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Three-dimensional hydrogeological reconstruction based on geological depositional model: A case study from the coastal plain of Arborea (Sardinia, Italy)

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ABSTRACT

This study presents a novel approach for the hydrogeological assessment of sedimentary coastal aquifers. Specifically, the methodology is tailored for modeling groundwater flow and nitrates contamination in typical Mediterranean coastal plains with high anthropogenic pressures, as exemplified by the Arborea plain (central western Sardinia, Italy). The study started with development of an updated geological–depositional model based on sequential stratigraphy. Geological and geophysical data, processed in a geographic information system (GIS) environment, supported the definition of a 3D hydrogeological conceptual model and provided a solid basis for the interpretation of groundwater flow directions. The 3D hydrogeological model allowed constraining groundwater circulation, flow paths and distribution of nitrate concentrations in the aquifers. The methodology appears as a valid tool applicable in other coastal areas to determine geological and hydrogeological settings. The definition of a quantitative hydrogeological framework will support the effective management of local water resources.

1. Introduction

The contamination by nitrate (NO_3^-) of groundwater is becoming a ubiquitous problem. The World Health Organization has recommended a threshold of 50 mg L^{-1} in drinking water (WHO, 2003), but groundwater concentrations in Europe commonly exceed this level in 22% of cultivated land (Sacco et al., 2007), and similar concentrations occur in arable areas of the USA (Canter, 1997). The concern about the potential pollution of groundwater because of increasing human pressure on the environment has led to the development of an extensive legal framework. Both the 91/676 and 2006/118 Directives, issued by European Commission respectively for the protection of waters from nitrates of agricultural origin and for the protection of groundwater against pollution and deterioration (Groundwater Directive — GWD), have been implemented in Italy. Nitrates Directive states that all areas of land which drain into waters exceeding the concentration of 50 mg L^{-1} of NO_3 and which contribute to nitrate pollution must be designated as "Nitrate Vulnerable Zones" (NVZs). In these areas, farmers are required to comply with specific measures directed to improve water quality. Although the Directive clearly states the criteria for identifying NVZs, the implementation of these criteria has varied from country to country. The designation of an NVZ must take into account all relevant physical and environmental factors (i.e. aquifer characteristics, flows and solute transport in the saturated zone, the behavior of nitrogen compounds in the environment and land use) that may influence the nitrogen dynamics.

Many NVZs worldwide are located in flat lands and in coastal areas where the intense agricultural activity, the high concentration of inhabitants and the seasonal population determine a significant water demand. In those areas, several environmental concerns may occur at the same time. Indeed, in farmed coastal zones the impacts on water resources include pollution due to nutrient and pesticide leaching and seawater intrusion into aquifers (Steinich et al., 1998; Zalidis et al., 2002; Ghiglieri et al., 2012). Groundwater management in coastal aquifers requires the elaboration of a local geological and hydrogeological conceptual model in order to understand the processes determining the quality of water, the hydrodynamic parameters and the productivity of aquifers.

During the last few years, techniques in 3D hydrogeological model reconstruction/visualization have been improved (Wu et al., 2005; Jones et al., 2009; Wycisk et al., 2009; Best and Lewis, 2010; Cox et al.,

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2013; Di Maio et al., 2014) by integrating different sets of data (e.g. geological, hydrogeological, geophysical). The 3D geological approach is routinely used in mineral deposits or hydrocarbon reservoir assessment (Jones et al., 2009). By contrast, for the hydrogeological studies and hydrogeochemical characterization of groundwater this approach is not yet routinely used (Raiber et al., 2012). Different methodologies to develop 3D geological models have been elaborated and tested (Lemon and Jones, 2003; Smirnoff et al., 2008; Tremblay et al., 2010). However, currently there are no perfect methods or a comprehensive modeling approach for the reconstruction of sedimentary stratigraphic systems. According to the international literature, one of the main problems is the discontinuous spatial distribution of stratigraphical information, mainly due to the lack of borehole data that can lead to an inaccurate 3D geological conceptual model.

The geology in coastal areas is complex because of the large number of interacting terrestrial and marine processes. Groundwater flow and travel time depend on stratigraphic setting which controls boundary conditions of the aquifers (Edington and Poeter, 2006). Moreover, in such environments sediment stacking (sand, gravel, clay) is typically repeated many times, allowing for a variety of possible correlations. Therefore, it is not straightforward to reconstruct a realistic geological model.

In order to correlate the sedimentary facies in a reliable and meaningful way, sequence stratigraphy, which describes succession through space and time in various depositional systems (Dalrymple and Choi, 2007), has been employed. For this purpose, the definition of the hydrogeological framework, obtained by integrating geological, stratigraphic and hydrogeological data, represented the basis for predicting groundwater circulation and pollutant diffusion (Di Salvo et al., 2012; Irace et al., 2010). The management of water resources is central to any attempt to conserve both water quality and quantity (Ghiglieri et al., 2009a,b).

The aim of the research was to develop a methodology suitable for sedimentary coastal aquifers for compiling quantitative hydrogeological information. The study was carried out within the framework of the interdisciplinary IDRISK (*Pollution risk and prevention of groundwater degradation*) and KNOW (implementing the Knowledge of NitrOgen in groundWater) Projects (http://nrd.uniss.it). It had the twin goal of elaborating a local hydrogeological conceptual model and defining the major groundwater flows, in order to predict the diffusion of NO_3^- in the aquifers.

To achieve these objectives, it was necessary to refine the depositional-geological model of the sedimentary basin underlying the Arborea plain (located on the West cost of Sardinia, Italy). The study then started with a geological characterization of the study area, based on a set of data arising from stratigraphic log wells and vertical electrical soundings (VESs). The data (stratigraphic, geological, hydrogeological and geochemical) were implemented in a Geographic Information System (GIS) and in a conceptual Data Base (DB). This DB was interfaced with several softwares e.g. Move (Midland Valley Exploration), to build a 3D hydrogeological model. A calibration and validation of the hydrogeological framework was obtained from measured NO_3^- concentrations in groundwater samples.

2. Description of the study area

The study area is located in the northern part of the Campidano plain (central-western Sardinia, Italy: Fig. 1a). It is limited to the north and to the east respectively by the volcanic complexes of Montiferru and Monte Arci, to the south by the Mogoro River, Marceddì and San Giovanni lagoons and by the sea of the Oristano Gulf to the west. The Tirso River, the most important river in Sardinia, crosses the northern part of the plain and flows in a SW direction towards the Oristano Gulf. The Arborea plain covers about 60 km^2 portion of the area, lying between the coast and the reclaimed Sassu lagoon (Fig. 1b). It was reclaimed during the 1920s for agricultural purposes and has been used to produce irrigated crops ever since. It remains one of the most productive agricultural locations on the island, achieving a level of dairy productivity among the highest in Italy. Double cropping of silage maize and Italian ryegrass is practiced on more than 80% of the irrigated area, and the biomass is used to feed about 35,000 dairy cattle raised in intensive systems (Giola et al., 2012); the remaining land is used to grow lucerne and various horticultural crops (Foddis et al., 2012).

2.1. Geological setting

Following the collision between the South European Plate and the Adria Plate during the early Miocene, Sardinia separated from the European continent during the Lower-Middle Miocene (Carmignani et al., 2001; Oggiano et al., 2009). During these major geodynamic events, several basins formed on the island, particularly on its western side. Volcano-sedimentary materials filled the basins aligned in a NNW–SSE direction and bounded by normal faults. During the Plio-Pleistocene, a new extensional phase associated with the South Tyrrhenian opening reactivated a series of NNW–SSE fault lines. Consequently the Campidano trough developed. The general subsidence associated with this extension, combined with climatic oscillations and regressive and transgressive marine variations, produced a landscape characterized by thick sedimentary layers of littoral-marine and fluvial-deltaic material. Seismic surveys and geological logs, conducted in the Campidano plain since the 1960s, provided information on the current state of the local stratigraphy and the geological structure at depth (Casula et al., 2001; Cocco et al., 2013). The Oristanese area is a half-graben bounded by faults arranged in N–S direction, which contributed to a deepening of the basin on its western edge, where the Sinis main fault lies. This structure, easily recognized in seismic cross-sections, was certainly active after the deposition of the basaltic-lava flows in early Pleistocene times (Cocco et al., 2013). In the Arborea plain, the sedimentary succession that fills the Campidano trough is up to 1000 m in thickness and overlies the Miocene volcano-sedimentary succession. During the Quaternary, the deposition of continental and coastal marine sediments related to the Quaternary glacioeustatic cycles affected the littoral and low-lying areas (Lecca and Carboni, 2007). Structural and morphological factors determined the thickness of these deposits, generally arranged in a highstand system geometry (Buttau et al., 2011).

3. Materials and methods

3.1. Stratigraphic analysis, geological cross sections and 3D hydrogeological model

Fig. 2 reports the conceptual workflow of the methodological approach. The stratigraphic analysis was based on a set of both surface and sub-surface observations.

The geological features of the study area were inferred by the official 1:25,000 map of Sardinia, available in digital form at www.sardegnageoportale.it. The stratigraphic data were gathered from 143 wells, provided by Sardinia Regional Agencies (ARPAS, LAORE) or available from previous projects (CASMEZ, 1976) and from unpublished work (Fig. 1b).

A set of 96 VESs (Casmez, 1976) evenly distributed across the study area was an important source of additional data (Fig. 1b). The resulting apparent resistivity curves of each VES were interpreted by a computer program, based on the linear digital filtering method (Koefoed, 1972, 1979; O'Neill and Merrick, 1984). Current software packages based on this approach are able to cope with extreme apparent resistivity contrasts and to deal with a large number of layers. The association of a specific lithology with a given resistivity value took into account the stratigraphic log of wells located close to each VES.

A GIS database was populated with the position, elevation, depth, characterization of litho-stratigraphic layering and the top and bottom surface elevations for each well and VES. An ArcGis tool (ArcGis eXacto