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Processes governing natural land subsidence in the shallow coastal aquifer of the Ravenna coast, Italy

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ABSTRACT

We identified the processes governing natural land subsidence in a shallow coastal aquifer near Ravenna (North eastern Italy) by analysing the relationships among different data set time series (water table level, rainfall, drainage, sea level, etc.) and establishing the correlations with vertical ground motion observed at a high-resolution settlement gauge. For the first time we establish the relationships between water table fluctuations and vertical displacement in a real field dataset as well as demonstrate the important contribution of primary consolidation and aquifer stratigraphy to natural land subsidence. Our study highlights the presence of three deformation components related to different processes controlling land subsidence: elastic, delayed-elastic, and irreversible (plastic) components. The elastic and delayed-elastic components are closely related to water table fluctuations that change the effective stress in two portions of the coastal aquifer at a daily (in the sandy unconfined portion) and seasonal time scales (in the finely layered clay-rich semiconfined prodelta portion), respectively. The irreversible component represents the trend in the land subsidence time series and is due to primary consolidation (pore water pressure dissipation) of the fine-grained prodelta levels above where the settlement gauge is located. The amplitudes of the elastic component can be up to 0.2–0.3 mm whereas the amplitude of the delayed-elastic component reaches 0.89 mm. The primary consolidation rate of deformation is 0.9 mm/year and constrains the likely age of prodelta sediments deposition to 1300–2800 years before present. The average degree of consolidation for the prodelta sediments varies from 0.8 to 0.99 according to consolidation coefficients varying from 1.58 to 3.15 m^2/year, which are accepted values in the literature. Our analysis point out that primary consolidation in the shallow fine-grained sediments of the shallow coastal aquifer is still ongoing. The delayed-elastic land subsidence rate has similar magnitude to that due to primary consolidation and is likely connected to poroelastic effects in the prodelta sequence following seasonal variations in water table. Our findings are important for planning land subsidence management and monitoring strategies especially where the surface aquifer structure is heterogeneous due to different depositional settings.

1. Introduction

Subsidence is one of the most diverse forms of downward settling of the ground with little horizontal movement, ranging from small or local collapses to broad regional lowering of the earth surface. It is a global problem and the principal causes are aquifer-system compaction (Sneed and Galloway, 2000), dewatering (oxidation) of peat or organic soils (Grzywna, 2017; Zanello et al., 2011), underground mining (Dong et al., 2015; Ishwar et al., 2017), hydrocompaction and sinkholes (Psimoulis et al., 2007; Yechieli et al., 2016), crustal deformation, withdrawal of fluids (groundwater, hydrocarbons, geothermal) (Donaldson et al., 1995), and thawing permafrost (Liang et al., 2006).

The relationships between land subsidence and fluid withdrawal from deep confined aquifers is extensively described in the literature (Corapcioglu, 1984; Domenico and Mifflin, 1965; Galloway et al., 1999; Poland and Davis, 1969; Schmidt and Bürgmann, 2003; Sun et al., 1999) and many analytical (Calderhead et al., 2011; Liu and Helm, 2008; Tarn and Lu, 1991) and numerical modelling (Baú et al., 2004; Galloway and Burbey, 2011; Gambolati et al., 1996) studies were done to identify the physical processes involved. Natural subsidence processes connected to the compaction of sediments or tectonic phenomena were also extensively treated in the literature (Amelung et al.,

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1999; Gambolati and Teatini, 1998; Gambolati et al., 1999; Carminati et al., 2003). On the other hand, very few studies consider the relationships between water table fluctuations and natural land subsidence (Chang et al., 2004; Strack et al., 2008). To the best of our knowledge, no high-resolution continuous time series of land subsidence and water table levels were ever presented and interpreted in the literature.

By using data from a high-resolution settlement gauge, our present work aims to define the processes governing shallow ground settlement (magnitude and development over time since the installation of the instrument) and verify land subsidence and water table fluctuations interactions in the shallow coastal aquifer of Ravenna. Our work highlights the contribution of natural processes such as primary consolidation (compaction of sediments under their own weight via expulsion of interstitial pore water) and water table fluctuations in the Holocene shallow coastal aquifer of Ravenna to the cumulative land subsidence rate observed in the area (Bertoni et al., 1995; Teatini et al., 2005; Baldi et al., 2009). The processes in the shallow coastal aquifer are uncoupled from other processes contributing to the cumulative land subsidence rate and that are primary and secondary consolidation of deep aquifers (Teatini et al., 2011), fluids extraction from reservoirs (Teatini et al., 2006), tectonism, and isostasy (Carminati et al., 2003). The methodology we used includes the decomposition of data time series (subsidence-settlement, water table level, precipitation, drainage, sea level) into the trend, seasonality and noise components and find correlation coefficients between each analyzed component, especially between settlement and changes in water levels. Analytical solutions are also applied to model the irrecoverable and elastic components of land subsidence.

2. Materials and methods

2.1. Study area

The area addressed by the present study includes the coastal area of the Ravenna city, in the Emilia-Romagna coastland, south of the Po River Delta (Northeastern Italy, Fig. 1). It is a lowland coastal area not exceeding 2 m above sea level (a.s.l.), with a large portion below mean sea level, because of the combined effects of natural and anthropogenic land subsidence, land reclamation, and sea level rise. In the study area, the trend in sea level rise during the time period 1990–2011 was estimated to be 2.2 ± 1.3 mm/year (Cerenzia et al., 2016), in agreement with the satellite altimetry trend of 3 mm/year obtained by Bonaduce et al. (2016) for the Northern Adriatic Sea.

Anthropogenic land subsidence, occurring since 1950s, is primarily related to groundwater pumping from shallow and deep aquifers as well as gas production from Plio-Pleistocene reservoirs. The cumulative land subsidence from 1897 to 2002 was about 1 m in the Ravenna area (Teatini et al., 2005, 2006). Natural land subsidence is the result of deep downward tectonic movement (Carminati et al., 2003) and consolidation of geologically recent deposits (Quaternary sediments) (Teatini et al., 2011). It was estimated in the range of 2–2.5 mm/year in the Ravenna area and twice as much in the Po River Delta (Gambolati et al., 1999). Land subsidence yields a loss of ground surface elevation, loss of efficiency of hydraulic infrastructures, damages to the historical heritage, increase in coastal erosion (Sytnik and Stecchi, 2014), and in coastal vulnerability to extreme events, such as winter storms and storm surges (Ciavola et al., 2007; Giambastiani et al., 2017). Moreover, the Emilia-Romagna coastal area is entirely drained through a dense network of canals connected to > 30 pumping stations. This system controls vadose zone thickness and permits agriculture and human activities in the low-lying coastal areas. Within the Ravenna area, a total of 12 pumping stations lift up an average of 70 million m^3 of water forward the sea. The drainage system runs through a large lowland territory rich in peaty soils (Mastrocicco et al., 2011) and organic-rich fine sediments deposited in paleo-marsh environment (Amorosi et al., 2005).

The concern for the effects of subsidence promoted a research activity on this topic, so that several administrative authorities established and developed networks for land subsidence monitoring where the phenomenon was more pronounced. In 1997–1998, ARPAe (Regional Agency for Prevention, Environment, and Energy of Emilia-Romagna) designed and established a plan for subsidence monitoring, which was made up of a high-precision network (with over 2300 geodetic levelling benchmarks and about 60 GPS points) along the Adriatic coastline (IDROSER, 1996). Since then, the network has been constantly integrated with new benchmarks, differential Global Positioning System (DGPS) and Synthetic Aperture Radar (SAR)-based techniques (Artese et al., 2016). In most studies performed in the area there is evidence of a close relationship between land subsidence, deep groundwater pumping, and deep gas field development (Teatini et al., 2005, 2006). Fig. 1b shows that the average rate of total land subsidence (natural + anthropogenic) in Ravenna is about 5 mm/year with the highest values recorded around the study area (values ranging from 17 to 10 mm/year). Starting from the measured land subsidence, however, it is hard to distinguish between its natural and anthropogenic components, because of their different spatial and time scales. For this reason, since 2014 two settlement gauges (at *Gorino* and *Lido di Classe*) were installed by the Geological Survey Department of the Emilia-Romagna Region in the shallow coastal aquifer with the aim to evaluate the contribution of Quaternary sediment consolidation to the overall land subsidence. The Quaternary (Holocene) cohesive soils, which originated in alluvial, lacustrine or shallow marine facies, are the most likely materials to still undergo a process of primary consolidation (Pardo et al., 2013).

2.1.1. Hydrogeological setting

The shallow coastal aquifer, where the instruments of this research are installed, consists of Holocene sediments; there are three fundamental units (Amorosi et al., 1999a, 1999b; Campo et al., 2017), as represented in the stratigraphic core log and Standard Cone Penetration Test (SCPT) in Fig. 2. Two sandy units, one at the surface, made up by medium- to fine-grained sand and with a thickness of about 8 m, and a deeper one (from −20 to −25 m a.s.l.), consisting of fine sand with very thin clay inter-layers. The intermediate unit is a package of alternating clay-silt and sandy-silt strata (prodelta sediments). The basement of the unconfined coastal aquifer consists of Pleistocene impermeable clay at a depth of 26–30 m a.s.l. Generally the hydraulic conductivity is 10^{-4} m/s in the sandy units, 10^{-6} m/s in the prodelta sediments, and 10^{-9} m/s in the impermeable basement (Giambastiani et al., 2012). In this paper, when we refer to the "shallow coastal aquifer of Ravenna", we mean the whole sediment package described above (depth 0–30 m), which is also monitored by the settlement gauge. It is apparent, however, that the upper part (0–8 m depth) is unconfined (phreatic), whereas below 8 m depth the aquifer is semi-confined or consists of aquitards.

The average water table in the study area is around mean sea level. Average water salinity is 11 g/l, with minimum values recorded in the shallow freshwater lenses below the coastal dunes (< 1 g/l) and with maximum values (25 g/l) in the deepest portion of the aquifer (Cozzolino et al., 2017). The shallow coastal aquifer of Ravenna is strongly salinized and its groundwater is considered brackish (5 to 25 g/l) up to the surface (Antonellini et al., 2015). Freshwater is present only in thin lenses (1–2 m thick) below the coastal dunes. The saltwater-freshwater interface below the dunes is 2 to 3 m wide and the seasonal variation of the freshwater lens thickness is in the order of 0.2–0.3 m (Cozzolino et al., 2017).

The water table elevation in the coastal zone of Ravenna is controlled by mechanical drainage operated by the Land Reclamation Authority in order to guarantee a vadose zone of 1 (summer period) to 1.5 m (winter period) in thickness. The locations of the settlement gauge and the piezometer used for continuous monitoring are close to