3D geological model to assess the fate of contaminant transport in groundwater: the case study of Maruzzella Landfill (Caserta, Italy)

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Short Note

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ABSTRACT

In order to assess the potential risk of aquifer pollution in an alluvial plain area used as a landfill, a detailed geological and hydraulic model of the subsoil was realised. The chosen area is represented by the transfer site for solid urban waste called "Maruzzella", in the lower plain of the Volturno River. The analysis of lithostratigraphic data allowed a 3D reconstruction of the subsoil, which was subsequently implemented thanks to a hydrostratigraphic characterization. Through the use of GIS, the calculation grids necessary for the characterization of the flows have been built, elaborated through the use of ModFlow with three different 3D models of the subsoil with increasing degrees of geological simplification. The dispersion models created with ModFlow made possible to establish the dispersive dynamics that predominate or coexist in relation to permeability and temporal progression considering different stress periods, respectively equal to 3650 days and 7300 days. The comparison of the geological scenarios highlighted the real dispersive processes, thus underlining the importance of a detailed knowledge of the stratigraphic architecture of the subsoil.

KEY-WORDS: Volturno River alluvial plain, Campania Plain, landfill, geological model, hydrostratigraphic characterization.

INTRODUCTION

Landfill is the most common method of managing solid waste all over the world. Landfills are not closed systems, nor are they inert ones. Deposited materials degrade, gases are emitted and water percolating through landfills will pick up and transport chemicals creating leachate: a complex mixture of suspended and soluble substances.

To prevent contamination of groundwater, modern landfills are usually engineered to contain and collect leachate (Vaverkovà, 2019); the latter is usually contained by an "impermeable" or low permeable liner system, collected in a drainage system, pumped out, and normally subjected to treatment prior to discharge to a surface water body. When the leachate is not properly managed, problems can arise for the groundwater system.

Groundwater represents an integral part of the hydrological cycle and is a widespread environmental concern. At global level, the vulnerability of aquifers is increasing at an alarming rate, due to environmental pollution and intensive human activities (De Filippis et al., 2020). Among these latter, in recent years there has been an incredible increase in the number of groundwater contamination incidents due to infiltration of dangerous chemical substances into the ground and, consequently, into the aquifers. These chemical substances are produced by waste leachate, if not properly controlled.

The surrounding media properties have a greatly influence on pollutant mobility and persistence. Thus, hydraulic transport modelling of leachate depends on several aspects: physic, geological and chemical parameters of aquifer, discharge way of pollutant in groundwater and space and time scaling of computational grid. The interaction of all these elements allows a correct mathematical simulation of real case study that is fundamental to design environmental remediation.

In this perspective, in order to avoid groundwater contamination by leachace, the most important factors to be taken into account while assessing landfill sites are the subsurface geological framework,the hydrogeological characteristics and conditions that dominate the overall region (Abou El-Magd et al., 2022). Groundwater flow and contaminant transport conditions must be taken into account and simulated in the best possible way to make a prediction of every possible effect and, so, to provide the proper aquifer protection (Sharma & Reddy, 2004).

Aim of the present study is to provide a 3D modelling of groundwater flow and leachate transport in the aquifer, with reference to a real case study of Maruzzella solid waste landfill in province of Caserta (Campania region, southern Italy, in the lower plain of the Volturno River; Fig. 1). Three different evolution scenarios of transport pollutant plume were simulated and analysed to assess the best geological subsoil model to be considered to track the leachate flow paths/rates for remediation interventions.

Since the late-Pleistocene, the sedimentary evolution of the plain was strongly controlled by an intense volcanic activity that provided a massive deposition of pyroclastic products. One of the last eruptions emplaced the Campania Grey Tuff deposits (CGT; ~39 Ky; Rolandi et al., 2020) that covered the whole Campania Plain; the pyroclastic flow deposits of the CGT blanketed the whole area and filled morphological depressions, dipping gently towards the central region of the plain, giving origin to a thick (on average 50 m), laterally continuous, volcaniclastic unit which covered

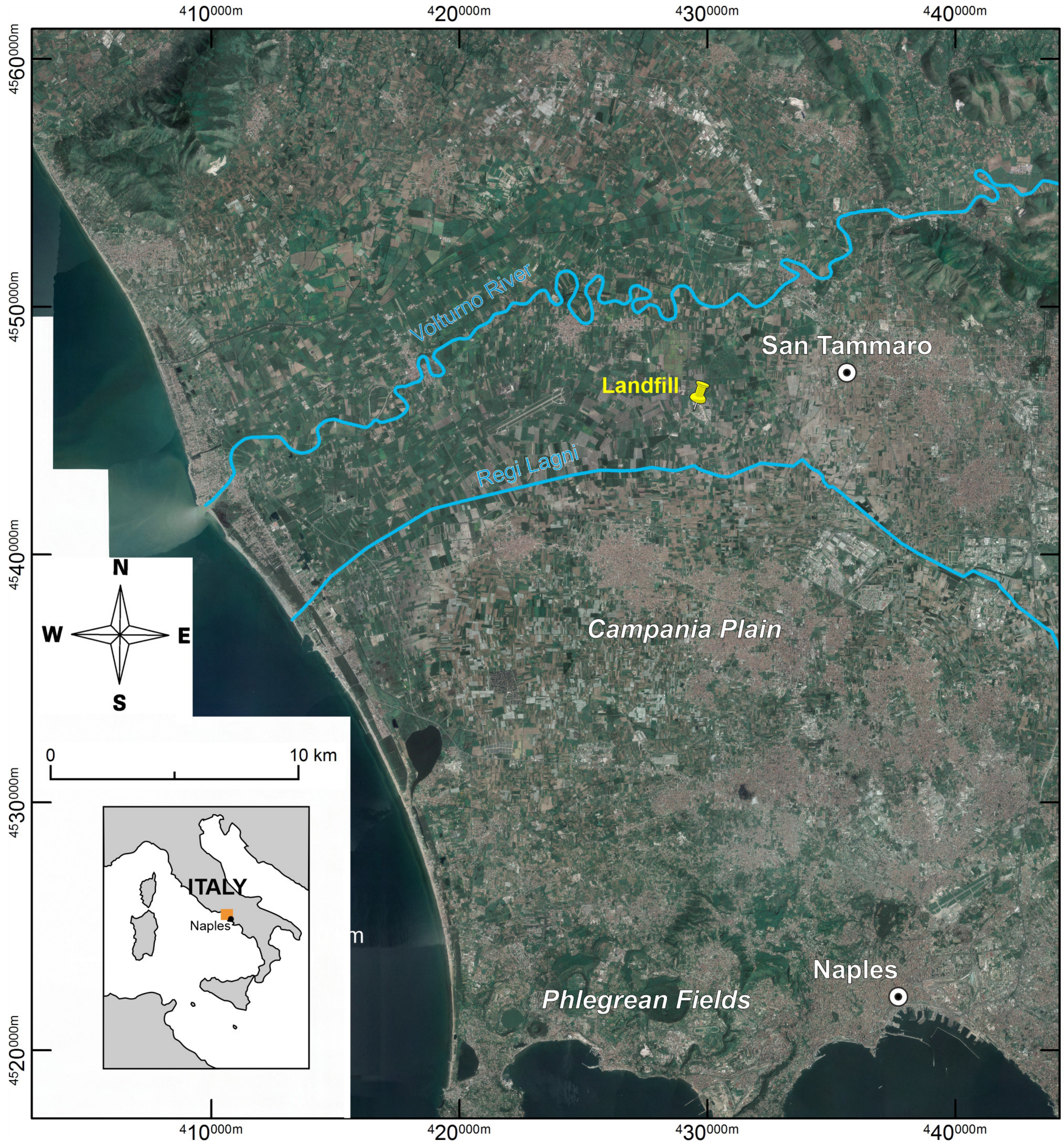

Fig. 1 - The northern Campania Plain and the location of the study site.

previous marine-transitional units (Putignano et al., 2007; Ruberti et al., 2020). These deposits were deeply eroded by the paleo-Volturno River in response to the Last Glacial Maximum sea-level drop (Ruberti et al., 2018). During the Pleistocene-Early Holocene (ca. 15 ka-6 ka) the post-glacial rising of sea level caused a rapid flooding of the Volturno River plain (Corrado et al., 2020; Ruberti et al., 2022). Since 6.5 ka BP a coastal progradational phase established, allowing the formation of the present-day alluvial plain and the wave-dominated delta system.

The area considered in the present study is the waste landfill of Maruzzella in the Municipality of San Tammaro (province of Caserta), between the Volturno River and the Regi Lagni Canal, in the central northern sector of the Campania Plain. The morphology of the area is almost flat with topographic altitudes between + 11 and + 13 m a.s.l. The stratigraphic architecture of the post-CGT deposits was conditioned both by the volcanic activity of the Phlegraean Fields and the presence of the Volturno and ancient Clanio (the current artificial canal of the Regi Lagni) Rivers (Fig. 2).

The water table is phreatic and the groundwater flux lines are NE-SW oriented. An impermeable layer is present at the bottom of the aquifer, hence a horizontal movement of the aquifer itself with the pollutants can be predicted (AA.VV., 2008). As most of the alluvial settings, which represent important natural water reservoirs, this sector of the Campania Plain is an area with strong anthropic impact caused by urban growth and agricultural and industrial activities. Thus, this setting offers a good opportunity to study issues related to the groundwater vulnerability and its protection (cf. Ruberti et al., 2014; Roviello et al., 2020; Vigliotti et al., 2020).

METHODS

Geological model

For the realization of a 3D model of the subsoil, lithostratigraphic data of about 20 boreholes were acquired in order to understand the lateral-vertical distribution of the different lithologies (Fig. 2).

The stratigraphies, different for description and data quality, were analyzed and homogenized through direct observations of cores and by literature data. Absolute permeability values were obtained from bibliographic data for each lithology identified (Civita et al., 1999).

The stratigraphic and lithological data and the permeability values related to all the lithological horizons were stored in a relational geodatabase, referred to the UTM 33 WGS 84 system and managed in a GIS environment. The database served as the basis for the realization, through the Rock Works 2006 software (Rockware TM, 200x), of a 3D model of the subsoil showing the stratigraphic architecture and the lateral-vertical arrangement of the lithologies, with different absolute permeability.

The three-dimensional modeling of the subsoil can be compared to a three-dimensional "gridding" process through which there is a discretization of the space to be characterized in single volume elements (voxels) regularly spaced and characterized by vertices of known coordinates. Each voxel is defined by the coordinates of its vertices (x, y, z) and the value of a fourth variable, "G". The latter represents the qualitative or quantitative value (e.g. the relative or absolute permeability values) of a given physical quantity to assign to each voxel, on the basis of the interpolation of the values of the same size known for the nodes, carried out through kriging.

The result is a solid model divided into cubes whose dimensions are a function of the chosen plano-altimetric resolution, arranged in the three dimensions of the space, and differentiated, according to the value of the quantity "G", associated with each of them. The software returns profiles, fences, block diagrams and even grids at the desired absolute heights.

In the present work, three different levels of approximation have been considered in defining the geological model of the subsoil. The first model includes all recognized lithologies; the second one, the CGT was differentiated from the following deposits, distinguished by facies; in the third model a uniform lithology was considered.

Modeling

Mathematical models are important tools to evaluate the effects of infiltrating leachate and design remedial options. The model used in this paper was PMWIN (Processing Modflow for Windows Applications), a three dimensional, finite-element model that solves Darcy's equation for the flow in groundwater and the transport equation.

We will not go into the details of the application because it is out of the aim of this paper, but we will discuss the three different approximations used to simulate a leachate flow through a hypothetical geomembrane hole. Among the assumptions required for the analytical models, in this study the downward flow through the geomembrane hole and the soil has been considered vertical. This assumes as perfect the contact between the geomembrane and the soil and the radius of the flow or wetted area as equal to the radius of the hole.

Based on a 3D geological model of the subsoil, the groundwater dispersion models of a pollutant were based using ModFlow.

The simulations carried out were divided into stress periods, time intervals in which the boundary conditions, external stress parameters, are considered constant (Sharma et al., 1994). The stress periods in turn are divided into time steps whose duration follows a geometric progression, 365 days, 3650 days, 7300 days.

Three voxcel models were made with RockWorks 2006 (Rockware TM), based on the three geological substrate models, with a 10 (h) x10 (l) x0.5 (p) mesh, limited in height, between the ground level (+ 12m a.s.l.) and the maximum useful depth reached at bottom of the hole (-13m a.s.l.); subsequently 8 grids were considered (spaced every 5 meters deep) made up individually of 5525 cells.

Data entry in ModFlow was reiterated three times, with different degrees of detail resulting from the application of the different simplified models of the subsoil.

In the first model (Case A), the individual lithologies are assigned a permeability value derived from the literature in order to attribute a hydrogeological-applicative value to a geological stratigraphic context of real detail.

In the second model (Case B), for each recognized stratigraphic unit, a permeability value was obtained and assigned by calculating the weighted average on the thicknesses of the different lithologies falling within the same unit.

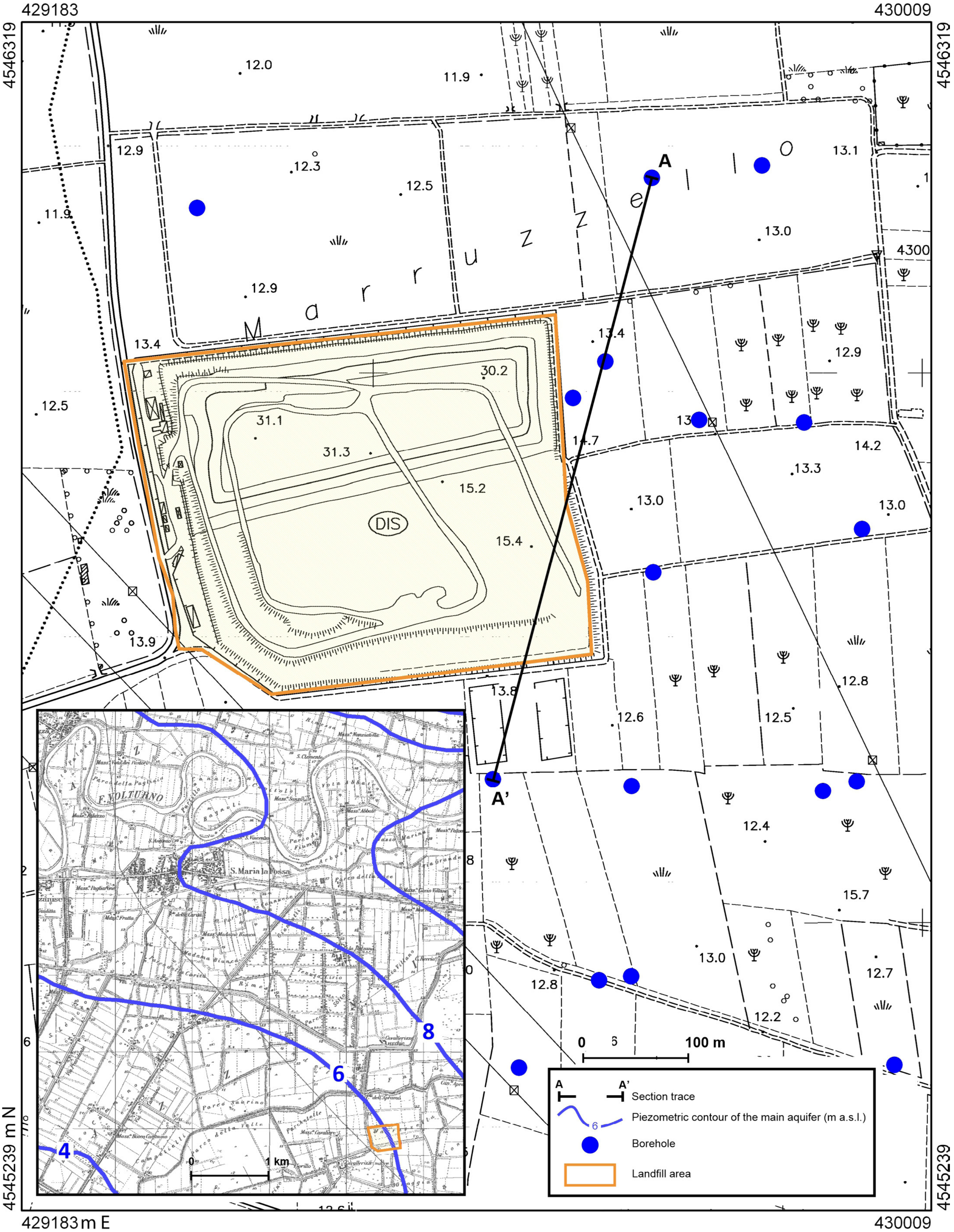

Fig. 2 - Location map of the Maruzzella landfill. The base map is the Technical Regional Map of the Campania Region 430102 Torre Fiorillo in scale 1:5000. The borehole used for the stratigraphic restoration are shown with blue dots. In the small box the piezometric contour of the main aquifer expressed in metres a.s.l. Trace AA' refers to the sections in Fig. 3.

For the third model (Case C), the most simplified one, it was assumed that the entire area is characterized by a single unit with a mediated permeability value.

The scenarios obtained by the elaboration of the different hypothesized geological models were read on the basis of the direction and shape outlined by the graphic representation of the isoconcentration curves. The different scenarios are related to the hydrodispersive parameters that regulate the process. In order of relevance they are: convection, due to the hydraulic gradient; dispersion, considered as the sum of mechanical dispersion and molecular diffusion due to concentration gradients. Finally, the software processes the scenarios based on the permeability attributed to the cells it encounters.

RESULTS AND DISCUSSION

Stratigraphic architecture

As previously mentioned, the stratigraphic evolution of the plain was conditioned above all by the late Pleistocene volcanic activity. The deposition of the CGT, in particular, determined the presence, in the subsoil of the entire plain, of an important stratigraphic marker that can be readily identified in cored successions due to its peculiar thickness and lithological attributes which make this lithofacies easily distinguishable from the overlying, mostly Holocene deposits. The stratigraphic reconstruction was initially made by considering the CGT volcanoclastic unit and the post-CGT deposits, the latter described in relation to the main facies associations (scenario B, Fig. 3b). Subsequently, the modeling that included the individual lithologies was carried out (scenario A, Fig. 3a).

From bottom to surface, the succession is characterized by: i) the CGT deposits, for a thickness of about 25 m; ii) clay and silty facies, locally sandy, for a total of 15 m; iii) a pedogenic horizon.

FIGURE 3

- CGT is characterized by alternating gravel with sand, gravelly sand and sand with silty gravel weakly clayey, from grey to dark grey in color, from moderately lithoid-to-loose, containing pumice and lapilli (maximum 15-20 mm in diameter) and frequent blackish glassy volcanic scoria (maximum 30-40 mm thick) (6 in Fig. 3a and 10 in Fig. 3b). These deposits have been interpreted as the cineritic facies of the CGT (Ruberti et al., 2020).

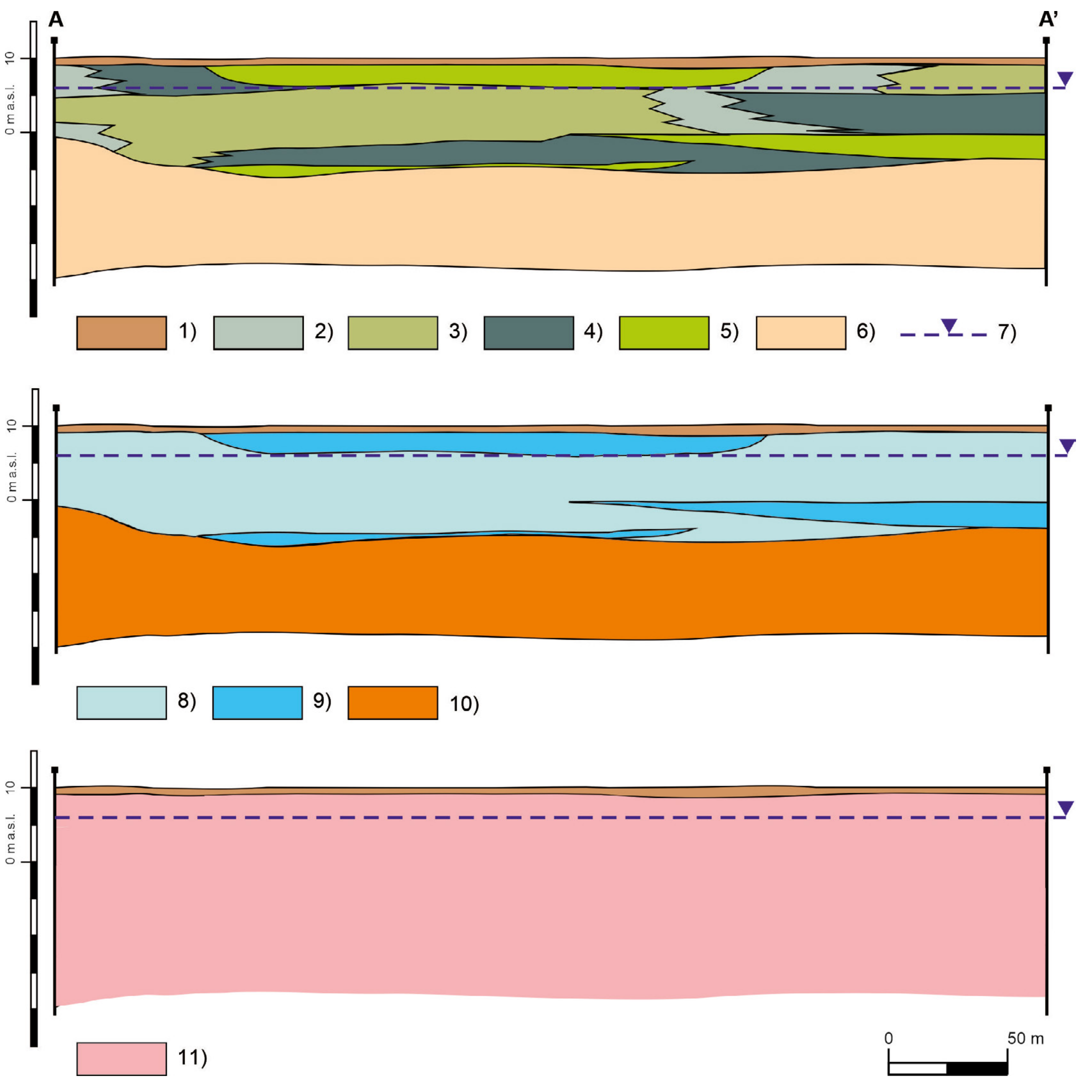

Fig. 3 - Reference geological section representing the three scenarios used in the flow modeling. a) Case A; b) Case B; c) Case C. Key: 1) pedogenized cover (top soil); 2) grey clay, 3) silty clay, 4) clayey silt with sand, 5) medium-fine silty sand with gravel, 6) silty gravelly sand 7) piezometric level, 8) alluvial deposits - floodplain, 9) alluvial deposits - channel, 10) Campania Grey Tuff, 11) homogeneous substrate.

- Above the CGT alluvial deposits occur. Silty clay and grey clay characterize most of the post-CGT deposits; the color varies from grey to blackish, or from grey-green to brown. Locally, grey silt and clay contain a thin sandy fraction made up of minute calcareous grains joined by a calcareous matrix, forming agglomerates with a maximum size of 10-15 mm, presumably originating from pedogenic processes (2,3 in Fig. 3a). Laterally or upwards they pass to grey-to-brownish clayey silt with sand (4 in Fig. 3a). These deposits can be interpreted as alluvial floodplain facies association (8 in Fig. 3b). The difficulty of recognizing sedimentary structures does not allow to provide more detailed interpretations. Fine-to-medium silty sand with scattered gravel layers at the base are intercalated with the latter deposits, with thicknesses from 2 to 6 meters (5 in Fig. 3a). They show a large-scale lenticular bedding, intercalated in the 2, 3 and 4 deposits. These deposits can be interpreted as alluvional fluvial-channel facies association (9 in Fig. 3a) and constitute aquifers in the plain (Corniello & Ducci, 2014).
- A pedogenized cover, up to 2 m thick, represents the superficial unit. It is characterized by sandy clayey silt, light brown to dark grey in color; small lapilli are common in the sandy fraction, red-brown in color.

Simulations

The results of the numerical simulation shows the evolution over run time of pollutant spots over time in the form of snapshots taken, respectively, after 1 year, 10 years and 20 years, considering

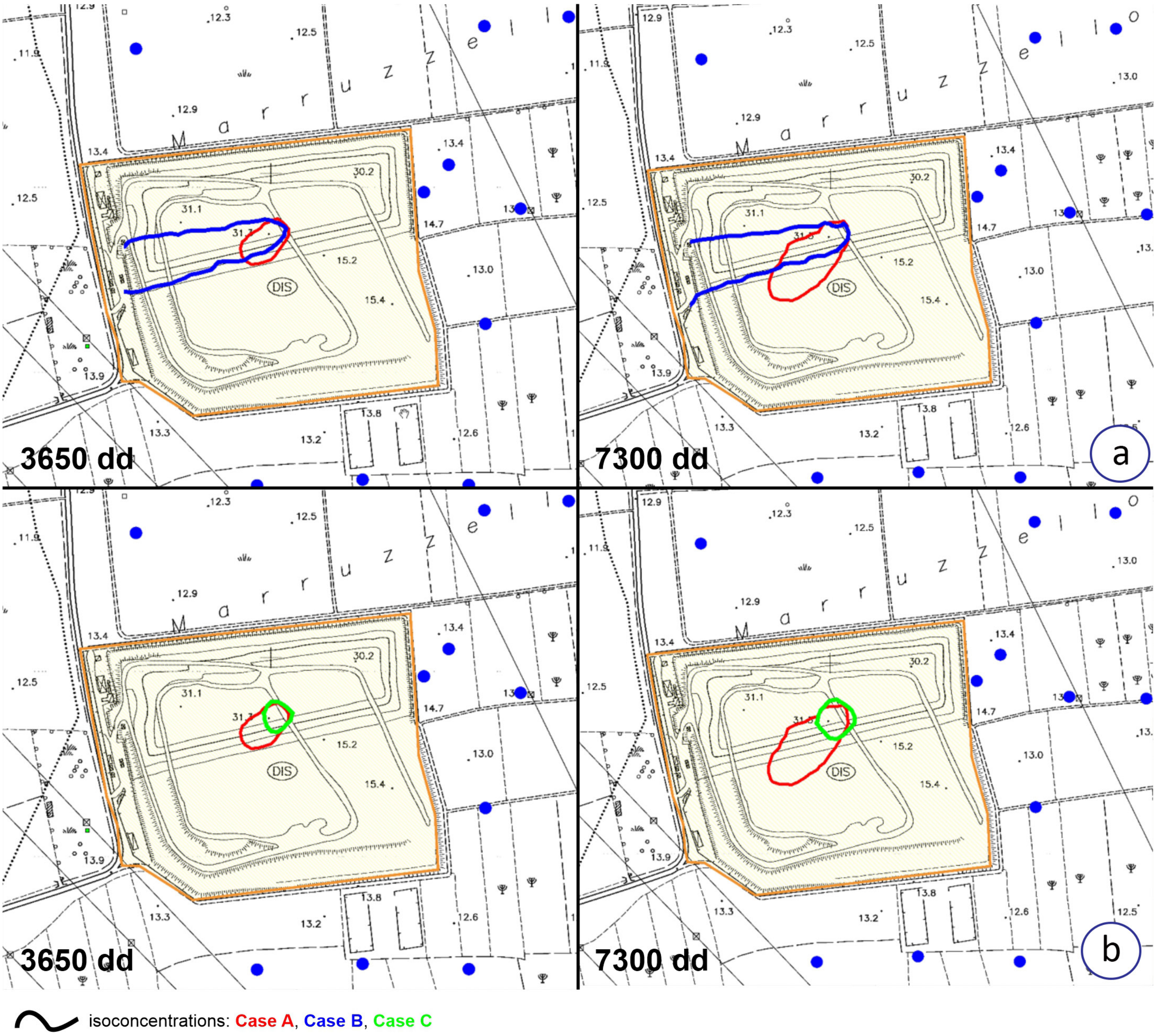

Fig. 4 - Results of the numerical simulation which shows the evolution over run time of pollutant spots in the form of snapshots taken, respectively, after 10 years and 20 years, at a depth of -3 m a.s.l., immediately below the free surface of the aquifer, considering the generic pollutant concentration limit (C_{lim}) fixed at 10 µg l^{-1}. With red color are represented concentrations of the Case A (geological section in Fig. 3a), blue color of the Case B (Fig. 3b) and the green color the Case C (Fig. 3c). For comments see the text.

the generic concentration limit of the pollutant (C_{lim}) set at 10 µg l^{-1}. In Figure 4 the isoconcentrations are reported at a depth of -3 m a.s.l., immediately below the free surface of the aquifer, in order to consider the trend in all the saturated sediments. The results of the following are compared: i) simulation conducted on the lithological model *vs.* that on the stratigraphic model; ii) simulation conducted on the lithological model *vs.* that one on the homogeneous model. For both, data over 10 and 20 year data have been reported, in order to highlight the process through time. In all the simulations carried out, the portion of substrate affected by the pollutant after one year was confined and at a limited depth. For this reason the representation at one year was not provided.

Case A: The trend of the isoconcentration curves assumes an ellipsoidal shape with the dispersion axis oriented in the NE-SW direction. The convective component predominates which favors the elongation of the plume in the direction of groundwater outflow. This dispersive morphology does not change as the time progression varies but increases in surface area with an increase directly proportional to time.

Case B: A high dispersion of the plume emerges from the study area and extends in the NE-SW direction. This behavior is mainly due to convection phenomena (transport in the direction of groundwater outflow) which favor dispersion along the direction of water outflow, while the widening of the isoconcentration curves can be attributed to both mechanical and diffusive dispersion.

Case C: This simulation was based on a simplified lithological model and was characterized by a single permeability value with an isotropic distribution in space. The isoconcentration curves assume a circular trend, symmetrical around the release point, and with an enlargement of the surface affected by the isolines directly proportional to the variation of time. The influence of convective phenomena on dispersion is not observed, which is therefore influenced only by mechanical and diffusive dispersion, which have an isotropic distribution of isoconcentrations in space.

Comparing the simulations carried out, the following can be noted:

- Case A vs Case B: it is observed that case B overestimates the real dispersive process especially in the long term (Fig. 4a).
- Case A vs Case C: case C underestimates the real distribution of the pollutant, this phenomenon is accentuated in the long term (Fig. 4b).

CONCLUSIONS

In order to assess the potential risk of aquifer pollution in an area of the alluvial plain of the Volturno river, a detailed subsoil model referred to a landfill area was created. The geological and hydraulic modeling of groundwater flows, obtained from a careful stratigraphic analysis in relation to hydrogeological data, faithfully represented both the position and the trend of the different recognized lithologies.

The dispersion models created with ModFlow allowed to establish the dispersive dynamics that predominate or coexist in relation to permeability and temporal progression considering different stress periods, respectively equal to 3650 days and 7300 days. The comparison of the real geological model (Case A) and the simplified ones (Case B and C) shows that the latter two underestimate and overestimate respectively the real dispersive processes; the curves described by the isoconcentration lines take on highly diversified trends in the three cases, thus underlining the importance of a thorough knowledge of the stratigraphic architecture of the subsoil. It follows that an accurate reconstruction of the lateral-vertical relationships of the deposits, especially in alluvial areas, is fundamental for the application of engineering techniques of modeling and environmental remediation. The suggested approach can be used for improving the environmental sustainability at a regional scale.

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