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Inferring the interconnections between surface water bodies, tile-drains and an unconfined aquifer–aquitard system: A case study

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SUMMARY

Shallow lenses in reclaimed coastal areas are precious sources of freshwater for crop development, but their seasonal behaviour is seldom known in tile-drained fields. In this study, field monitoring and numerical modelling provide a robust conceptual model of these complex environments. Crop and meteorological data are used to implement an unsaturated flow model to reconstruct daily recharge. Groundwater fluxes and salinity, water table elevation, tile-drains' discharge and salinity are used to calibrate a 2D density-dependent numerical model to quantify non-reactive solute transport within the aquifer–aquitard system. Results suggest that lateral fluxes in low hydraulic conductivity sediments are limited, while water table fluctuation is significant. The use of depth-integrated monitoring to calibrate the model results in poor efficiency, while multi-level soil profiles are crucial to define the mixing zone between fresh and brackish groundwater. Measured fluxes and chloride concentrations from tile-drains not fully compare with calculated ones due to preferential flow through cracks.

1. Introduction

In reclaimed coastal agricultural land, the presence of saline and brackish groundwater is the rule rather than the exception. Many examples are found in The Netherlands (Raats, 2015), Belgium (Vandenbohede et al., 2010), Italy (Da Lio et al., 2015), Australia (Kobryn et al., 2015), USA (McMahon et al., 2015) and China (Sun et al., 2012), just to cite the most recent. Tile-drains in reclaimed agricultural soils are often used as a mean to limit soil salinity in the root zone (Ali et al., 2000; Ayars et al., 2006), leading to complex groundwater flow patterns that can add significant uncertainty to the prediction of local-scale flow and transport (Gooday et al., 2008). In this framework, the numerical modelling of flow and transport processes has undergone some significant advances in the last years, with the general recognition of tile-drains as an important feature linking surface waters to groundwater (De Schepper et al., 2015; Warsta et al., 2013). Despite of these general advances, there are many aspects that still need to be clearly understood both at the site's scale and at the watershed scale. In general, there is little agreement on how to deal with the input of a specific yield parameter to simulate water table fluctuation (Acharya et al., 2012), how to model the flow resistance towards tile-drains (Hansen et al., 2013; Kohler et al., 2001), or how to model evapotranspiration fluxes from the saturated zone (Adeloye et al., 2012; Camporese et al., 2015). The literature paid more attention on modelling nutrient leaching through tile-drains, since they usually provide a preferential pathway for eutrophication of surface freshwater resources and heavy metal export (Rozemeijer et al., 2010); while only recently field based numerical models have been implemented including variable density flow and transport features, or drains and recharge fluxes from the vadose zone (Colombani et al., 2015; De Louw et al., 2013). Undoubtedly, without a clear and robust conceptual model of the water fluxes in complex environments it is meaningless to build up a mass balance of reactive species like nutrients or heavy metals.

Thus, the aim of this study is to quantify the variable density flow and transport patterns within an unconfined aquifer–aquitard system affected by brackish groundwater and located beneath a tile-drained agricultural field. The data consist of precipitation and evapotranspiration, groundwater levels, groundwater and soil

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water salinities and chloride concentrations, tile-drains' discharge and salinity. A set of nested numerical flow and transport models are used to support the development of a robust conceptual model concerning the seasonal behaviour of tile-drains and to give some insight on the capabilities/limitations of the actual monitoring techniques.

2. Materials and methods

2.1. The study area

The experimental site is located in the Po River lowland, Northern Italy (45°50′33″ N and 12°05′40″ E), on the boundary of two different soil facies: the Thionic Fluvisols and the Humic Thionic Fluvisols, following the W.R.B. classification from F.A.O. (2014).

The area is characterised by an interplay of deltaic and littoral deposits (Stefani and Vincenzi, 2005), with a diachronous splay of Po distributary channels bounded to the North by Alps sourced paleo-channels of the Adige River and to the South by Apennines derived paleo-rivers, associated with inland delta deposits reclaimed from 1860 to the present day (Di Giuseppe et al., 2014). The crop type is a rotation of rain fed winter cereals and maize. Tile-drains (Fig. 1) are employed to prevent water-logging conditions during winter time and for sub-irrigation purposes during prolonged dry periods. This field has been selected and studied within the ZeoLIFE project – Water pollution reduction and water saving using a natural zeolitite cycle (LIFE+10 ENV/IT/00321).

2.2. Field site characterisation and analytical procedure

The soil, consisting of recent interfluvial silty-clay deposits (Mastrocicco et al., 2013), was investigated from the top layer to −4 m below ground level, whose elevation varies from −2.75 to −3.30 m above sea level (a.s.l.). Six 1" PVC monitoring wells, 4 m long and screened in the last meter, were installed along a transect (Fig. 1). Core samples were collected several times from October 2011 to September 2014 in proximity of the six monitoring wells; samples were taken every 30–50 cm by mean of an auger equipment, stored in a cool box at 4 °C and immediately transported in the laboratory for sedimentological and chemical analysis. Particle size curves of 50 soil samples were gained using a sedimentation balance for the coarse fraction and an X-ray diffraction sedigraph for the fine fraction; the two particle size curves were linked using a spreadsheet. Samples were grouped into two different types: an upper tilled horizon and a lower undisturbed horizon (Table 1).

The dry bulk density and the water content were determined gravimetrically. The gravimetric water content was measured at saturated condition. The residual water content was measured gravimetrically in triplicates on air dried sediments after heating for 24 h at 105 °C. The organic matter content was determined by dry combustion (Tiessen and Moir, 1993).

To estimate the hydraulic conductivity (k_s) distribution along the vadose zone profile both pedotransfer functions and field measurements via a Guelph Permeameter were performed (Mastrocicco et al., 2013). To obtain k_s in the saturated zone, slug tests were performed in some monitoring wells (Fig. 1). From the k_s characterisation a clear decreasing trend is found in the first 3 m of soil, here designated as unconfined aquifer; while a nearly constant k_s value is found from approximately −5 m a.s.l., here designated as aquitard. The k_s decreasing trend in the unconfined aquifer is most probably due to sediments compaction rather than changes in sediments' grain size distribution (see Table 2).

Chloride (Cl^-) was determined both in pore-water and groundwater. Ultrapure water was used to extract water-soluble Cl^- from the sediment samples, using a sediment to water weight ratio of 1:5. The sediment and the water were mixed and sealed in bakers, shaken for 1 h, and centrifuged for 1 h at 25 °C to separate the sediment from the solution. Pore-water samples were filtered through 0.22 μm Dionex polypropylene filters, prior to be analysed for anions. Groundwater samples were collected in each monitoring well via a low flow purging and sampling technique. The collected groundwater samples were filtered through 0.22 μm Dionex polypropylene filters, stored in a cool box at 4 °C and analysed in the laboratory. Major anions in groundwater and soil were analysed using an isocratic dual pump ion chromatography. Quality Control (QC) samples were run every 10 samples and the standard deviation for all QC samples run was better than 4%.

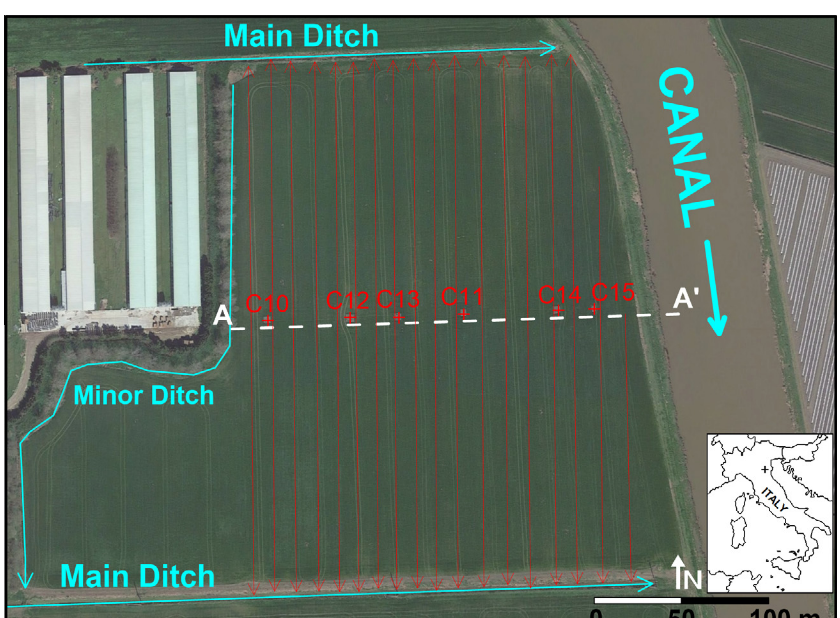

Fig. 1. Field site location with the main hydraulic features highlighted: tile-drains (red lines), ditches (cyan lines), monitoring wells (red crosses) and the model transect A–A′ (dashed white line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)