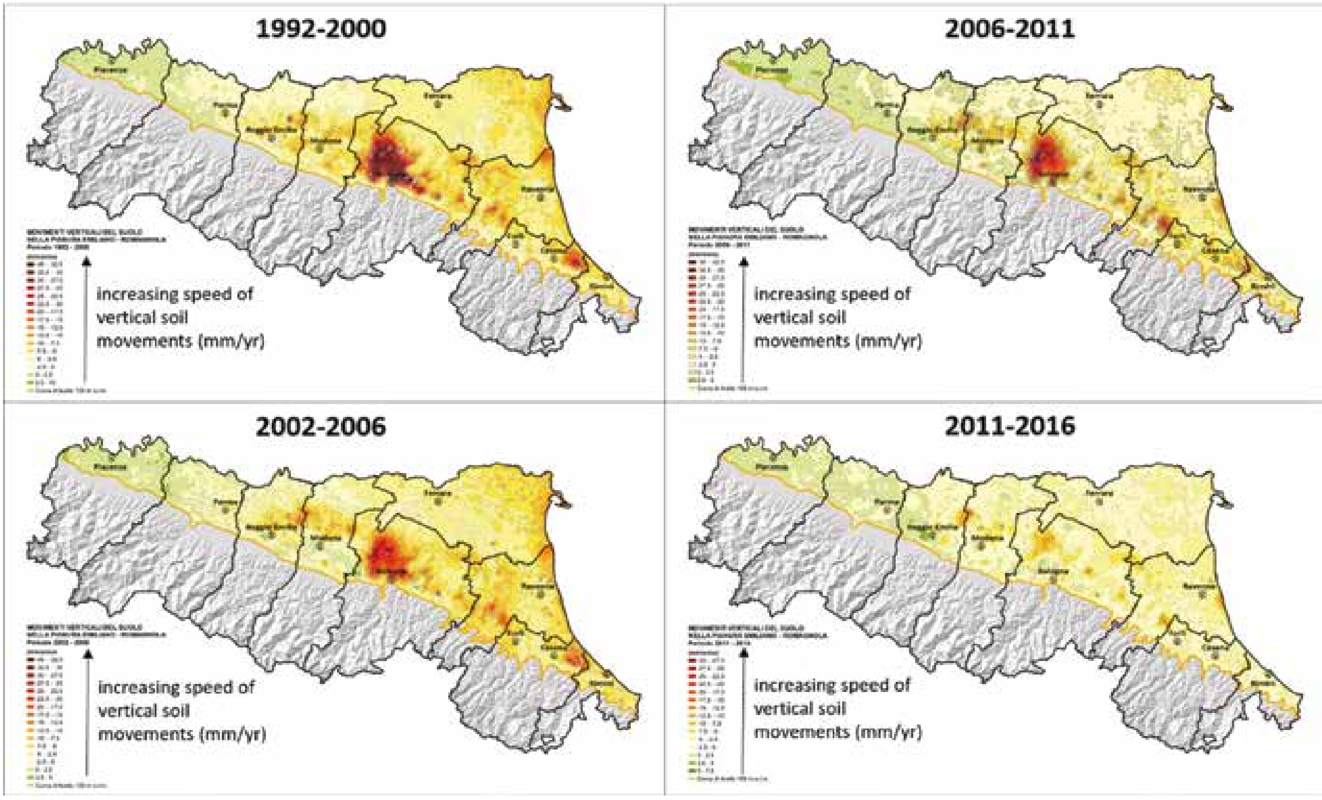

Fig. 1 – Maps showing present-day subsidence in Emilia-Romagna for four time periods from 1992 till 2016 (from ARPAE 2007, 2012, 2018a).

sion during the middle Eocene to Miocene and the Northern Apennines due to a NNE-SSW compression during the Oligocene to Pliocene-Pleistocene (Ghielmi *et al.*, 2013). The Po Plain can be divided into two zones; the northern zone mostly connected to the tectonic system of the Southern Alps and the southern zone connected to the Northern Appenines. The southern Po Plain is characterized by a series of tectonic fronts made up of three blind thrusts and folds belts, named from west to east the Monferrato, Emilia and Ferrara-Romagna Arcs (Fig. 2a, Livani *et al.*, 2023 and references therein). The buried fronts of the Apennines to the NE lie under the present coastal plain and are made up of SW dipping thrusts and folds related to the Ferrara-Romagna Arcs that are subdivided into the Ferrara (the most external structures of this arc), Romagna and Adriatic Folds (Fig. 2a,b). These folds have been tectonically active since the early Pliocene and are still

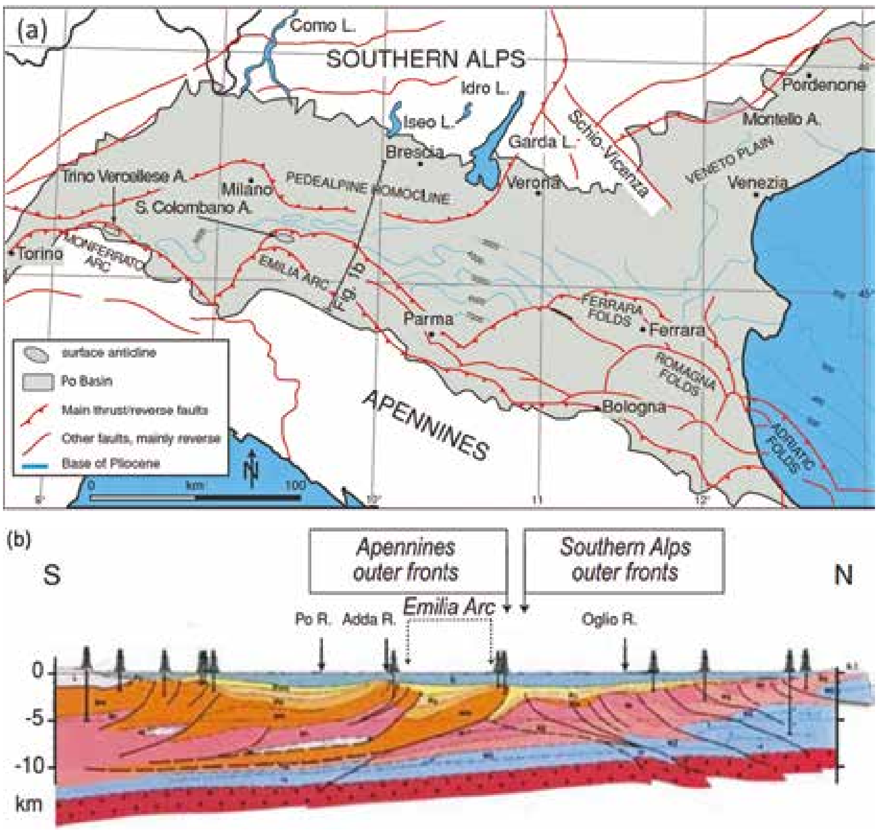

Fig. 2 – (a) Simplified structural map of the Po Plain (b) Cross-section of the central Po Plain (location of trace shown above) showing the sedimentary cover overlying the outer fronts of the Northern Apennines and Southern Alps (modified from Burrato *et al.*, 2003).

considered active by the moderate to high seismicity affecting the Po Plain, such as the 2012 Emilia earthquake (e.g. Bonini *et al.*, 2014). As for the northern Po Plain related to the Alps chain, its external fronts are represented by the retrobelt of the mountain chain that almost reaches the Northern Apennines front in the southernmost western extent (Fig. 2b, Fantoni and Franciosi, 2010).

The overall stratigraphy of the Po Plain with its bounding mountain chains was interpreted using seismic profiles and deep exploration wells for hydrocarbon (e.g. Regione Emilia-Romagna and ENI-AGIP, 1998; Regione Lombardia and Eni, 2002; Amorosi *et al.*, 2008; Ghielmi *et al.*, 2013). It consists mainly of Mesozoic carbonate and marly sequences underlying the largely Cenozoic clastic deposits, with the whole sedimentary record deposited on a Hercynian crystalline basement (Turrini *et al.*, 2014). The Plio-Quaternary alluvial cover represents the most recent sedimentation derived from the erosion of the mountain chains and has a thickness that ranges from 6 to 8 km in the central Plain to around 100 m at the top of the buried anticlines of the Apennines (Amadori *et al.*, 2019).

The Plio-Quaternary basin fill shows a cyclic facies architecture, subdivided into six third-order depositional sequences (*sensu* Mitchum *et al.*, 1977) bounded by tectonic-driven unconformities. The overall trend of the basin fill is regressive, showing deep-sea deposits from Late Miocene-Pliocene replaced by continental and coastal deposits during the Pleistocene (Rossi *et al.*, 2021). The uppermost part of the succession makes up the Po Supersynthem (Amorosi *et al.*, 2008) with its lower boundary being a major unconformity that dates back to 0.87 Ma. The Po Supersynthem is divided into the Upper and Lower Po Synthems separated by a minor unconformity aging 0.45 Ma (Fig. 2, Martelli *et al.*, 2017). Each Synthem consists of four subsynthems that are vertically stacked and make up eight fourth-order or transgressive-regressive (T-R) cycles.

The lithological characterization depends on the difference sectors of the Po Plain. In the distal sector of the southern Po Plain plain (underneath the modern coastal areas), the Upper Po Synthem is characterized by the cyclic alternation of alluvial and shallow-marine deposits (Fig. 3), with the latter accumulated during interglacial periods of sea-level rise (transgression). In the proximal area beneath the Po River and along the Apennines margin, muddy overbank deposits underlie extensive and elongated fluvial channel deposits (Fig. 3) accumulated during glacial periods of forced sea-level drop (Bruno *et al.*, 2021; Rossi *et al.*, 2021). However, the northern Po Plain zone is dominated by sandy and coarse deposits in generally tabular shapes (Vai, 2001; Fantoni and Franciosi, 2010).

3. *Hydrogeological setting*

The hydrogeological setting of the Po Plain is characterized by a multilayered aquifer system represented by the depositional sequences that make up the Po Supersynthem discussed in section 2. The aquifer reaches depths of 2000 m in syncline areas that separate the buried anticlines but is heavily reduced to depths of 100 m on top of the buried anticlines (Cinti *et al.*, 2023). In the Emilia-Romagna alluvial plain, the aquifer system occupies the Upper and Lower Emilia-Romagna Synthems, denoted as AES and AEI respectively (Fig. 4b) and corresponding to the Upper and Lower Po Synthems (section 2). It locally exceeds 500 m of thickness and is made up of sand and gravel deposits alternating with silty and muddy layers (Regione Emilia-Romagna and ENI-AGIP, 1998). The gravels originate from Apennine alluvial fans whereas the interlayers of sand and clay have been eroded by the Po river. Gravels are dominated by arenaceous and calcareous sandstones whereas clays are mostly made up of illite and chlorite minerals. The sands, derived from both Apennine and Alpine origins, are represented by: quartz, feldspars, micas and femic minerals (Martinelli *et al.*, 2014). Maximum thicknesses are identified in areas corresponding to the river conoids of Emilia-Romagna. It encompasses freshwater, saltwater and brackish waters, with their boun-

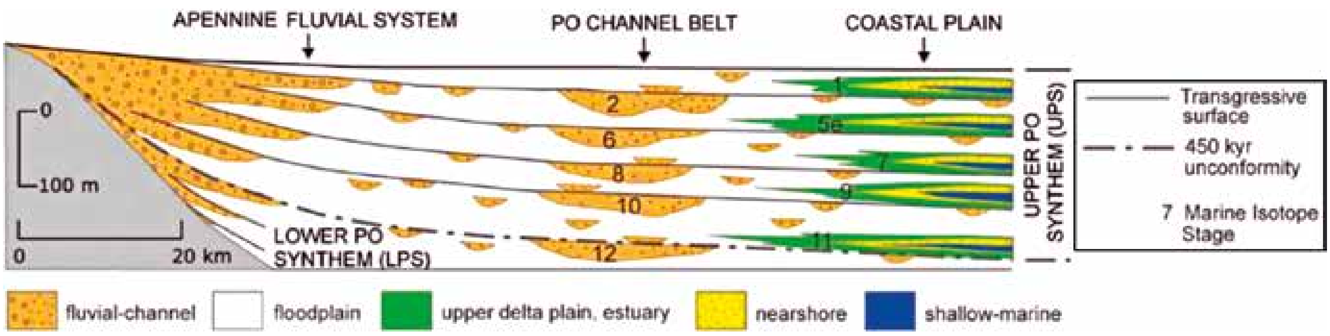

Fig. 3 – Schematic stratigraphic architecture of the Upper Po Synthem (from Bruno *et al.*, 2021).

daries found at varying depths depending on the buried structures. This is indicated by the presence of some chemical compositions such as Na-Cl and $Na-HCO_3$ that indicate the combining of freshwater and saltwater during marine transgressions (Carminati and Martinelli, 2002). Above buried anticlines, brackish waters usually reach the surface whereas above synclines, fresh waters extend to grater depths (Rapti-Caputo and Martinelli, 2008). Regione Emilia-Romagna and ENI-AGIP (1998) identified three main hydrostratigraphic units, hence aquifer groups: A, B and C in increasing order of age. Aquifer groups A and B are both subdivided into four bodies (A1-A4 and B1-B4, Fig. 4b) and are mostly made up of alluvial plain deposits and deposits of meandric origin. Aquifer group C is mainly characterized by marine deltaic deposits. The recharge of the aquifer groups is restricted to direct meteoric infiltration for the upper non-confined aquifer (named A0) ranging in depth from 0-30 m whereas the confined aquifers (A1 to C) are laterally recharged by the waters from the mountain chains. In Emilia-Romagna, the total recharge of local groundwater is $710x10^6$ m^3/year. In the central and eastern part of the Po Plain, fine-grained aquifers display low hydraulic gradients (1-2%) and low circulation velocities of a maximum of 0.1 m per day (Martinelli *et al.*, 2017). The fine-grained aquifers are characterized by fine sediments derived by the Po river separating coarse-grained deposits derived from the Apennines. These aquifers lack present-day recharge processes (Pilla *et al.*, 2006) and are subject to a tectonic pressure due to the shortening of the crust between the Alps and the Apennines. On the other hand, coarse-grained aquifers are located on the foothills of the Alps and the Apennines and display high hydraulic gradients (10%) and high circulation velocities, reaching up to 4 m/day (Martinelli *et al.*, 2017).

4. Emilia-Romagna groundwater reserves

The Emilia-Romagna aquifers are subdivided vertically into two groundwater bodies: the upper portion consisting of the superficial aquifers A1 and A2 and the lower portion consisting of the remaining aquifer complexes A3, A4, B and C (Regione Emilia-Romagna, 2010a). They are referred to as the upper confined groundwater bodies and lower confined bodies, respectively. A single free, unconfined aquifer (A0) overlies these two bodies and is present in the Apennine alluvial fans (Fig. 5).

Water production in the Emilia-Romagna plain is usually concentrated from aquifer group A, and can originate from three hydrogeological complexes: Apennine alluvial fans, Apennine plain and Po Plain (Regione Emilia-Romagna and ARPA, 2003). Fig. 6 shows the distribution of these complexes in aquifer A. The Apennine alluvial fans are subdivided into major, intermediate and minor fans based on the volume of the coarse deposits present in them. A further subdivision distinguishes the proximal fans at the foothill of the chain from the distal fans, with the latter representing the transition between

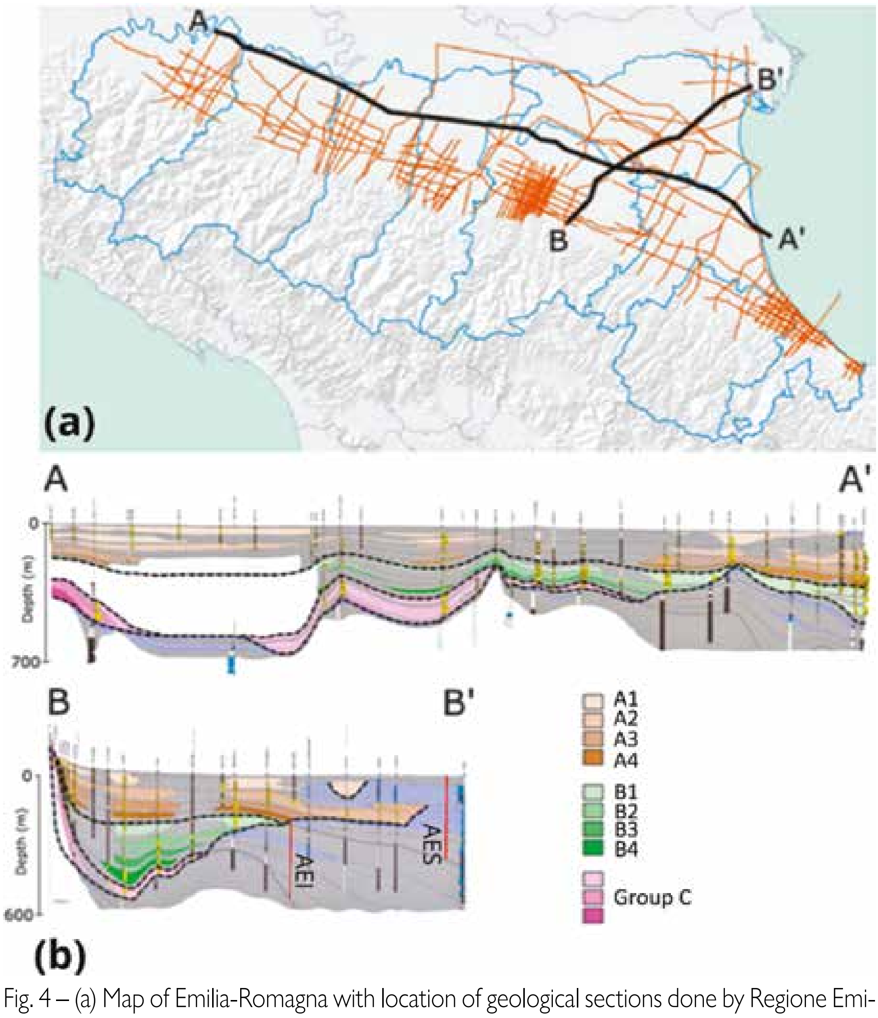

Fig. 4 – (a) Map of Emilia-Romagna with location of geological sections done by Regione Emilia-Romagna (b) Cross-sections (location of traces in (a)) displaying the main aquifer groups and the Emilia-Romagna Synthems. AES=Upper Emilia-Romagna Synthem, AEI=Lower Emilia-Romagna Synthem (modified from Eid *et al.*, 2022).

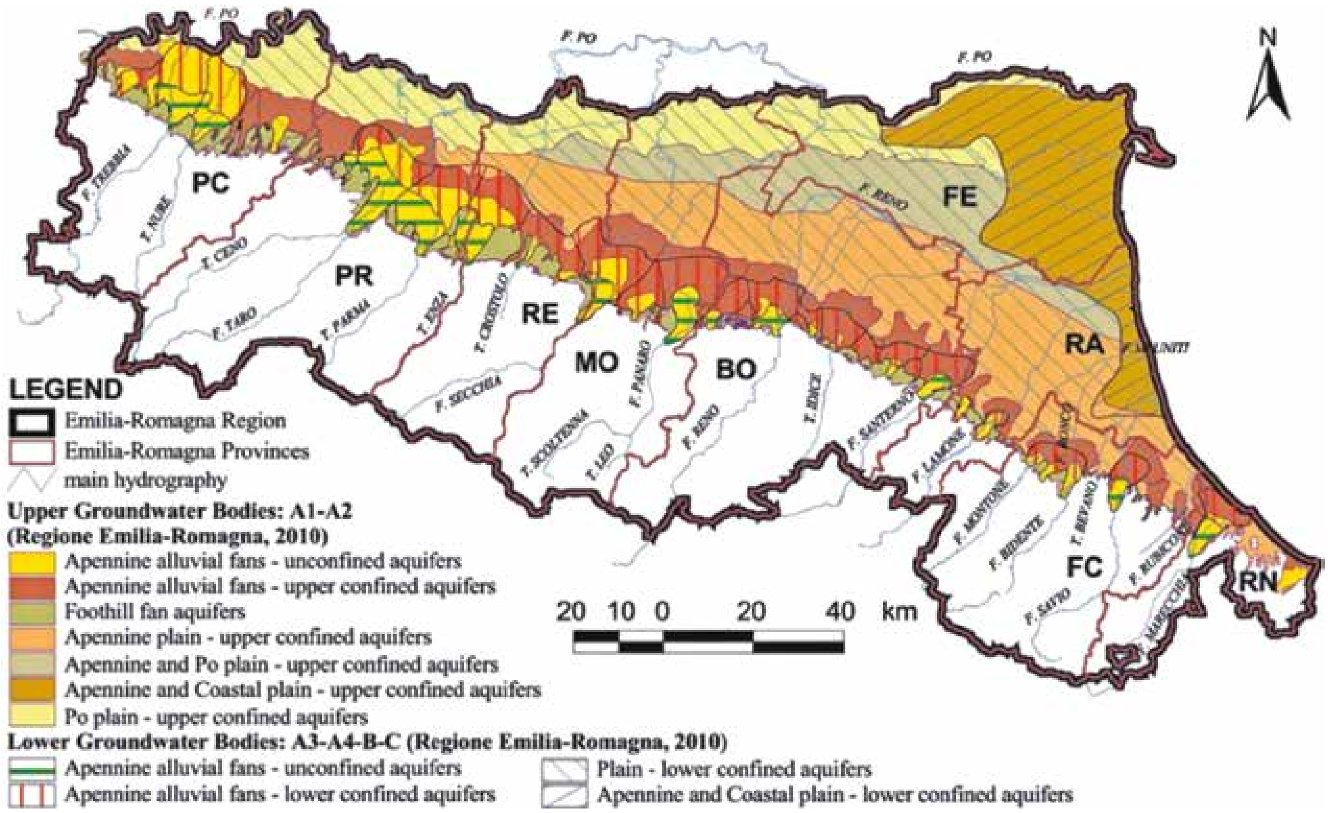

Fig. 5 – Characterization of Emilia-Romagna groundwater bodies (from Regione Emilia-Romagna, 2010a).

the Apennine alluvial fans and the Apennine and Po plains.

The history of water production in the Emilia-Romagna region is delineated as follows: production rates of about 200x10^6 m^3/year were recorded in the 1950s followed by a drastic increase following World War II and its post-development economic boom to rates up to 740x10^6 m^3/year in the late 1970s. Since then, regional and local governments implemented new strategies to decrease the extraction of groundwater on a municipal basis and manage it more efficiently. Production rates of 710x10^6 m^3/year and 703x10^6 m^3/year were recorded for the years 1992 and 1999, respectively. Fig. 7 demonstrates the rates for the more recent years, from 2003 till 2018 with a slight decrease from 663x10^6 m^3/year to 623x10^6 m^3/year (Eid *et al.*, 2022). The volumes represent the total production per municipality, combining the withdrawals extracted for different purposes: agricultural, civil and industrial. Civil and industrial production rates can be accurately recorded and measured whereas agricultural rates are usually estimated. The spatial distribution of groundwater withdrawals for civil use is concentrated along the Apennine alluvial fans to the south whereas the remaining distribution for civil and agricultural purposes is uniform along the plain and is locally defined (Regione Emilia-Romagna, 2010a).

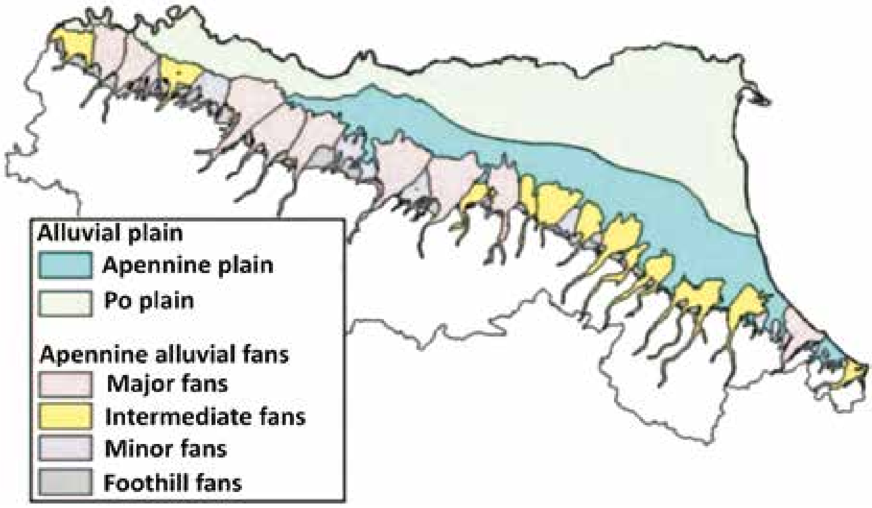

Fig. 6 – Hydrogeological complexes of aquifer group A (modified from Regione Emilia-Romagna and ARPA, 2003).

5. Conclusion

A geological review of an area undergoing subsidence is a preliminary step that lays the groundwork for the accurate monitoring and prediction of the phenomenon and informs effective mitigation strategies. The Emilia-Romagna region and the Po Plain in general, has been subject to rapid subsidence rates throughout the past century induced from natural and anthropogenic drivers. Anthropogenic land subsidence caused by groundwater extraction, following the economic development in the 1950s, represents the most important cases in the region. The distribution and density of the water extractions is related to their specific use that can be either for agricultural, civil or industrial purposes. The latter is linked to dense water extractions with local distributions while water withdrawals for civil purposes are concentrated along the Apennine alluvial fans. Agricultural water production is uniform in the Emilia-Romagna region. This paper delineates the main characteristics in terms of hydrogeological setting of the shallow portion of the Po plain deposits in the Emilia-Romagna region focusing on its stratigraphic evolution and the characterization of its alluvial plain, which contains the aquifers utilized for the extraction of groundwater.

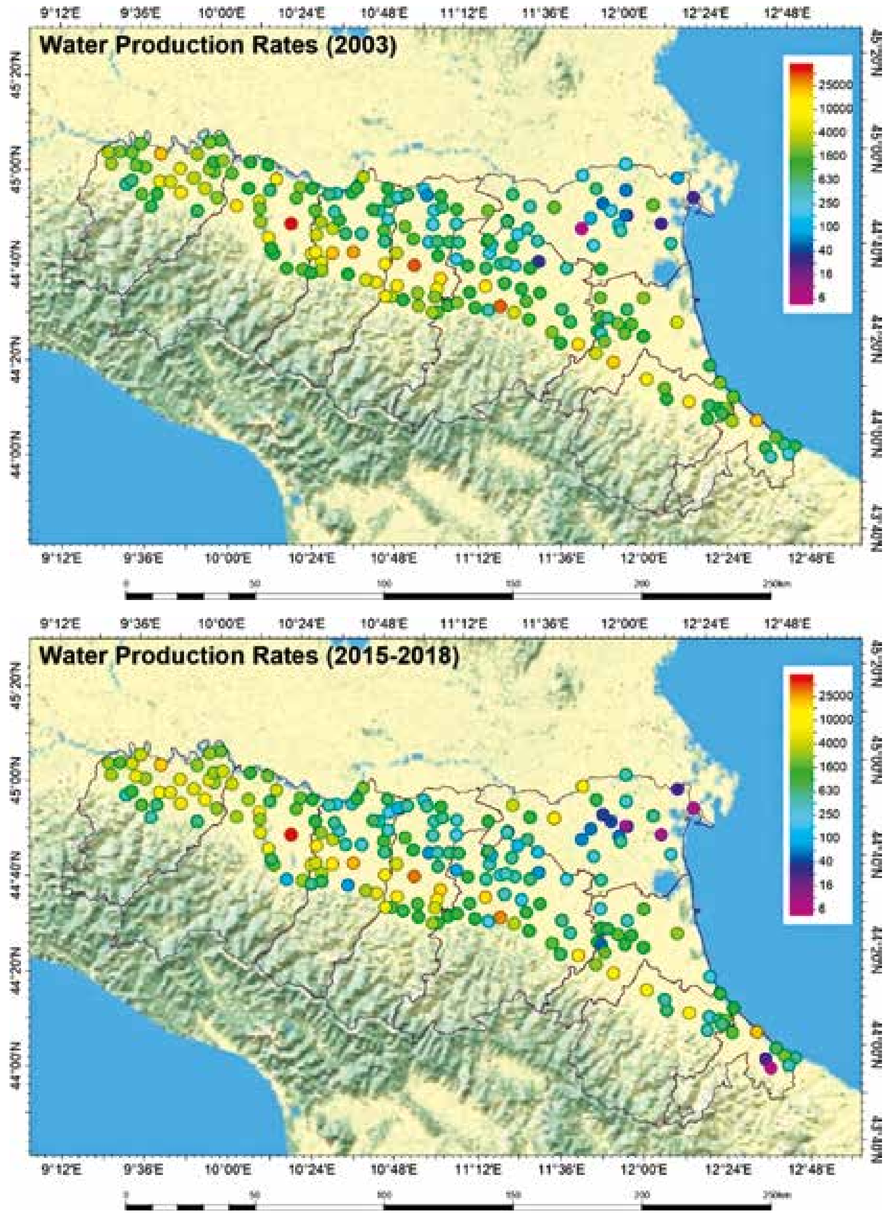

Fig. 7 – Total water production rates (in 106 m3/year) for the years 2003 (above) and 2015-2018 (below, from Eid *et al.*, 2022).

References

Amadori, C., Toscani, G., Di Giulio, A., Maesano, F.E., D'Ambrogi, C., Ghielmi, M. and Fantoni, R., (2019). From cylindrical to non-cylindrical foreland basin: Pliocene-Pleistocene evolution of the Po Plain-Northern Adriatic basin (Italy). Basin Research, 31(5), pp. 991-1015.

Amorosi, A., Pavesi, M., Ricci Lucchi, M., Sarti, G., Piccin, A., (2008). Climatic signature of cyclic fluvial architecture from the Quaternary of the Central Po Plain, Italy. Sediment. Geol. 209, 1-4, pp. 58-68.

ARPAE (Agenzia Prevenzione Ambientale Energia Emilia-Romagna). Rilievo della subsidenza nella pianura emiliano-romagnola. Analisi interferometrica anno: 2007.

ARPAE (Agenzia Prevenzione Ambientale Energia Emilia-Romagna). Rilievo della subsidenza nella pianura emiliano-romagnola – seconda fase anno: 2012.

ARPAE (Agenzia Prevenzione Ambientale Energia Emilia-Romagna). Rilievo della subsidenza nella pianura emiliano-romagnola – seconda fase, Bologna, 2018a.

Bonini, L., Toscani, G. and Seno, S., (2014). Three-dimensional segmentation and different rupture behavior during the 2012 Emilia seismic sequence (Northern Italy). Tectonophysics, 630, pp. 33-42.

Bruno, L., Amorosi, A., Lugli, S., Sammartino, I., Fontana, D., (2021). Trunk river and tributary interactions recorded in the Pleistocene–Holocene stratigraphy of the Po Plain (northern Italy). Sedimentology, 68, pp. 2918-2943.

Burrato, P., Ciucci, F., Valensise, G., (2003). An inventory of river anomalies in the Po Plain, Northern Italy: evidence for active blind thrust faulting. Annals of Geophysics, 46, pp. 865-882.

Carbognin, L., Gatto, P., and Mozzi, G., (1984). Case history 9.15. Ravenna, Italy. in J.F. Polland (Ed.), Guidebook to studies of land subsidence due to

groundwater withdrawal, pp. 291-305. UNESCO, Paris.
Carminati, E. & Martinelli, G., (2002). Subsidence rates in the Po Plain, northern Italy: the relative impact of natural and anthropogenic causation. Engineering Geology, 66, pp. 241-255.
Cenni, N., Viti, M., Baldi, P., Mantovani, E., Bacchetti, M., Vannucchi, A., (2013). Present vertical movements in central and northern Italy from GPS data: possible role of natural and anthropogenic causes. Journal of Geodynamics, 71, pp. 74-85.
Cinti, D., Sciarra, A., Cantucci, B., Galli, G., Pizzino, L., Procesi, L., Poncia, P.P., (2023). Hydrogeochemical investigation of shallow aquifers before and after the 2012 Emilia seismic sequence (Northern Italy). Applied Geochemistry, 151, 105624.
Eid, C., Benetatos, C., Rocca, V., (2022). Fluid Production Dataset for the Assessment of the Anthropogenic Subsidence in the Po Plain Area (Northern Italy). Resources, 11, 53.
Fantoni, R. and Franciosi, R., (2010). Tectono-sedimentary setting of the Po Plain and Adriatic foreland. Rendiconti Lincei. Scienze Fisiche e Naturali, 21, pp. 197-209.
Galloway, D.L., (2014). The current situations and developing trend of international land subsidence research. Shanghai Land & Resources, 35 (2).
Ghielmi, M., Minervini, M., Nini, C., Rogledi, S., Rossi, M., (2013). Late Miocene-Middle Pleistocene sequences in the Po Plain-Northern Adriatic Sea (Italy): The stratigraphic record of modification phases affecting a complex foreland basin. Marine and Petroleum Geology, 42, pp. 50-81.
Livani, M., Petracchini, L., Benetatos, C., Marzano, F., Billi, A., Carminati, E., Doglioni, C., Petricca, P., Maffucci, R., Codegone, G., Rocca, V., Verga, F., & Antoncecchi, I., (2023). Subsurface geological and geophysical data from the Po Plain and the northern Adriatic Sea (North Italy). Earth System Science Data, 15(9), 4261.
Martelli, L., Bonini, M., Calabrese, L., Corti, G., Ercolessi, G., Molinari, F.C., Piccardi, L., Pondrelli, S., Sani, F., Severi, P., (2017) Seismotectonic map of Emilia Romagna Region and surrounding areas to scale 1:250.000. D.R.E.Am. MAP, Pistoia.
Martinelli, G., Chahoud, A., Dadomo, A., Fava, A., (2014). Isotopic features of Emilia-Romagna region (North Italy) groundwaters: Environmental and climatological implications. Journal of Hydrology, 519, pp. 1928-1938.
Martinelli, G., Dadomo, A., Italiano, F., Petrini, R., Slejko, F.F., (2017). Geochemical monitoring of the 2012 Po Valley seismic sequence: A review and update. Chemical Geology, 467, pp. 147-162.
Mitchum, J.R.M.,Vail, P.R., Thomson III, S., (1977). Seismic stratigraphy and global changes of sealevel, Part 2: The depositional sequence as a basic unit for stratigraphic analysis. In American Association of Petroleum Geologists Memoir 26; Payton, C.E., Ed.; American Association of Petroleum Geologists: Tulsa, OR, USA, 1977, pp. 53-62.
Pilla, G., Sacchi, E., Zuppi, G.M., Braga, G., Ciancetti, G., (2006). Hydrochemistry and isotope geochemistry as tools for groundwater hydrodynamic investigation in multilayer aquifers: a case study from Lomellina, Po plain, South Western Lombardy, Italy. Hydrogeology Journal, 14, pp. 795-808.
Rapti-Caputo, D., Martinelli, G., (2008). The geochemical and isotopic composition of aquifer systems in the deltaic region of the Po plain (northern Italy). Hydrogeology Journal, 17, pp. 467-480.
Regione Emilia-Romagna & ENI-AGIP (1998). Riserve idriche sotterranee della Regione Emilia-Romagna. A cura di G. Di Dio. Selca, Firenze.
Regione Emilia-Romagna & ARPA (2003). Le caratteristiche degli acquiferi della Regione Emilia-Romagna – Report 2003. A cura di A. Fava, M. Farina e M. Marcaccio.
Regione Emilia-Romagna (2010a). Delibera di Giunta n. 350 del 8/02/2010, Allegato 2 Tipizzazione/caratterizzazione e individuazione dei corpi idrici superficiali e sotterranei, prima individuazione delle reti di monitoraggio “Surface and groundwater bodies definition and characterization, first monitoring network set-up”.
Regione Lombardia & ENI DIVISIONE AGIP (2002). Geologia degli Acquiferi Padani della Regione Lombardia. Selca, Firenze.
Rossi, M., Minervini, M., Ghielmi, M., Rogledi, S., (2015). Messinian and Pliocene erosional surfaces in the Po Plain-Adriatic Basin: insights from allostratigraphy and sequence stratigraphy in assessing play concepts related to accommodation and gateway turnarounds in tectonically active margins. Marine and Petroleum Geology, 66, pp. 192-216.
Rossi, M., Amorosi, A., Barbieri, G., Vaiani, S.C., Germano, M., Bruno, C., (2021). A Long-Term Record of Quaternary Facies Patterns and Palaeonvironmental Trends from the Po Plain (NE Italy) as Revealed by Bio-Sedimentary Data. Geosciences, 11, 401 p.
Teatini, P., Ferronato, M., Gambolati, G., Bertoni, W., Gonella, M., (2005). A century of land subsidence in Ravenna, Italy. Environmental Geology, 47(6), pp. 831-846.
Teatini, P., Ferronato, M., Gambolati, G., Gonella, M., (2006). Groundwater pumping and land subsidence in the Emilia-Romagna coastland, Italy; Modeling the past occurrence and the future trend. Water Resources Research, 42.
Turrini, C., Lacombe, O., Roure, F., (2014). Present-day 3D structural model of the Po Valley basin, Northern Italy. Marine and Petroleum Geology, 56, pp. 266-289.
Turrini, C., Angeloni, P., Lacombe, O., Ponton, M., Roure, F., (2015). Three-dimensional seismo-tectonics in the Po Valley basin, Northern Italy. Tectonophysics, 661, pp. 156-179.
Vai, G.B., (2001). Structure and stratigraphy: an overview. In: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an Orogen. The Apennines and Adjacent Mediterranean Basins. Springer, Dordrecht, pp. 15-31.