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The effects of irrigation on groundwater quality and quantity in a human-modified hydro-system: The Oglio River basin, Po Plain, northern Italy

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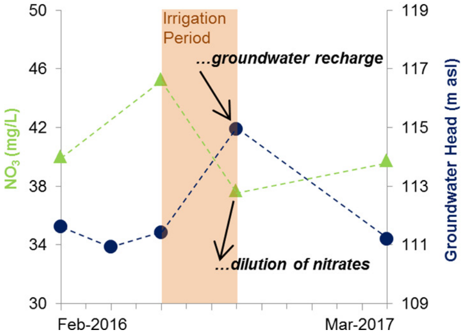
HIGHLIGHTS

- Surface irrigation in the Po Plain has altered the area's hydrologic balance.
- Irrigation on unconfined aquifers boosts aquifer recharge and dilutes groundwater NO_3.
- Recharge from irrigation sustains present-day groundwater use by humans & ecosystems.
- This should be considered in surface water conservation policies.

GRAPHICAL ABSTRACT

Surface irrigation in the higher Po Plain leads to…



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ABSTRACT

For several hundred years, farming in the Po Plain of Italy (46,000 km^2, 20 million inhabitants) has been supported by intensive surface irrigation with lake and river water. Despite the longevity of irrigation, its effects on the quality and quantity of groundwater is poorly known and so is investigated here through seasonal measurements of hydraulic heads and water quality in groundwaters, rivers, lake, springs and rainwaters.

In the north of the study region, an unconfined coarse-grained alluvial aquifer, infiltration of surface irrigation water, sourced from the Oglio River and low in NO_3, contributes much to aquifer recharge (up to 88%, as evidenced by a δ^2H-Cl/Br mixing model) and has positive effects on groundwater quality by diluting high concentrations of NO_3 (decrease by 17% between June and September). This recharge also helps to maintain numerous local springs that form important local micro-environments. Any increase in water-use efficiency in irrigation will reduce this recharge, imperil the spring environments, and lessen the dilution of NO_3 leading to increasing NO_3 concentrations in groundwater.

These findings can be extended by analogy to the entire Po Plain region and other surface-water-irrigated systems worldwide where inefficient irrigation methods are used and similar hydrogeological features occur.

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1. Introduction

Groundwater is the main source of freshwater in many regions worldwide (Filimonau and Barth, 2016). To guarantee sustainable use of groundwater by humans and ecosystems (EC, 2000, 2006), its quantity must be protected against depletion and its quality protected from pollution. Strategies for the protection and sustainable management of groundwater resources should be based on a detailed, pre-exploitation, knowledge of aquifer properties, groundwater flow, and water quality in the aquifer and sources of recharge. Including surface waters in such studies is vital, since surface waters may recharge aquifers and be linked to groundwater in a hydrologic continuum (Menció et al., 2014; Rozemeijer and Broers, 2007; Sophocleous, 2002; Zhang et al., 2016). In addition to the natural elements composing a hydrological system (*i.e.* groundwater, rivers, lakes, springs, rainfall), anthropogenic activities may add new components and/or change the natural hydrological cycle by, for example, abstracting groundwater, diverting rivers, creating artificial channels and introducing irrigation, so that the concept of the human-modified hydro-system should be adopted (Nalbantis et al., 2011; Wagener et al., 2010).

Irrigation is a human practice capable of altering both quality and quantity of groundwater resources (Bouwer, 1987). Previous works in many regions worldwide reported a variety of effects of irrigation on groundwater resources (Leng et al., 2015), such us increased aquifer recharge in areas irrigated with surface water (Jiménez-Martínez et al., 2009; Kendy and Bredehoeft, 2006; Ochoa et al., 2007); depletion of groundwater resources where it supplies irrigation demand (Leng et al., 2014; Pfeiffer and Lin, 2014; Scanlon et al., 2012), and impairment of groundwater quality (Chen et al., 2010; Gallegos et al., 1999; Rattan et al., 2005; Schmidt and Sherman, 1987; Yesilnacar and Gulluoglu, 2008). An example of a hydro-system modified by irrigation is the Po Plain (northern Italy), in particular the Lombardy Region, where networks of irrigation channel have been used since the Middle Ages (*i.e.* since the 12th century; Fantoni, 2008; Marchetti, 2002) to divert water from rivers and lakes and distribute it to the fields through surface irrigation. This distribution system must have profoundly altered the natural hydrological cycle, given the large amounts of water that has been diverted from rivers and lakes and distributed to fields. Where soils are permeable, much of this irrigation water infiltrate to recharge underlying aquifers. Giuliano (1995) reported that irrigation is the primary recharge of Po Plain aquifers, estimated as 7×10^9 m^3/y for the entire Po Plain. This author also estimated effective precipitation as 3×10^9 m^3/y and loss to aquifer through losing streams as 2.5×10^9 m^3/y. These global figures illustrate the importance of surface sources to aquifer recharge in the region, but provide no detail of process nor of the effects on both water quality and water balance.

With the considerations outlined above in mind, the main aim of this report is to present an assessment of the effects of irrigation on groundwater quantity and quality in the intensively irrigated Po Plain, in Lombardy Region, northern Italy. We provide a conceptual model of the system in order to support the protection and sustainable management of water resources in the region. Our report also provides a framework for future numerical modeling of groundwater flow and groundwater/surface-water interactions. To these ends, an holistic approach investigating both surface water (lakes, rivers, springs and rain waters) and groundwaters is used (Wagener et al., 2010). Groundwater/surface-water interactions, and the effects of irrigation on groundwater, are investigated through Darcy's law and mass-balance methodologies (Menció et al., 2014). In particular, stable water isotopes, Cl/Br and major ions measurements with seasonal frequency are interpreted and an end-member mixing model, using Cl/Br and δ^2H, is used to assess the contribution of irrigation to aquifer recharge and its impact on groundwater quality. Particular attention is given to the main environmental problems affecting the groundwaters of the Po Plain, which are pollution by nitrate (Lasagna et al., 2016; Martinelli et al., 2018; Masetti et al., 2008; Sacchi et al., 2013) and arsenic (Carraro et al., 2015; Dalla Libera et al., 2016; Rotiroti et al., 2014, 2015). Pollution by nitrate arises from agricultural and animal husbandry (Martinelli et al., 2018), although point sources from sewage systems can be relevant (Rotiroti et al., 2017; Sacchi et al., 2013), whereas arsenic pollution is of natural origin (Carraro et al., 2013; Rotiroti et al., 2014, 2018).

2. Study area

The study covers a ~2000 km^2 area beside the ~95 km long stretch of the Oglio River (N Italy) extending from the outflow from Lake Iseo to the confluence with Mella River (Fig. 1). The Oglio River is one of the longer tributaries of the Po River and has a total length of ~280 km. It originates in the Alps and flows ~80 km in Alpine terrain, crossing the Camonica Valley before enters Lake Iseo, a subalpine lake with a surface of 65.3 km^2 and a maximum depth of 251 m (Site LTER_EU_IT_008 – "Southern Alpine Lakes"; www.lter-europe.net). Lake Iseo is a warm monomictic in which water temperatures do not drop below 4 °C. Vertical mixing occurs during or close to winter. Owing to its morphological characteristics and climatic conditions, however, Lake Iseo does not overturn completely every year; the last, recorded, complete overturns since 1978 occurred in March 2005 and March 2006 (Leoni et al., 2014). In the last five years, the thickness of vertical water mixing has been between 30 and 75 m below surface, thus damping seasonal variations in water quality at the outlet into the Oglio River. From its origin in Lake Iseo, the Oglio River crosses the Po Plain for a length of 156 km before entering the Po River. Within the study area, the Oglio River collects waters from 5 main tributaries (Fig. 1): the Cherio River, the Scolmatore di Genivolta Channel, the Saverona Stream, the Strone River, and the Mella River.

The climate of the study area is temperate continental, with cold winters and wet and warm summers. Mean annual precipitation and temperature in the area (Chiari station) are ~900 mm/y and ~12.5 °C (Bonomi et al., 2008). Precipitations are usually higher in spring and autumn than in winter or summer, although in recent years this pattern has been less evident, as shown by precipitations during 2016 (Fig. S1). The northern part of the study area is located at the transition between the Alps and the Po Plain, and is marked by moraines of the Alpine foothills. Across the rest of the area, the Po Plain decreases gently in elevation from north to south with a gradient of 0.3–4 m per km (Fig. 1). The plain area can therefore be subdivided into higher (northern) and lower (southern) plain. The transition is marked by the so-called "springs belt" (Fig. 1), a narrow area with numerous (semi)natural groundwater outflows (Balestrini et al., 2016; De Luca et al., 2014; Fumagalli et al., 2017). These springs form important local micro-environments (*i.e.* groundwater-dependent ecosystems; Abdelahad et al., 2015; Pieri et al., 2007; Rossetti et al., 2005). The Oglio River and other rivers are losing streams north of the springs belt and gaining stream south of it (Bartoli et al., 2012; Delconte et al., 2014).

Beneath the higher plain, the aquifer is monolithic and comprised of coarse sediments (gravel and sand). Southward toward the lower plain, the sediments become finer and split into a multilayer aquifer system comprised of multiple sand bodies intercalated within silt and clay (Bonomi et al., 2014; Perego et al., 2014). The higher plain is the recharge area of the whole (*i.e.* higher and lower) aquifer system (Éupolis Lombardia, 2015; Pilla et al., 2006; Rotiroti et al., 2017). In the lower plain, groundwater has a sluggish circulation and so has a longer residence time than the higher plain aquifer under natural conditions of flow (Martinelli et al., 2014). Land use in the study area is mostly for agriculture (Fig. S2). Corn cultivation dominates, mainly used as animal fodder. The crop's high requirement for water under the climatic condition of the Po Plain (Perego et al., 2012) is met by irrigation water supplied by two sources: a) the Oglio River and b) groundwater. Irrigation water from the Oglio River is distributed through an extensive network of centuries-old irrigation channels that bring water to fields of both right and left banks in the higher plain, and of the right bank only in the lower plain (Fig. 1). In the lower

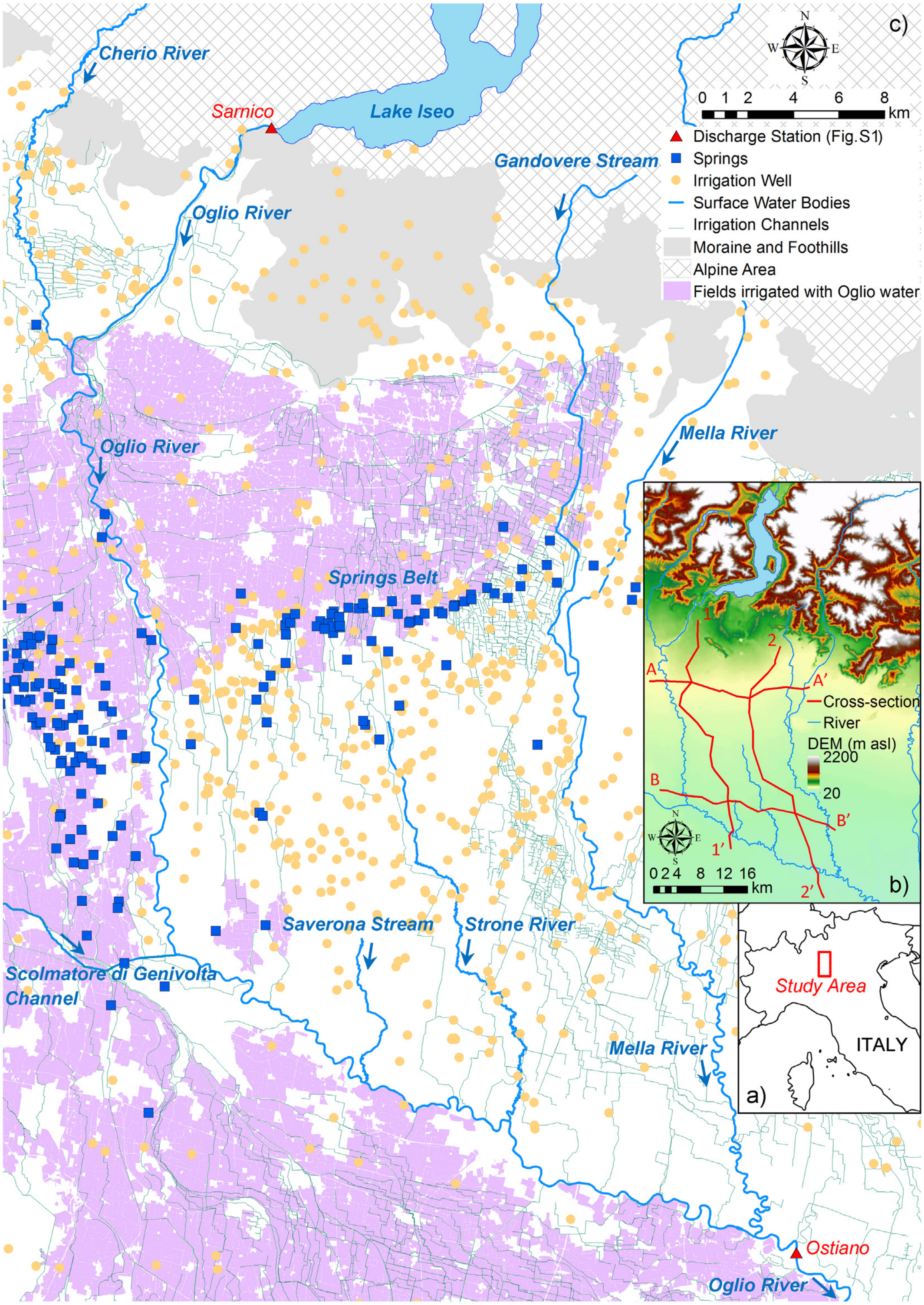

Fig. 1. a) Location of the study area. b) Digital Elevation Model (DEM) of the study area; 1–1', 2–2', A–A', and B–B' indicate the location of the cross-sections shown in Fig. 2. c) Surface water bodies, irrigation channels, irrigation wells and location of Oglio River discharge stations in Fig. S1; in purple the fields irrigated with Oglio River water distributed through the irrigation-channel network managed by the Consorzio dell'Oglio.

plain, the area of the left bank of the Oglio River is irrigated with groundwater abstracted through hundreds of irrigation wells (Fig. 1). The diversions of Oglio River water that feed the irrigation channel network occur within 35 km of the outflow from Lake Iseo. At the outflow from Lake Iseo into the Oglio River, a dam regulates water release in response to irrigation demand, while maintaining in the Oglio River flow sufficient to sustain the health of downstream ecosystems (the so-called "environmental flow"; D. G. R. Lombardia 6990/17, 2017). This minimum flow varies in the study area from 5.8 to 9.9 m^3/s (D. G. R. Lombardia 7391/17, 2017). Oglio River discharges, irrigation diversions, and local precipitations for 2016 are given in Fig. S1 as an example of the functioning of the hydro-system under analysis: during the irrigation period of June to September, the water discharged from Lake Iseo to Oglio River (Sarnico station, location in Fig. 1) increases in order to feed the irrigation diversions, which accounted for a total ~0.6×10^9 m^3 from June to September (Consorzio dell'Oglio, 2016), and the level in the Oglio River downstream (Ostiano station, location in Fig. 1) is lowered to its environmental flow when no precipitations occurred.

3. Materials and methods

3.1. Characterization of aquifers

A schematic of the aquifer structure was constructed from 66 lithological logs of boreholes in the TANGRAM database (Bonomi et al., 2014), combining 4 lithological cross-sections, two oriented N—S and two oriented W–E (for locations, see Fig. 1b). Sediments were classified as conglomerate, pebble and gravel, sand, silt and clay, or peat.

3.2. Hydrodynamic data

Groundwater heads in up to 57 wells and river stages at up to 33 locations (Fig. S3) were measured during 5 field surveys in February, April, June and September 2016 and in March 2017. Groundwater heads and river stages (m asl) were measured relative to datums determined using differential GPS (TOPCON HIPER PRO®) with an average error of 8 mm for latitude and longitude and 14 mm for altitude after post-processing correction, over a total range in head of ~125 m.

3.3. Hydrochemical and isotopic data

During 4 field surveys (February, June, September 2016 and March 2017), 43 groundwater, 17 Oglio River and its main tributaries, 1 Lake Iseo and 6 springs samples (67 total samples for each survey) were collected; the locations of sampling points are reported in Fig. S4. In addition, rainwater was collected during each rainfall event between November 2015 and December 2017 at 2 locations (P151 and P152 in Fig. S4) using rain collectors designed to minimize re-evaporation (Gröning et al., 2012). At each rainwater-collection point, 12 cumulative samples were acquired over periods ranging between 1 and 4 months, depending on the amount of precipitation.

Groundwater was sampled from wells supplying water for irrigation, livestock farming, domestic use and public water-supply. Before sampling, wells were purged until pH, electrical conductivity (EC), water temperature and dissolved oxygen (DO) were constant, which was usually after the removal of 2–3 well volumes. Samples were filtered in the field through 0.2 μm filters, those for As, Fe and Mn analysis were acidified to be 1% with respect to nitric acid. After collection, samples were stored in a portable fridge at 4 °C.

Collected samples were analysed for pH, EC, DO, water temperature, alkalinity, Cl, NO_3, SO_4, NH_4, Ca, Mg, Na, K, As, Fe, Mn, Br (the latter only in June and September 2016) and $\delta^{18}O/\delta^2H$ in water. Rainwater was analysed for $\delta^{18}O/\delta^2H$ in water and Cl/Br, the latter only from November 2015 to November 2016.

In the field, measurements were made of temperature, EC, pH, and DO using the WTW® Multi 3430 meter in a closed flow-cell. Alkalinity was analysed by H_2SO_4 titration within 24 h of samples collection. Major ions were analysed by ion chromatography (Thermo Scientific® Dionex™ ICS-1100). Ammonium was analysed by spectrophotometry with Nessler's reagent (PerkinElmer® Lambda™ EZ 201) within 24 h of samples collection. Iron and manganese were analysed by Inductively coupled plasma – optical emission spectroscopy (ICP-OES; PerkinElmer® Optima™ 7000 DV). Arsenic was analysed by graphite furnace atomic absorption spectrometry (GFAAS; PerkinElmer® AAnalyst™ 600) for samples collected in February and March and by inductively coupled plasma mass-spectrometry (ICP-MS; Varian® 820-MS) for samples collected in June and September. Bromide was analysed by ICP-MS (Varian® 820-MS) and water isotopes by wavelength-scanned cavity ring-down spectroscopy (WS-CRDS; Picarro® L2120-i). Each chemical analysis was performed on the same machine by the same operator using the same standards. Concerning trace elements, all samples were analysed at the end of each respective sampling survey; for bromide and arsenic by ICP-MS, samples of June and September were analysed together at the same time. Method detection limits (DL) are reported in Table S1. The average (mean ± standard deviation) analytical uncertainty (*i.e.* % deviation of measured values from known values of standards) for all analysed parameters was 2.5 ± 2.7%. The average charge-balance error (CBE) was −0.05 ± 0.75%; in terms of absolute values, the average CBE was 0.55 ± 0.51%, largely below the recommended threshold of 2% (Fritz, 1994).

3.4. Data elaboration

Potentiometric maps were reconstructed for the shallow and for the deep aquifers using water levels collected in March 2017, the time for which most data was available. Groundwater heads in wells and rivers stages along gaining river stretches were interpolated using ordinary kriging with breaklines (Legleiter and Kyriakidis, 2008); breaklines (*i.e.* lines along which known values are maintained in the interpolation) were used in the northern part of the area to ensure conformity of contours with the morphology of the foothills of the Alps. Higher and lower plain data were interpolated separately since they showed different spatial features, *i.e.* the former required a detrending process, the latter none.

Hydrochemical data for 67 sampling points were clustered into 8 groups on the basis of water types, geomorphology (*i.e.* higher or lower plain), groundwater/surface water interactions (*i.e.* losing or gaining stream) and results of a cluster analysis made on previous measurements in the area (Rotiroti et al., 2019). These groups are (Fig. S4): a) Lake Iseo water (LI; one location); b) Oglio River water in its losing stretch (OR lo; 3 locations); c) Oglio River water in its gaining stretch in the higher plain (OR ga-HP; 4 locations); d) Oglio River water in its gaining stretch in the lower plain (OR ga-LP; 5 locations); e) surface water of tributaries of the Oglio River (Tr; 5 locations); f) groundwater in the higher plain (GW HP; 14 locations); g) spring water (Sp; 6 locations); h) groundwater in the lower plain (GW LP; 29 locations).

An evaluation of the significance of seasonal variations of groundwater concentrations with respect to the analytical error was done. This is of great importance since seasonal variations of chemical composition in recharge are smoothed by hydrodynamic dispersion in the aquifer, resulting in seasonal amplitudes that decline along flow-lines. Small variations in concentration are therefore hard to separate from analytical variability. In the present study, the variations with season of species concentrations in groundwater are considered real only where the variations have a magnitude greater than analytical uncertainty. In order to assess analytical uncertainty, standards of known composition were inserted into analytical runs as unknowns and the uncertainty calculated as % deviation of measured values from known values. This evaluation was done for the main pollutants affecting the area, that is, NO_3 in groundwater from the higher plain and As in groundwater from the lower plain. Seasonal concentration variations were evaluated using median values which is less affected by outliers and skewed data than is the mean.

A local meteoric water line (LMWL) was calculated using reduced major axis (RMA) regression of collected rain samples, excluding a few samples that had clearly suffered some evaporation in the sampler (summer samples of location P151, spring and summer samples of location P152; Fig. S5). Evaporated samples were used in the calculation of volume-weighted means of $\delta^{18}O$ and δ^2H values (Table S2), after extrapolation back along evaporation lines to their intersection with the LMWL (Balestrini et al., 2014).

End-member mixing models using Cl/Br (mass) ratio and δ^2H were developed to identify the source of recharge to aquifers. Values of Cl/Br are taken here to be a conservative tracer of the origin of water (Alcalá and Custodio, 2008; Davis et al., 2004; McArthur et al., 2012; Panno et al., 2006; Rotiroti et al., 2017; Vengosh and Pankratov, 1998); δ^2H is used since it has a lower kinetic fractionation during evaporation than δ^{18}O (Clark, 2015; Clark and Fritz, 1997). The mixing model was developed only for the higher plain aquifer, where the composition of the end-members can be identified. For the lower plain aquifer, a mixing model was not developed since end-member compositions cannot be distinguished, *e.g.* recharge by irrigation through channels fed by the Oglio River has the same composition as pumping-induced riverbank infiltration from the Oglio River, that seems to influence composition in some wells (see Section 5.2.2 for details). Two end-members were used in the mixing models for the higher plain aquifer: (a) rainfall and (b) combined Lake Iseo-Oglio River-water in the losing stretch, taken to reflect the composition of irrigation water feeding the channel network. The volume-weighted mean precipitation values of Cl/Br and δ^2H for rainfall were respectively 119 and − 51.2‰, for location P151, and respectively 204 and − 50.9‰ for location P152. The values for Oglio River and Lake Iseo represent means of values from surveys of June and September 2016 for points L130 (Lake Iseo; 474 and − 64.7‰, respectively) and R106 (Oglio River; 733 and − 65.1‰, respectively). Indeed, the Oglio River in point R106 has a Cl/Br ratio higher than that of Lake Iseo, due to the discharge of effluents from the wastewater treatment plant treating the sewage coming from villages around Lake Iseo. The use of Cl/Br in the mixing model rather than Cl or Br alone allows precipitations to be used as end-member of recharge in the higher plain, since the Cl/Br of rainwater (as well as stable water isotopes) is mostly conservative during infiltration and circulation in the subsurface (Alcalá and Custodio, 2008), although local exceptions occur where additional inputs of Cl or Br have been noted (see Section 4.4 for details). Plots of δ^2H *vs* Cl and δ^2H *vs* Br are reported in the Supplementary Data (Fig. S6) for a comparison.

4. Results

4.1. The aquifers of the study area

Four lithological cross-sections through the field area are shown in Fig. 2. These show a) a mono-layer aquifer mainly composed of pebble and gravels, fractured or poorly consolidated conglomerate or sands in the higher plain and b) a multi-layer aquifer in the lower plain comprised of vertical alternation of sands with silty clays and peat, with 3 main aquifer subunits: shallow (<40 m bgs), intermediate (between 40 and 100 m bgs) and deep (>100 m bgs). Our findings confirm the typical structure of alluvial aquifers in the Alpine sector of the Po Plain reported in previous studies (Carcano and Piccin, 2002; Éupolis Lombardia, 2015).

4.2. Groundwater heads and Oglio River stages

The potentiometric maps of March 2017 for the shallow and deep aquifers are shown in Fig. S7. In the lower plain, the former map includes data for the shallowest aquifer (depth < 40 m bgs) whereas the latter map includes data for intermediate and deep aquifers (depth > 40 m bgs). Both maps include all data for the higher plain aquifer since no groundwater head variations with depth can be observed on this scale in this monolithic aquifer. Groundwater heads ranged between ~160 m asl in the north-western part of the study area to ~35 m asl in the south-eastern part. In the shallow aquifer, groundwater flows generally from NW to SE although its strong interactions with surface water bodies impart strong local variations to its flow direction, in particular in the lower plain where the rivers (*i.e.* Oglio, Saverona, Strone and Mella) are gaining. These variations are more evident on the right bank area of Oglio River where groundwater flow is from SW to NE owing to the proximity of the gaining Oglio River. Conversely, the deep aquifer in the lower plain has a regular groundwater flow directed from NW to SE, that reflects the regional flow direction (Éupolis Lombardia, 2015). The mono-layer aquifer of the higher plain is unconfined, with a groundwater level around 50 m bgl in the northern part. The water level decreases progressively toward the springs belt reaching depths <5 m bgl and 0 m at the springs. The aquifers of the lower plain are generally confined, expect where the confining layer thins locally to create semi-confined or unconfined conditions.

Groundwater heads in the shallow aquifer fluctuated over the monitored period (Fig. 3). The lowest heads were registered in spring (April) due to low precipitation in winter and spring (Fig. S1). During the irrigation period from June to September, fluctuations in groundwater head were locality-dependent: an increase of around 4 m was registered in the higher plain (well HL13); stability can be observed around the spring belt (well LL65); a decrease of ~0.8 m was registered in the lower plain on the left bank area of Oglio River (well LL50). In the lower plain on the Oglio River's right bank, heads increased ~1 m (well LR55) or were stable (well LR58). For the deep aquifers of the lower plain (Fig. S8), a decrease of ~1.5 m was seen in both right bank (well OV76, screen interval of 110–120 m bgl) and left bank (well LL74, screen interval of 120–150 m bgl).

In the lower plain, a progressive decrease of head occurs from shallow to deep confined aquifers, *e.g.* in the three nearby wells LR59, LR61 and LR60 (Fig. S7). These are screened 21–25, 97–153 and 167–182 m bgl, respectively. In March 2017, their hydraulic heads were 41.84, 35.60 and 33.50 m asl, respectively. In the river valleys (Fig. S9), in particular in the Oglio River valley, where ground elevations are low, hydraulic heads of deep aquifers are higher than those of the shallow aquifer and levels in the Oglio River, and some wells are artesian (*e.g.* OV70 and OV72). For example, hydraulic heads in March 2017 in wells OV76 and OV77 were 38.37 and 36.59 m asl whereas Oglio River stages in nearby points were 31.60 (point RO13) and 30.10 (point RO14) m asl (see Fig. S7 for points location).

The elevation of the Oglio River ranged from ~185 m asl at the outflow from Lake Iseo to ~30 m asl at the confluence with Mella River. Fluctuations of Oglio River stages in the monitoring period were <1 m and generally around 0.5 m. Fig. S10 shows the comparison between Oglio River stages and groundwater heads in wells located close to the river where the Oglio river transitions from losing to gaining behaviour (Delconte et al., 2014). The transition point is identifiable as the point where contours of Oglio River stage intersect contours of groundwater head. Fig. S10 shows that this transition point moved from around the 134th km of Oglio River (WGS 84 Long: 9° 51' 12.784" and Lat: 45° 32' 23.816") in October 2016, when groundwater heads were the highest in the higher plain aquifer, to around the 139th km (WGS 84 Long: 9° 51' 40.049" and Lat: 45° 30' 20.800") in the other sampling periods.

4.3. Water quality

Water quality in the monitoring period is summarized by the statistical parameters reported in Table S1. Results of selected species and parameters are shown through box-plot graphs in Fig. 4 and S11, the latter reporting a focus on lower plain groundwaters divided by shallow (depth <40 m bgs), intermediate (between 40 and 100 m bgs) and deep (>100 m bgs) aquifers. Water quality in Lake Iseo and the losing stretch of the Oglio River was better (lower EC, Cl, NO_3 and trace elements) compared to groundwater. In many groundwaters of the lower plain, concentrations of As, Fe, Mn and NH_4 exceeded Italian regulatory limits of 10, 200, 50 and 500 μg/L, respectively (D. Lgs. 152/06, 2006; D. Lgs. 30/09, 2009). In the higher plain, NO_3 concentrations in many groundwaters exceeded the regulatory limit of 50 mg/L (D. Lgs. 30/09, 2009). Spring water reflected the composition of groundwater in the higher plain aquifer. The quality of Oglio River tributaries was worse than that of Oglio River itself, as evidenced by EC, Cl, NO_3, *etc.*

The O_2 content was highest in Lake Iseo (median of 10.0 mg/L) and Oglio River in its losing stretch (median of 10.4 mg/L). Groundwater was oxic in the higher plain, with a median O_2 concentration of 6.0 mg/L, but very low in the lower plain (median concentration of 0.02 mg/L). The EC and Cl had low values in Lake Iseo (median of 250 μS/cm and 3.2 mg/L, respectively) and show increases along the

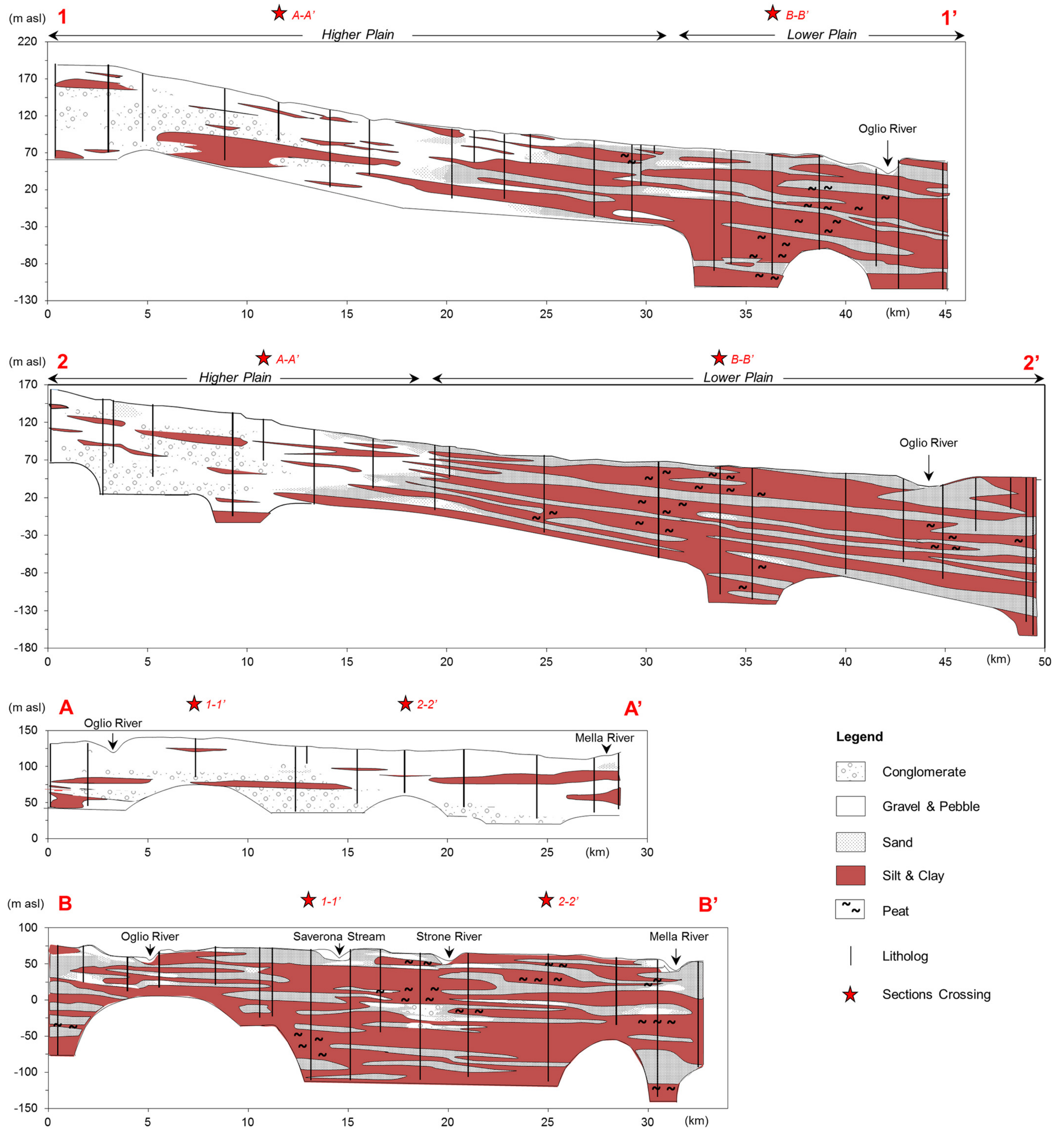

Fig. 2. Lithological cross-sections of study area. Location of cross-sections is shown in Fig. 1b.

Oglio River up to 565 μS/cm and 16.1 mg/L in its gaining stretch along the lower plain; tributaries of Oglio River had higher values (median of 653 μS/cm and 16.5 mg/L). Groundwater in the higher plain and springs had comparable values of EC and Cl with medians of 640 and 655 μS/cm and 12.3 and 9.9 mg/L, respectively, whereas groundwater in the lower plain had lower values (median of 471 μS/cm and 3.0 mg/L, respectively).

Concentrations of NO_3 were higher in groundwater from the higher plain and spring water (median of 39.8 and 40.6 mg/L, respectively) than in groundwater from the lower plain, where concentrations were generally <DL. The upper reaches of the Oglio River, where it is a losing stream, had low concentrations of NO_3 that nevertheless increased downstream from a concentration of 2.5 mg/L (median) at Lake Iseo to around 20.6 mg/L (median) in its lower reaches where it is a gaining stream; Oglio River tributaries had higher concentrations (median of 29.4 mg/L) than the main Oglio River. Concentrations of SO_4 had comparable values in most surface waters and groundwaters with medians between 40.9 and 45.6 mg/L, with the exception of groundwater in the lower plain which had lower values (median of 11.6 mg/L). A slight increase of SO_4 was observed along the course of the Oglio River passing

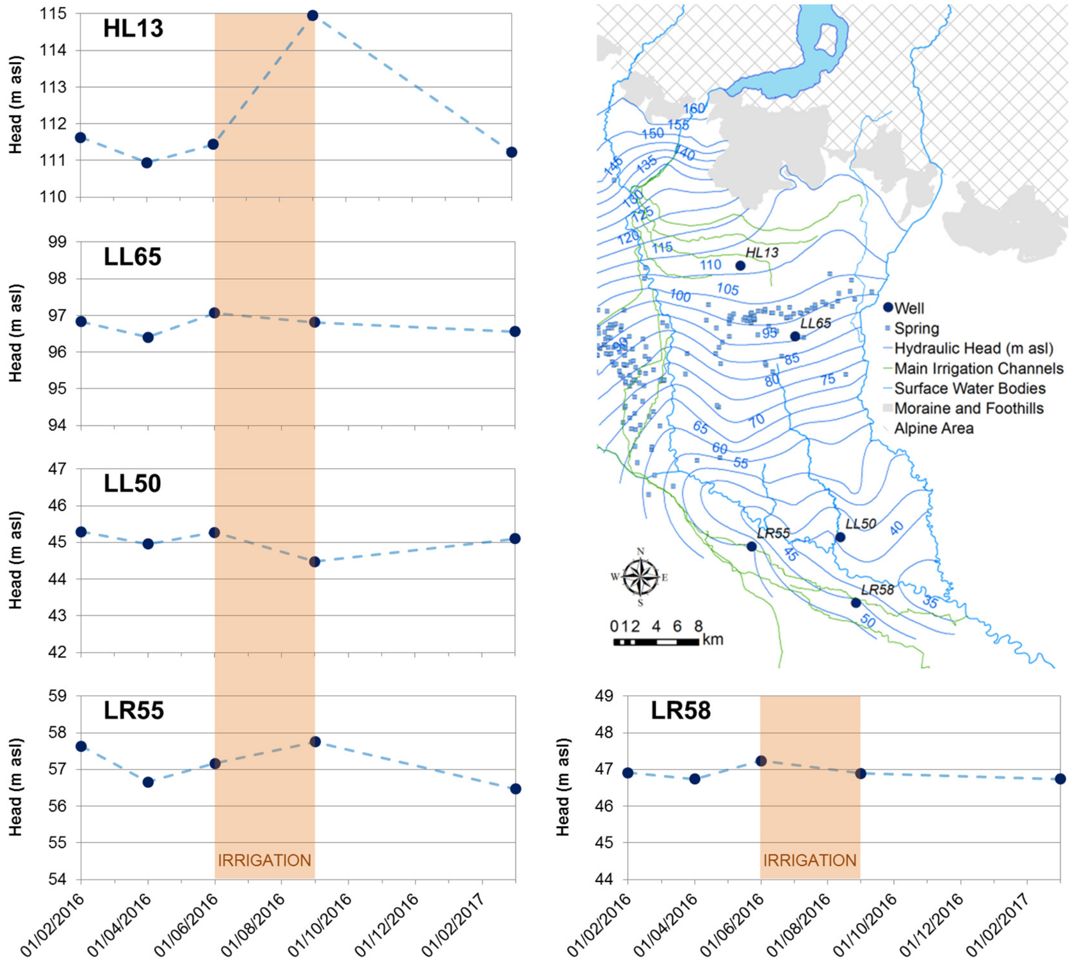

Fig. 3. Fluctuations of groundwater heads in the shallow aquifer over the monitored period in wells representative of different aquifer behaviours. Potentiometric maps are reported in full in Fig. S7.

from higher to lower plain (Fig. 8), likely due to the contribution of tributaries that had the highest concentrations (<61.4 mg/L). In groundwater in the lower plain, concentrations of As, Fe, Mn and NH_4 were higher than Italian regulatory limits, reaching up to 289, 3270, 267 and 5061 μg/L, respectively, proving the presence of anoxic conditions. Sporadic high values were registered for Mn and NH_4 also in spring and tributaries water. The lower plain groundwaters did not show any relevant trend of concentrations over depth, with the exception of Mn that exhibited a decrease over depth (Fig. S11).

4.4. Water isotopes and mixing model

Mean $\delta^{18}O$ and $\delta^{2}H$ values for each monitoring point are plotted in Fig. 5a. Rainwater samples are expressed as volume weighted mean $\delta^{18}O$ and $\delta^{2}H$ values over the period November 2015–December 2017. Values are −7.8 and − 51.2‰ for point P151 and − 7.9 and − 50.9‰ for point P152, respectively. Fig. 5a plots also the local meteoric water line (LMWL) for northern Italy ($\delta^{2}H = 7.71\ \delta^{18}O + 9.40$) reported by Longinelli and Selmo (2003) and the LMWL calculated with RMA regression of rain samples from P151 and P152 ($r = 0.99$, $n = 18$). The slope of the LMWL is 8.45 and the deuterium excess is 15.45. Lake Iseo had the most depleted $\delta^{18}O$ and $\delta^{2}H$ values (−9.6 and − 65.1‰, respectively) owing to its catchment being at a higher altitude than other sites and its more northerly latitude, typically with $\delta^{18}O < -9$ (Longinelli and Selmo, 2003). Baseflow of groundwater into the Oglio River progressively enriched the composition downstream, reaching $\delta^{18}O$ and $\delta^{2}H$ values of −9.0 and − 60.8‰ in the gaining stretch in the lower plain. The isotopic composition of tributaries ranged from −9.2 and − 63.1‰, for the Scolmatore di Genivolta (R104), which is fed partially by Oglio River water, to −8.1 and − 54.4‰, for the Cherio River (R105), which has an Alpine origin with a catchment area covering lower altitudes and latitudes than that of the Lake Iseo (Longinelli and Selmo, 2003). Groundwater in the lower plain aligns with the LMWL and mostly ranged between −9.1 and − 8.4% in $\delta^{18}O$ and − 62.0 and − 55.1 in $\delta^{2}H$, with the exception of a few points that were more depleted (up to −9.5 and − 65.0% in $\delta^{18}O$ and $\delta^{2}H$, respectively) matching the values of the closest Oglio River water. Groundwater in the higher plain clusters into two groups: a) samples with $\delta^{18}O$ and $\delta^{2}H$ values ranging respectively from −9.2 and − 62.9‰ (approaching those of Oglio River) to −8.7 and − 59.2‰ and b) samples with $\delta^{18}O$ and $\delta^{2}H$ values ranging respectively from −8.0 and − 53.1‰ to −7.4 and − 49.9‰, the latter approaching the rainfall signature. Both groups showed slight evaporative trends. Evaporation percentages, calculated through the Gonfiantini (1986) equation, were up to 1.1% (well HL11) in the first group and up to 2.5% (well HL09) in the second group. Springs had $\delta^{18}O$ and $\delta^{2}H$ values ranging respectively from −9.3 and − 63.2‰ to −8.7 and − 59.0‰ and matching the more depleted groundwaters in the higher plain.

Fig. 5b shows the plots of mean $\delta^{18}O$ in groundwaters plotted against well-screen depths. No trends can be observed. The intermediate and deep wells in the multi-layer aquifer of the lower plain generally fall within the range − 9.0 to −8.2‰ reported by previous studies for the

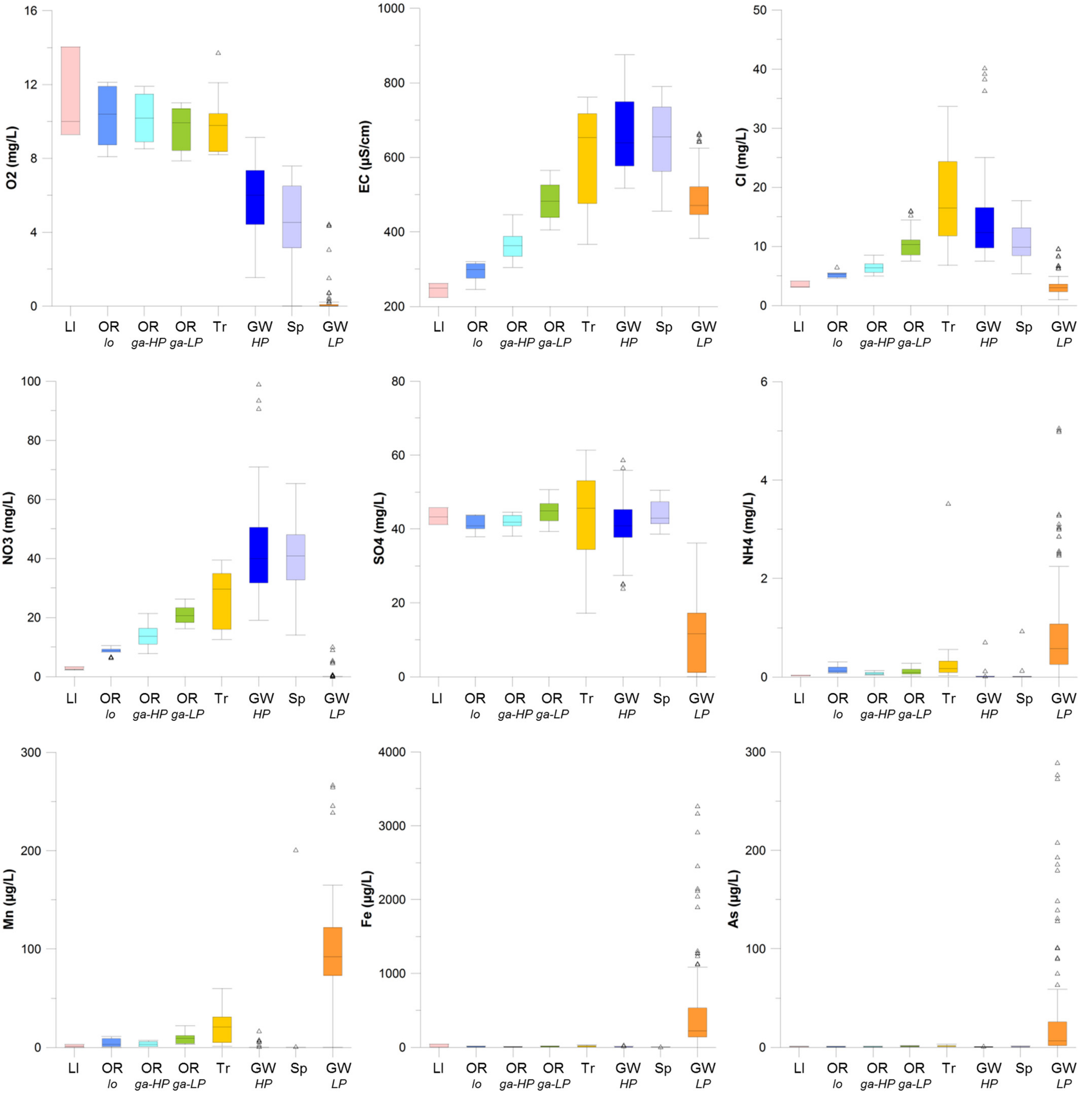

Fig. 4. Box-plots of data acquired from 4 surveys (February, June, September 2016 and March 2017); triangles represent outliers (*i.e.* values less than the first quartile or greater than the third quartile by >1.5 times the interquartile range). LI: Lake Iseo water; OR lo: Oglio River water in its losing stretch; OR ga-HP: Oglio River water in its gaining stretch in the higher plain; OR ga-LP: Oglio River water in its gaining stretch in the lower plain; Tr: water of tributaries of the Oglio River; GW HP: groundwater in the higher plain; Sp: spring water; GW LP: groundwater in the lower plain.

deep aquifers in the Po Plain (Pilla et al., 2006; Rotiroti et al., 2017). However, a few samples deviate from this range toward more depleted values that are close to the values for $\delta^{18}O$ of the Oglio River.

Mean values of Cl/Br and δ^2H in groundwater samples are plotted in Fig. 6, together with mixing lines between two end-members: (a) rainfall and (b) Lake Iseo and Oglio River in the losing stretch (from where irrigation channels are sourced). These groups represent the main sources of recharge to the higher plain aquifer. Groundwaters in the higher plain plot within the mixing area (*i.e.* the area between the mixing lines), with the exception of 3 samples (HL04, HL08 and HL09) that are above it. Reasons why these points plot above the mixing area include local anthropogenic inputs that may be high in Cl (Vengosh and Pankratov, 1998). Most groundwaters in the higher plain fall in the mixing area with >50% of irrigation water whereas the remaining few points have <20% of it. In the lower plain, groundwaters clusters into two groups of Fig. 6: a) those shifted toward lower Cl/Br with respect to higher plain groundwaters (*i.e.* Cl/Br < 340) and δ^2H values between −60 and − 55‰, and b) those with higher Cl/Br values (*i.e.* Cl/Br

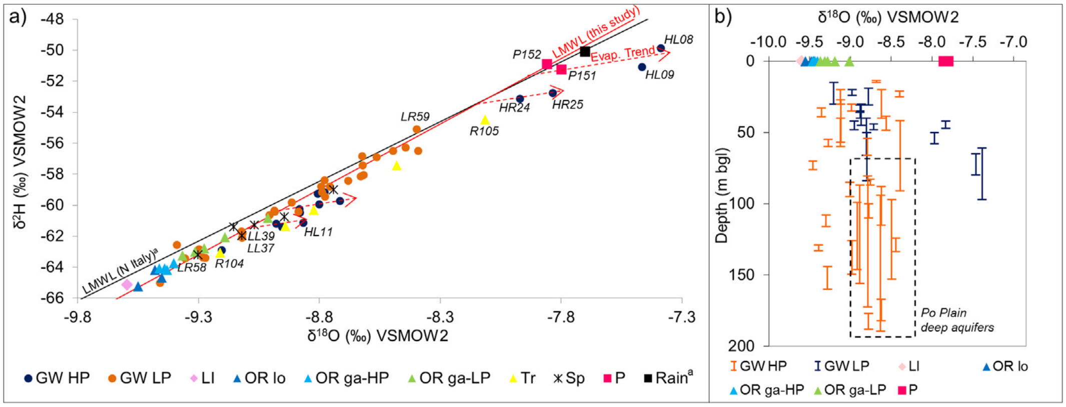

Fig. 5. a) Mean δ^2H *vs* δ^{18}O values for each monitoring point. Samples labelled with ID number are cited in the text. The local meteoric water line (LMWL) for N Italy ($\delta^2H = 7.71\ \delta^{18}O + 9.40$) and rain at Sarnico station (black square) are from ᵃLonginelli and Selmo (2003). LMWL from this study ($\delta^2H = 8.45\ \delta^{18}O + 15.45$; $n = 18$) is based on RMA regression. b) Mean δ^{18}O in groundwater over depth; symbol length corresponds to length between the top of the first well screen and the bottom of the last well screen; the dashed box represent reference range values for deep aquifers in the Po Plain (Pilla et al., 2006). GW HP: groundwater in the higher plain; GW LP: groundwater in the lower plain; LI: Lake Iseo water; OR lo: Oglio River water in its losing stretch; OR ga-HP: Oglio River water in its gaining stretch in the higher plain; OR ga-LP: Oglio River water in its gaining stretch in the lower plain; Tr: water of tributaries of the Oglio River; Sp: spring water; P: rainwater.

> 340) and δ^2H values between −65 and − 50‰, with the sole exception of point LL45 having a more enriched δ^2H value. The low Cl/Br of the first cluster can be related to additional Br entering the waters by diffusion from decaying organic-rich aquitards (McArthur et al., 2012; Nissenbaum and Magaritz, 1991; Rotiroti et al., 2017). This process is more pronounced in those aquifers of the multi-layer system of the Po Plain that have the longer residence times and so, older recharge (Rotiroti et al., 2014, 2015). Low Cl/Br also identifies recharge that occurred before anthropogenic influences were felt across the region. The stable water isotope composition of groundwaters in the first cluster (δ^2H between −60 and − 55‰ that corresponds approximately to δ^{18}O between −8.9 and − 8.4‰) confirms their longer circulation paths since it falls within the range reported above for the deep Po Plain aquifers. Therefore, it can be inferred that points falling within the first cluster indicate groundwaters with older recharge. These wells have little or no younger recharge from local precipitations or irrigation water sourced both from Oglio River and groundwater itself; the latter would be indicated by the sole increase of Cl/Br values due to the likely leaching of fertilizers by irrigation water before re-infiltrating the aquifer; this could be the case of well LL45. Conversely, the points falling within the second cluster, that have Cl/Br and δ^2H values approaching those of the Oglio River, can indicate groundwaters with a component of younger recharge.

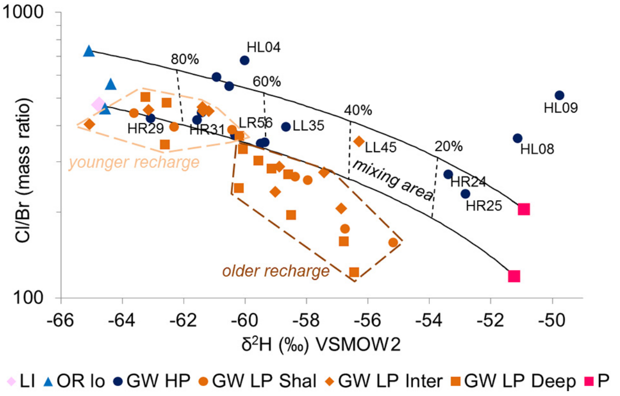

Fig. 6. Plot of mean Cl/Br *vs* δ^2H for groundwater samples and mixing lines between end-members of recharge in the higher plain aquifer (see Section 3.4 for end-members composition). Samples labelled with ID number are cited in the text. Percentage labels on the mixing lines show the fractional contribution to mixing of the high-Cl/Br end-members. LI: Lake Iseo water; OR lo: Oglio River water in its losing stretch; GW HP: groundwater in the higher plain; GW LP Shal: groundwater in the lower plain shallow aquifer (depth < 40 m bgs); GW LP Inter: groundwater in the lower plain intermediate aquifer (between 40 and 100 m bgs); GW LP Deep: groundwater in the lower plain deep aquifer (>100 m bgs); P: rainwater.

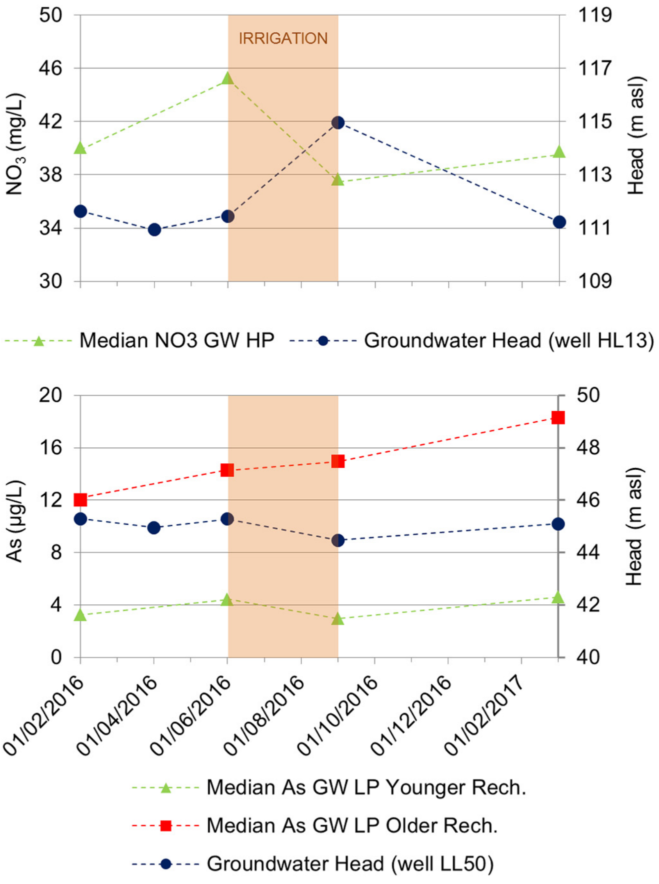

Fig. 7. Seasonal variations of median concentrations of groundwater NO_3 in the higher plain (GW HP), As in the lower plain (GW LP) and groundwater heads in wells representative of higher (HL13) and lower (LL50) plain aquifers. The comparison between median concentration and variations in analytical uncertainty is reported in Table 1.

4.5. Seasonal variations of NO_3 and As concentrations

Seasonal variations of median concentrations of groundwater NO_3 in the higher plain and As in the lower plain are shown in Fig. 7, together with the variation of hydraulic heads in wells representative of higher (well HL13) and lower (well LL50) plain aquifers. Table 1 evaluates the significance of time variations of concentrations with respect to the analytical uncertainty. For As, median concentrations were calculated for each of the two groups differentiated by Cl/Br and δ^2H (Section 4.4; Fig. 6) and so likely differentiated by age. This classification is adopted, rather than one based on depth, because the former yields a clear pattern of As concentrations (Fig. S12).

In the higher plain, NO_3 increased by 13% between February 2016 (40.0 mg/L) and June 2016 (45.3 mg/L), had decreased by 17% by September 2016 (37.7 mg/L), and then increased again by 6% to March 2017 (39.8 mg/L). In the lower plain, As in younger groundwaters increased by 26% between February 2016 (3.3 μg/L) and June 2016 (4.4 μg/L), decreased by 49% by September 2016 (3.0 μg/L) and increased by 36% by March 2017 (4.6 μg/L). In older groundwaters, As increased over the study period, with an increase of 16% from February 2016 (12.0 μg/L) to June 2016 (14.3 μg/L) and of 5% and 18% to September 2016 (15.0 μg/L) and March 2017 (18.3 μg/L), respectively. All these median concentration variations resulted significant (see Section 3.4) with respect to the variation of analytical uncertainty (Table 1).

5. Discussion

5.1. The role of irrigation on groundwater recharge-discharge in the higher plain

In the higher plain, irrigation water sourced by the Oglio River is the main source of recharge in the areas covered by the irrigation channel network; groundwater samples mainly recharged by this irrigation water are mapped in (Fig. 8). This assumption is sustained by the increase up to 4 m of groundwater heads during the irrigation period in this area (Fig. 3, well HL13) and by the percentage of irrigation water in these samples estimated by the Cl/Br-δ^2H mixing model of Fig. 6 to be between 55% (well LL35) and 88% (well HR29). These samples are the more depleted groundwaters shown in Fig. 5a that experienced a slight evaporation (up to 1.1%, see Section 4.4 for details). Evaporation in irrigation channels can give an evaporative signature to groundwaters recharged by irrigation (Harvey and Sibray, 2001). The small evaporative signature seen in these samples confirms that recharge here is made by irrigation rather than the Oglio River in its losing stretch, as the Oglio River samples plot on the LWML (calculated in this study), thus showing no evaporation.

Where groundwaters contain >50% of irrigation water, stable isotopic composition remained invariant over the monitored year ($\delta^{18}O$ and δ^2H of −8.8 and − 60.4‰ in February 2016, −8.9 and − 60.5‰ in June 2016, −8.9 and − 60.6‰ in September 2016 and − 8.9 and − 60.8‰ in March 2017). Although hydrodynamic dispersion in groundwater smooths seasonal variations of the isotopic signature (Clark and Fritz, 1997), it remains surprising that little inhomogeneity between irrigation and no irrigation periods is detected given (a) the unconfined and coarse nature of the aquifer sediments beneath the higher plain, both of which would promote rapid flow, (b) the rapid infiltration rate to the aquifer; Masetti et al. (2016) reported penetration to 30–40 m bgl in <5 days at a site in the Po Plain with hydrogeological features similar to ours, (c) the huge amount of irrigation water spread over the fields (~0.6 billion of m^3 derived from the Oglio River from June to September 2016) and (d) the rapid change of groundwater heads during the irrigation period of up to around 4 m. The absence of much isotopic variation highlights the dominant role played by irrigation channels in providing recharge, in addition to the role played by irrigation water distributed to fields during the growing season. Indeed, main irrigation channels are kept full all year to prevent collapse of channel banks and, since most are unlined, they recharge the aquifer year-round. This agrees with previous studies (Facchi et al., 2004; Vassena et al., 2012; Alberti et al., 2016) and is confirmed by our results: indeed, the wells with the highest percentages of irrigation water (*i.e.* wells HR29 and HR31 with 88% and 76%, respectively) are located close to one of these main channels (Fig.S4). However, the absence of detectable seasonal isotopic variation could be also related to the long period (*i.e.* centuries) of use of these irrigation practises, that could have progressively hidden the isotopic signature of local precipitations with those of irrigation water.

Irrigation channels are rare north of the main irrigated area, so precipitation is the sole or main source of recharge. This is evidenced by wells HL08, HL09, HR24 and HR25, located in this area (Fig. 8), that show a high percentage of rainwater in the mixing model and an isotopic signature close to that of local precipitations (Figs. 5a and 6). However, the fact that these samples showed an evaporative trend, although minimal (<2.5%, see Section 4.4), could indicate that they are mainly recharged by precipitations fallen on the Alps and/or the foothills of the Alps that then experienced some evaporation during surface runoff and flow within the streams or small rivers that bring this water to the plain. This seems confirmed in the plot of Fig. 5a by the proximity in composition of the Cherio River point (R105) to the wells HR24 and HR25 which are located downstream of it. Similarly, the area where wells HL08 and HL09 are located could be mainly recharged by the streams flowing down from the foothills of the Alps, such as the Gandovere stream (Fig. 1). A confirmation of this is given by that the evaporative lines shown in Fig. 5a intercept the LMWL at more depleted values with respect to the precipitations measured in the plain and this agrees with the general trend observed by Longinelli and Selmo (2003) of more depleted rainwater moving from the Po Plain to the Alps.

Concerning groundwater discharge, our results suggest that the higher plain aquifer has four main sinks of groundwater: a) gaining behaviour of Oglio River, b) outflow through the springs belt, c) outflow to the lower plain aquifer and d) abstraction through livestock, water supply, industrial and domestic wells. The increase of groundwater quantity and hydraulic heads in the higher plain due to irrigation during the growing season is not transferred to the lower plain aquifer due to the presence of the springs belt, which intercepts and discharges this excess groundwater. This excess is transferred downstream *via* increased spring discharge (Balderacchi et al., 2016; De Luca et al., 2014; Fumagalli et al., 2017), leaving groundwater heads within the spring belt and just downstream of it almost unaltered (Fig. 3, well LL65).

Table 1
Median concentration and variations in analytical uncertainty over the monitored period for NO_3 in higher plain groundwater and As in lower plain groundwater.

Survey	NO_3 in higher plain groundwater				As in lower plain groundwater with younger recharge				As in lower plain groundwater with older recharge			
	Median (mg/L)	Median variation (%)	Analytical uncertainty (%)	Uncertainty variation (%)	Median (μg/L)	Median variation (%)	Analytical uncertainty (%)	Uncertainty variation (%)	Median (μg/L)	Median variation (%)	Analytical uncertainty (%)	Uncertainty variation (%)
February 2016	40.0	–	−0.2	–	3.3	–	−1.5	–	12.0	–	−1.5	–
June 2016	45.3	13	1.8	2	4.4	26	5.0	7	14.3	16	5.0	7
September 2016	37.7	−17	2.3	1	3.0	−49	5.0	0	15.0	5	5.0	0
March 2017	39.8	6	−1.3	−4	4.6	36	−0.7	−6	18.3	18	−0.7	−6

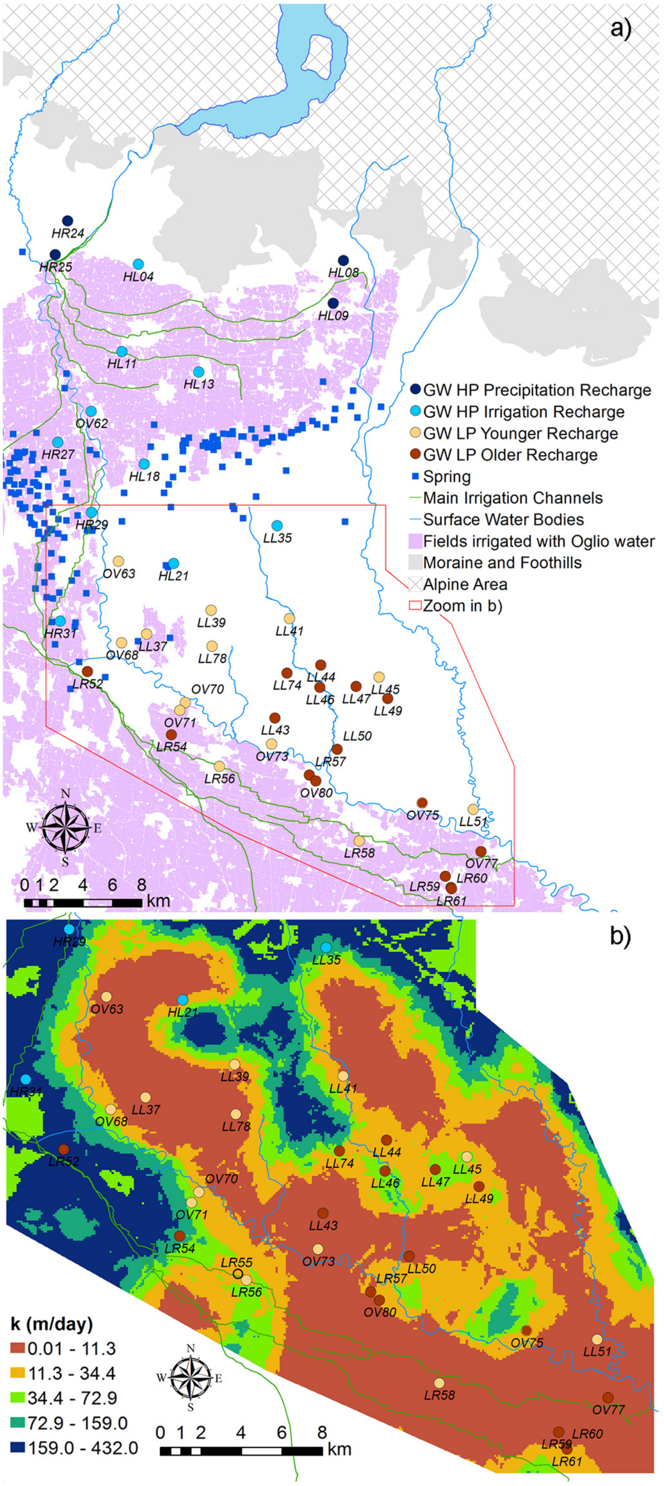

Fig. 8. a) Map showing type of groundwaters resulted from the interpretation of the Cl/Br–δ^2H plot (Fig. 6). b) Hydraulic conductivity (k) for the first ~20 m of depth in the lower plain (data and methods for the estimation of k values in Taviani et al., 2017).

5.2. The role of irrigation on groundwater recharge-discharge in the lower plain

5.2.1. Regional-scale features

In the lower plain, there is no or very slow recharge of irrigation water and rainwater due to the widespread presence of shallow confining clays and silts (Fig. 8b). Abstraction for irrigation, coupled to the increase in domestic water demand in summer, constitutes a significant discharge from the aquifer system during the growing season, as evidenced by the decrease of ~1–1.5 m of groundwater heads observed between June and September (wells LL50, LL74 and OV76 in Figs. 3 and S8). Despite ensuing drawdowns, multiple aquitards prevent or restrict recharge from surface sources so the aquifers are mainly recharged by the groundwater inflow from the higher plain, leading to long groundwater residence times. This is evidenced by a) the presence of anoxic groundwaters (Fig. 4) and b) the transitional state in the isotopic composition of wells LL37 and LL39 (Figs. 5 and 6), located at the transition between higher and lower plain, that matches that of springs and higher plain groundwater. Irrigation thus plays no or little role in recharging the aquifers of the lower plain. Rather, excess irrigation water runs off to the tributaries of the Oglio River. This is confirmed by the higher concentrations of EC, Cl and NO_3 in the tributaries than does the Oglio River and groundwater in the lower plain (Fig. 4).

Despite the overarching considerations discussed above that explain why many lower plain groundwaters fall in the group with older recharge (Figs. 6 and 8), local variations and exceptions occur, and these are discussed in the following section.

5.2.2. Local-scale features and site-specific variations

Within river valleys, deeper aquifers have higher groundwater heads than do shallow aquifers (as reported in Section 4.2), so recharge of deep aquifers from surface sources is clearly not possible. The Cl/Br-δ^2H plot indicated that seven wells located close to the Oglio, Strone and Mella rivers (wells OV63-73, LL41 and LL54, respectively) have a component of young recharge (Fig. 8). This cannot be related to recharge by irrigation/channel water since there are no channels here and the deep aquifers have higher groundwater heads than shallow aquifers, as discussed above. A likely explanation is that groundwater abstraction through these wells locally induces a fall of hydraulic heads inducing a reversal of water flow between aquifers and rivers, which are normally gaining here. For example, well OV70, that is artesian under static condition, experienced an hydraulic head drop of around 25 m under working condition. Therefore in the vicinity of these wells, a pumping-induced recharge from rivers can be assumed.

In the right bank area of the Oglio River, irrigation water is mostly sourced from channels fed by the Oglio River. Local windows formed by patchy courser sediments (Fig. 8b) allow some local groundwater recharge by return irrigation water or irrigation channels. For example, well LR55, located close to a main irrigation channel, showed an increase of ~1 m of groundwater head from June to September 2016 (Fig. 3), owing to localised higher hydraulic conductivity (Fig. 8b). Moreover, groundwater from LR56, a nearby deep well screened at 99–146 m bgl, falls within the groundwaters that have a component of younger recharge on the Cl/Br-δ^2H plot (Fig. 6), confirming local recharge by the irrigation channel. Given the depth of the well-screen, this recharge clearly occurs in response to drawdown from pumping. In a second example, well LR58, located near a main irrigation channel, but where hydraulic conductivity is lower (Fig. 8b), shows no increase of hydraulic heads in the irrigation season (Fig. 3) but have δ^{18}O and δ^2H values that approach those of irrigation water sourced by Oglio River (Fig. 5a), suggesting a component of induced recharge from the irrigation channel. Overall, these minor exceptions prove the rule that little recharge occurs from irrigation water in the right bank area of the Oglio River, mostly depending on the lithology of shallow layers and the proximity to irrigation channels.

5.3. The effect of irrigation on groundwater NO_3 and As

Where irrigation channels are absent or sparse, groundwaters contain <20% of irrigation water (Figs. 6 and 8) and NO_3 concentrations are high (mean 56.4, maximum 99.0 mg/L). Where irrigation channels are common, groundwaters contain >50% of irrigation water (Figs. 6 and 8) and NO_3 are lower (mean 38.4, maximum 56.6 mg/L). The differences arise because irrigation water sourced from the Oglio River has a low concentration of NO_3 (median of 8.6 mg/L) and so contributes to the dilution of the high NO_3 derived from other anthropogenic sources. Seasonal variations of NO_3 contents (Fig. 7) confirm this conclusion. In June, early in the irrigation season, concentrations of NO_3 are higher than in March, before irrigation starts. The increase is sourced from leaching of surplus nitrogen from the soils (Bartoli et al., 2012), since most applications of nitrogenous fertilizers are made in the autumn and winter onto bare soils, sometimes followed by a late-spring supplement (Perego et al., 2012). By September, at the end of the irrigation period, this early NO_3 spike has been diluted by infiltration of irrigation water, aided by the nitrogen uptake by the crops. This process is confirmed also by results of Cl/Br and δ^2H mixing model, calculated separately for the surveys of June and September 2016 (Fig. S13): in June there is little correlation ($r = -0.39$) between % of irrigation water and NO_3 concentrations for those samples within the mixing area and with >50% of irrigation water, whereas a significant negative correlation ($r = -0.82$) is observed in September (Fig. 9).

Concerning As in the lower plain aquifer, the effects of irrigation on its concentrations are evaluated in terms of increased groundwater abstraction (Section 5.2.1). Groundwaters with a component of younger recharge show different trends with time of As concentration than do groundwaters with older recharge (Fig. 7). The younger groundwaters show a slight decrease of As concentrations when hydraulic head is at a minimum, possibly because of induced recharge of low-As water during increased aquifer exploitation in the summer. The older groundwaters show an increase of As over all the monitored period that seems uncorrelated to the hydraulic head fluctuations.

5.4. Implications for Po Plain aquifers and future scenarios

Irrigation in the higher plain plays an important and positive role on groundwater quantity by increasing recharge over natural rates, and on water quality by diluting otherwise-high concentrations of NO_3 in groundwater. Recharge is substantial because surface irrigation, that is an inefficient irrigation system, is used and main irrigation channels, that are mostly unlined, are kept full through the whole year. A substantial reduction in the NO_3 concentrations of groundwater is achieved by this recharge because irrigation water sourced from Lake Iseo and the Oglio River water has a low content of NO_3. These are conditions that characterize also other areas of the higher part of the Po Plain, indeed a) surface irrigation is widely used (applied on 52% of irrigated lands in the entire Po Plain; Zucaro, 2011), b) most of the irrigation water (67%, Zucaro, 2011) is sourced from surface water bodies, in particular from the sub-Alpine Lakes Maggiore, Como, Iseo and Garda (Zucaro, 2011), and is distributed through the field by irrigation channels networks, having a total length for the entire Po Plain of 11,600 km (Zucaro, 2011), and c) the NO_3 concentrations of the sub-Alpine lakes that feed irrigation channels is generally low (<3.8 mg/L; Premazzi et al., 2003). Therefore, the findings of the present study that surface irrigation in the higher plain boosts groundwater recharge and can dilute groundwater nitrates can be extended by analogy to other areas of the Po Plain. Moreover, the positive effect of contributing to aquifer recharge made by an inefficient irrigation practice and the use of surface water as irrigation water can be extended to other areas worldwide where similar hydrogeological features occur.

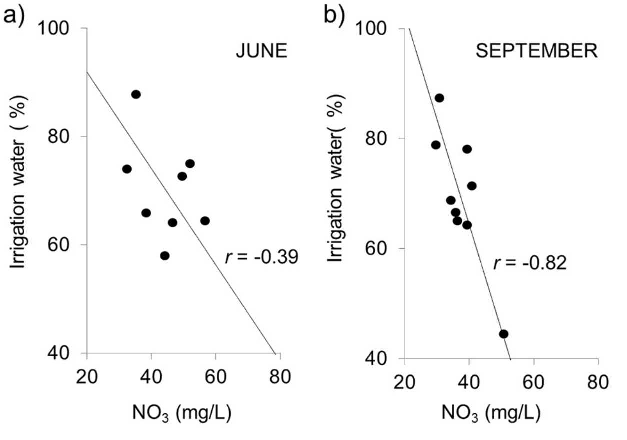

Fig. 9. Plot of % of irrigation water and NO_3 concentrations in a) June and b) September 2016 for higher plain groundwaters falling within the mixing area and with >50% of irrigation water (see Fig. S13 for mixing models). Regression lines were calculated using RMA method; *r*: Pearson correlation coefficient.

Surface irrigation using water diverted by surface water bodies has been employed in the Po Plain since the 12th century, and the disturbance to the natural hydrologic cycle this has caused is now a fundamental source of water to the aquifer that sustains present-day water use by humans and ecosystems. If this condition is not considered in promoting and executing a more efficient surface water-use and surface water conservation policies, more negative than positive results would be reached. Employment of, for example, more efficient sprinkler/drip/micro irrigation methods would decrease recharge, increase nitrate concentrations in groundwater and lessen the flow that maintains the springs of the springs belt. The depletion of water flow through the springs belt would threaten the preservation of this groundwater-dependent ecosystem (Balderacchi et al., 2016). Moreover, the decrease of aquifer recharge would imperil the present-day groundwater extraction rates from abstraction wells that sustain drinking water supply and many industrial uses. Finally, if groundwater will be used in the higher plain instead of the low-NO_3 water of Oglio River as source of irrigation water, the concentrations of NO_3 in groundwater will probably reach higher values, as already happens in the area not covered by the irrigation channel network.

The inefficient use of surface water in irrigation should be viewed as a positive; it is a form of water storage in the subsurface, that is more efficient than storing water in lakes, since these lose water by evaporation. Aquifer recharge and storage is a strategy for insuring against the problem of hydroclimatic extremes (*e.g.* droughts), that are increasing in frequency owing to a changing climate; aquifers are reservoirs of immediately accessible water for use under emergency conditions (Ducci et al., 2017), if their recharge is preserved over long periods.

6. Conclusions

This work evaluated the effects of intensive irrigation on groundwater quantity and quality in the human-modified hydro-system of Oglio River basin in the Po Plain, interpreting hydrodynamic, hydrochemical and isotopic data.

Our main findings are:

- irrigation water, sourced from the Oglio River and distributed by channels, plays a fundamental role in recharging the aquifer in the higher plain; it provides between 55 and 88% of the aquifer recharge and increases groundwater table by up to 4 m in the irrigation season; perennially-filled unlined channels recharge the aquifer year-round;
- the extensive irrigation has also positive effects on groundwater quality in the higher plain: the recharge water has a low concentration of NO_3 and dilutes anthropogenic NO_3 maintaining concentrations below the regulatory limit of 50 mg/L;
- in the higher plain, abandonment of surface irrigation with low-NO_3 water in favour of water conservation through more efficient irrigation methods would decrease recharge, imperil the spring ecosystems and present-day groundwater abstraction rates, and suppress the dilution effect leading to a likely increase of groundwater NO_3 concentrations in the higher plain;

- in the lower plain, irrigation water is mainly sourced from groundwater abstraction, so groundwater levels in the confined aquifers decrease in the summer irrigation season; vertical recharge is restricted and localised to small areas of courser deposits in confining aquitards;
- no relevant effects of irrigation, considered as increased groundwater abstractions, were observed on As concentrations in groundwater of the lower plain;
- the result that surface irrigation in the higher plain boosts groundwater recharge and dilute groundwater NO_3 can be extended by analogy to other areas of the Po Plain; the positive role of recharging the aquifer played by an inefficient irrigation practice and the use of surface water as irrigation water can be extended to other hydro-systems worldwide where similar hydrogeological features occur.

This work showed how the combined hydrodynamic, hydrochemical and isotopic analysis of surface water and groundwater is an appropriate method for investigating complex hydrosystems that have strong groundwater/surface-water interactions and/or anthropogenic modifications. Therefore, the methodology used in this study could be applied in other highly irrigated regions worldwide in order to identify the effects of irrigation on groundwater resources.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.03.427.

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