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Stochastic modelling of groundwater flow for hazard assessment along the underground infrastructures in Milan (northern Italy)

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ABSTRACT

The paper discusses the hydrogeological hazard for the underground infrastructures caused by the rise of the groundwater level observed in Milan (Italy). The study is the prosecution of a previous paper (Gattinoni and Scesi, "The groundwater rise in the urban area of Milan (Italy) and its interactions with underground structures and infrastructures" TUST 62(2017): 103–114), that analysed the phenomenon through a deterministic groundwater flow numerical model, pointing out the related potential hazards and the possible mitigation solutions. Starting from the reconstruction of the phenomenon previously obtained, in the present paper the 3D numerical model of the groundwater flow was turned out into a stochastic model in order to assess the hydrogeological hazard (in probabilistic terms) for the underground infrastructures. At this aim, different scenarios of the aquifer system were considered: (1) the probability distribution of the recharge describing the present day conditions; (2) the decrease in the pumping rate of wells expected in the next 15 years; (3) an increase of the regional groundwater table, based on the projection of the rising trend for the next 15 years. Modelling results have pointed out a significant increase in water level by 5 m in the next 15 years, depending on the scenarios taken into account. The water table rise interests mainly the north-western zone of the study area, and it affects the metro tunnels located in the centre of the city. Therefore, some metro tunnels will be flooded (or even submerged) with different occurrence probability. The flooding hazard increases with the increasing depth of the infrastructures, especially in the northern-central zone of the study area.

1. Introduction

Since the end of the last century, rising trends of the groundwater table were observed in urban aquifers all around the world: from Buenos Aires (Hernandez, 2006) in Southern America to New Haven (Bjerklie et al., 2012) in Northern America, from Cairo City (Selim et al., 2014) in Africa to Vietnam (Erban et al., 2013), Bangkok (Phienwej et al., 2006) and Tokyo (Hayashi et al., 2009) in Asia. Many European cities are affected by the same phenomenon: from Barcellona (Vasquez-Sune et al., 1997) to London (Wilkinson, 1985), from Paris (Lamé, 2013) to Milan (Beretta et al., 2004). These examples show that the water table rising in the urban areas is the result of many causes:

- the deindustrialization process;
- the abandon of the public pumping wells, because of the water pollution and/or land subsidence;
- a global rising of the sea level along coastal areas.

In addition to the causes previously listed, another important parameter affecting the regional groundwater trend is the recharge. Different methods for assessing its contribution to groundwater are listed in the international literature: from numerical modelling (Gattinoni and Francani, 2010) to isotopes analysis (Morgenstern et al., 2012; Prada et al., 2016) and Geographical Information System (Yeh et al., 2007). Although these methods are considered quite goods for the definition of the recharge zones within both catchment basins and urban areas (Foster and Chilton, 2004), their main limitation is the uncertainty in the quantification of the recharge rate. Some uncertainty analyses have been used to overcome the problem by using stochastic methods (Baalousha, 2016a; Bekesi and McConchie, 1999), such as Monte Carlo simulations (Baalousha, 2016b).

As far as the consequences, the changes in the boundary conditions of urban aquifer systems brought about local rises of the water table, ranging from 3 m to 30–40 m, affecting a relevant thickness of previously desaturated soils. The main consequences of the water table rise are (Dean and Sholley, 2006):

- the flooding of underground structures (e.g. cellars and parking lots)

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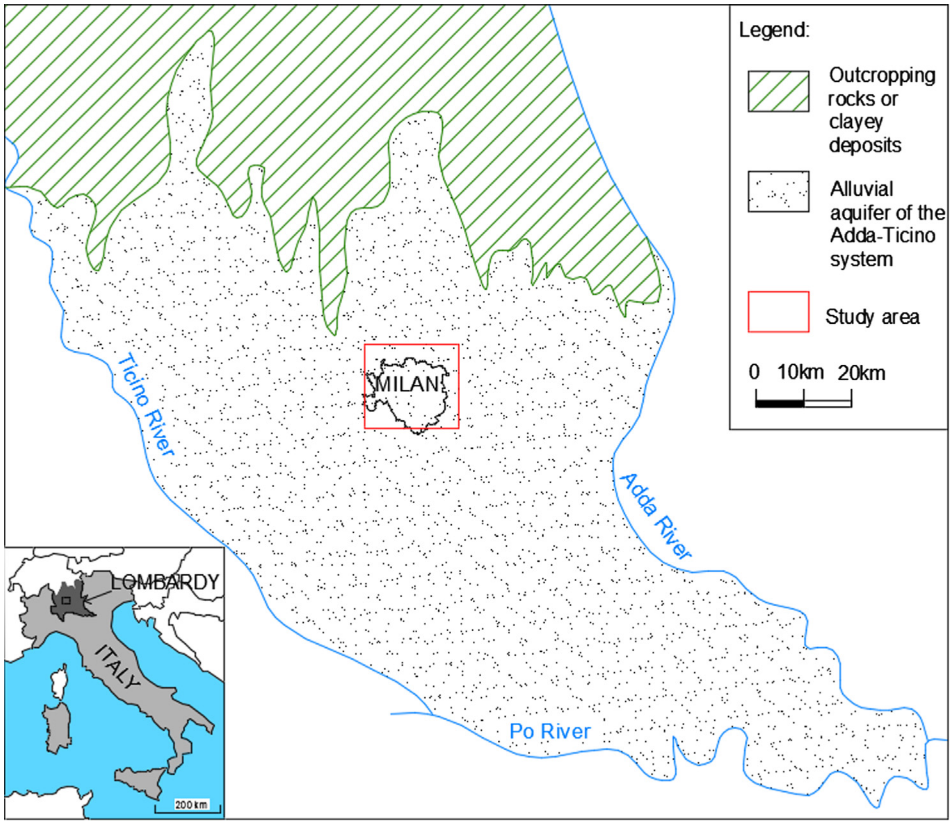

Fig. 1. Location of the study area within the Adda-Ticino aquifer system.

and infrastructures (e.g. subways);
- an increase of the hydrostatic stress exerted on the submerged structures;
- the corrosion of foundations;
- an increase of groundwater pollution, arising from the saturation of polluted soils.

Previous Authors studied the impact of disturbance caused by underground structures (tunnels, basements of buildings, deep foundations, etc.) on the groundwater flow in urban aquifers (Colombo et al., 2017), pointing out that they act both as obstacles to the flow and as disturbance of the groundwater budget (Attard et al., 2016) and references therein).

The present paper deals with the urban area of Milan, which lies on one of the largest aquifer system in northern Italy (Fig. 1). A previous study on the same area (Gattinoni and Scesi, 2017) analysed the water table rise and the related potential hazards. This paper is aimed at defining a methodology in order to assess the hydrogeological hazard for the metro lines and stations because of the water table rise. Different scenarios of the groundwater system evolution are defined and stochastically simulated, in order to reconstruct the occurrence probability of the changes in the groundwater level and flow path, and therefore to evaluate the related hydrogeological hazard for the underground infrastructures. At this aim, both the recharge and the withdrawals are considered as probability distributions and Monte Carlo simulations are carried out to obtain the probability distributions of the groundwater levels. Actually, uncertainty is inherent in any model-based risk assessment (Walker et al., 2003). This uncertainty is particularly high when the aim of the work is to forecast beyond the available data (meteorological data, water supply wells and groundwater levels, which are the main parameters influencing the overall groundwater budget) and to analyse future impact (Gattinoni and Francani, 2010; Troldborg et al., 2010). In this paper, the Monte Carlo simulation method (Raychaudhuri, 2008) was used to assess the uncertainty for future scenarios.

2. Background on the groundwater rise in Milan

Gattinoni and Scesi (2017) already discussed the issue of the groundwater rise in the urban area of Milan (the reader can refer to their paper for a more comprehensive description of the problem and the hydrogeological setting of the study area). In the following, a brief summary of the results achieved in their study is presented.

The city of Milan (Lombardy, Northern Italy, Fig. 1) lies on a wide regional aquifer, which extends from the Adda to the Ticino River (East and Western physical boundaries), from the Prealps to the Po River (North and South boundaries). This area is extremely dense in its urban, industrial and agricultural development. Therefore, the history of the groundwater level in Milan passed through a phase of intense exploitation: since the early sixties until the early nineties of the last century, big factories in the north of Milan led a significant groundwater drawdown, by pumping large quantities of water. In the meantime, the unsaturated zone has been utilised for the development of car parks, transport and other facilities. Since the early nineties, the closure of many factories led to a reversal of the trend and the aquifer began to rise, reaching levels close to those of the fifties of the last century. This rising trend interferes with the structures and infrastructures, bringing about both management troubles for the railway urban system and safety issues for the structures.

In order to study the problem from a quantitative point of view, a 3D groundwater flow model was developed for the study area (the red box in Fig. 1). Numerical results allowed identifying the interferences between the existing underground infrastructures (i.e. metro tunnels and stations) and the rising water table, pointing out the related potential hazards. In the present day scenario, modelling results pointed out a local increasing of the groundwater levels over wide areas located