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Irrigation practices affect relationship between reduced nitrogen fertilizer use and improvement of river and groundwater chemistry

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ABSTRACT

In the last decades, the intensification of agricultural practices has deeply altered nitrogen (N) and water cycles. Climate change and drought events are expected to further increase the human impacts on the hydrological and biogeochemical cycles, and these impacts are gaining the attention of the scientific community. Here we show how the Chiese River watershed (Lombardy Region, Italy) represents an interesting opportunity to analyse the effects of traditional irrigation practices on N contamination in the context of water scarcity. During summer, flood irrigation is mostly sustained by groundwater withdrawal. Additional water withdrawals from the river contribute to the dry out of the Chiese River. The use of wells for irrigation over permeable and fertilized soils and the percolation of nitrate (NO_3^-) from the vadose zone to groundwater result in the accumulation of NO_3^- in groundwater and limited N losses via denitrification due to dominant oxic conditions. These practices contrast other measures targeting the reduction of N excess over arable land. In the Chiese River watershed, the N surplus from Soil System Budget calculations decreased by 43% since the early 2000 s but NO_3^- concentration in groundwater remained high and stable (up to 98.0 mg NO_3^- L^{-1}). The dried-out Chiese River gains groundwater and NO_3^- concentration at the river mouth approaches 32.2 mg NO_3^- L^{-1}. Our results suggest how the mismanagement of the watershed (overabundant fertilization and flood irrigation using groundwater) increases the N concentration both in the river and groundwater, leading to the violation of both Nitrate and Water Framework directives. We anticipate our assay to be a starting point for the conversion of the northern Po Plain to more efficient irrigation and fertilization practices to contrast severe droughts driven by climate change like the one who struck the Po Plain in summer 2022.

1. Introduction

The agricultural sector underwent deep changes since the beginning of the 19th century.

The first commercial fertilizer to be widely used was guano, a N-rich product that was found on the arid coastal islands of Peru and imported to the United States of America since 1843. Guano was rich in nitrogen (N) and contained substantial amounts of phosphate (PO_4^{3-}). During the second half of the 19th century, commercial N fertilizers consisted mainly of natural organic products including Peruvian guano, cotton-seed meal, bone meal, fish scraps, tank- age, and dried blood. Farm manure and legumes were also utilised but as non-commercial sources of N (Sheridan, 1979; Taylor, 1947).

Although three processes were developed in Europe in the early 1900 s for the fixation of atmospheric N, it was only in 1913 that the first commercial plant to produce ammonia using the Haber process went into operation. Industrial N fixation alleviated the soil limitation of this nutrient to plants growth, making large pools of unreactive molecular N available and directly usable (Galloway et al., 2008; Overeem et al., 2013). The continuous growth in the global population and the demand for food led to the intensification of agricultural practices, through mechanisation, irrigation, and the use of fertilizers, often in excess of crops demand (Billen et al., 2013). The population growth was mainly supported by the green revolution during the second half of the 20th century, when international agricultural research centres, in collaboration with national research programs, contributed to the development of

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"modern varieties" (MVs) for many crops with the objective of increasing the crop production. Productivity increase from MVs allowed food production to increase sensibly with only modest increases in area planted with food crops and with a relatively low increase of fertilizer and irrigation inputs (Evenson and Gollin, 2000). As the trend of population growth has not reached a plateau yet, agriculture is expected to double the overall food production by the 2050 s (Ainsworth et al., 2012).

The widespread use of natural and synthetic fertilizers following the Green Revolution has produced unintentional N pollution on a major portion of inland and coastal systems worldwide (Conley et al., 2009). In Europe, most freshwater bodies are far from the good ecological status required by the EU Water Framework Directive (WFD, 2000/60/EC), and hotspots of N pollution have been identified in Denmark, Belgium, the Netherlands, and northern Italy (Grizzetti et al., 2021). Since the early 1990 s, the European Union has implemented several directives targeting improvements in agricultural practices and wastewater treatment plants, but these policies have been more effective in reducing point rather than diffuse pollution due to their easiest management and correction (Bouraoui and Grizzetti, 2011; Grizzetti et al., 2021). Such ineffectiveness was attributed to 1) the difficulty of enforcing the compliance of farmers' management, 2) N accumulation in groundwater and soils (i.e., N legacy), and 3) multiple factors displacing soluble N from terrestrial to aquatic ecosystems, including precipitation or irrigation practices (Ascott et al., 2017; Macdonald et al., 2012; Pinardi et al., 2022).

The human-induced climate change adds uncertainties to the effects it will produce on future N dynamics, on the effectiveness of EU policies to contrast N-related environmental issues, and on agriculture practices, in particular water use (Blöschl et al., 2019; Greaver et al., 2016a). More and more frequent climatic anomalies are being observed, including dry summer or winter periods with unusually high temperatures followed by extreme precipitation events that represent outliers when plotted over historical data, especially in Southern Europe (Christidis and Stott, 2021; European Academies' Science Advisory Council, 2018; Intergovernmental Panel on Climate Change, 2014; Madsen et al., 2014; Sperna Weiland et al., 2021). Climate change can affect the timing and rates of aquifer recharge, average river discharge, and the frequency of flash floods and drought events, with extremely negative impacts on agroecosystems.

The effects of climate change on N cycling and losses have been widely investigated in natural ecosystems (e.g., Greaver et al., 2016b; Magri et al., 2020), but many uncertainties still require attention by the scientific community in agroecosystems (Bowles et al., 2018). As compared with natural ecosystems, N cycle in agroecosystems undergoes large and regular external inputs (fertilization) generally exceeding in situ N fixation rates and crops N need. During crops vegetative phase, besides plant assimilation and microbial processes, the N cycle is affected by irrigation, the solubilisation of reactive forms, and the horizontal and vertical N transfer driven by irrigation water dynamics.

Climate change is expected to affect N cycling in both direct and indirect ways. By increasing drought periods, climate change will affect the dependency of agriculture on irrigation (Fader et al., 2016). By affecting river discharge, climate change will also affect irrigation practices (e.g., abstraction from surface water is expected to decrease due to water scarcity whereas well irrigation is expected to increase) (Taylor et al., 2012). The latter implications are important as water withdrawal for irrigation purposes increased at an equal rate of agriculture and accounts for ~72% of the total water that is withdrawn from both surface and groundwater (Wisser et al., 2008). Although the overall irrigation volumes may be relatively small if compared to the global water cycle, the effects of water withdrawals at regional or local scales can be severe, perturbing the surface and subsurface hydrology and, with them, nitrate transport and transformations. During the crop season, droughts and high evapotranspiration rates force farmers to withdraw more water from rivers and aquifers for irrigation purposes, affecting N mobility and microbial processes (i.e., denitrification in soils and riverbeds) (Birgand et al., 2007).

This experimental study was carried out in a sub-basin of the Po River watershed, which is recognised as a N-contamination hotspot due to intensive agriculture, animal farming, large use of manure and synthetic fertilizers, and is heavily impacted by droughts (Baronetti et al., 2020; Bonaldo et al., 2023; Viaroli et al., 2018). This area is particularly vulnerable to climate change due to traditional irrigation practices, mostly based on large water use via flood irrigation (Racchetti et al., 2019). Despite this, the region's adaptive measures, including water-saving irrigation practices and the selection of less water and fertilizers demanding crops, were poorly implemented. The region's overall water consumption remained stable, sustained by a transition from surface to groundwater abstraction. In this context, the specific objective of this study was to explore whether and how water scarcity and the use of groundwater instead of surface water for irrigation affect N transformations and dynamics. To investigate these issues, a comparison was made between the main N inputs to and N surplus in agricultural land and long-term trends of N concentrations in both river and groundwater. Successively, the spatial and temporal hotspots of N contamination in the last two years were characterised with a more circumstantiated sampling. We hypothesised positive feedback on N contamination in both surface and groundwater due to i) the high hydraulic conductivity of the area, ii) the rapid percolation and solubilisation of soil N excess, iii) the dominance of oxic microbial pathways, iv) the accumulation of nitrate in groundwater, and v) the mobilization of N polluted groundwater to the surface drainage system. Ultimately, we speculate that the shift to well irrigation may offset past and present policies targeting the reduction of diffuse N pollution, especially under future drought scenarios driven by climate change.

2. Material and methods

2.1. Study area

The Chiese River and its basin lay in the central part of the Po River watershed. The Chiese River is the emissary of Lake Idro, it flows for 150 km and is a tributary of the Oglio River (Fig. 1a). The geological setting of the watershed is characterised by a complex stratigraphic and lithological setting in the alpine portion (Flavio et al., 1990). The plain portion of the watershed, where this research is focused, is a fraction of the Po River flood plain, characterised by a multilayer alluvial aquifer. In the northern portion of the study area (high plain), the mono-layer aquifer is phreatic and constituted by gravel and sand (Fig. 1c) vertically interrupted by silt and clay. In the southern portion, the aquifer becomes multilayer and semi-confined (Fig. A1). The groundwater in this region flows from the Alps (North) to the Po River (South) as reported in the regional potentiometric maps of the shallow aquifer calculated in 2014 by Lombardy Region (https://www.geoportale.regione.lombardia.it/). These maps were compared with more detailed and recent maps of the nearby areas (Rotiroti et al., 2019; Severini et al., 2022) to prove their reliability. The transitional area between the high and low plain (the so-called *spring belt*) hosts many natural springs caused by the change in permeability. This general setting is common in the Lombardy region and has been characterised in detail by other authors for the river basins surrounding the Oglio and Mincio rivers (Fumagalli et al., 2017; Rotiroti et al., 2019; Severini et al., 2022). This area is known for NO_3^- contamination in both surface and groundwater due to these activities and it is entirely considered as a nitrate vulnerable zone (NVZ) according to the European Nitrate Directive (91/676/EEC). For these reasons, the Chiese watershed and aquifer are seasonally monitored by the regional environmental agencies (see Section 2.2).

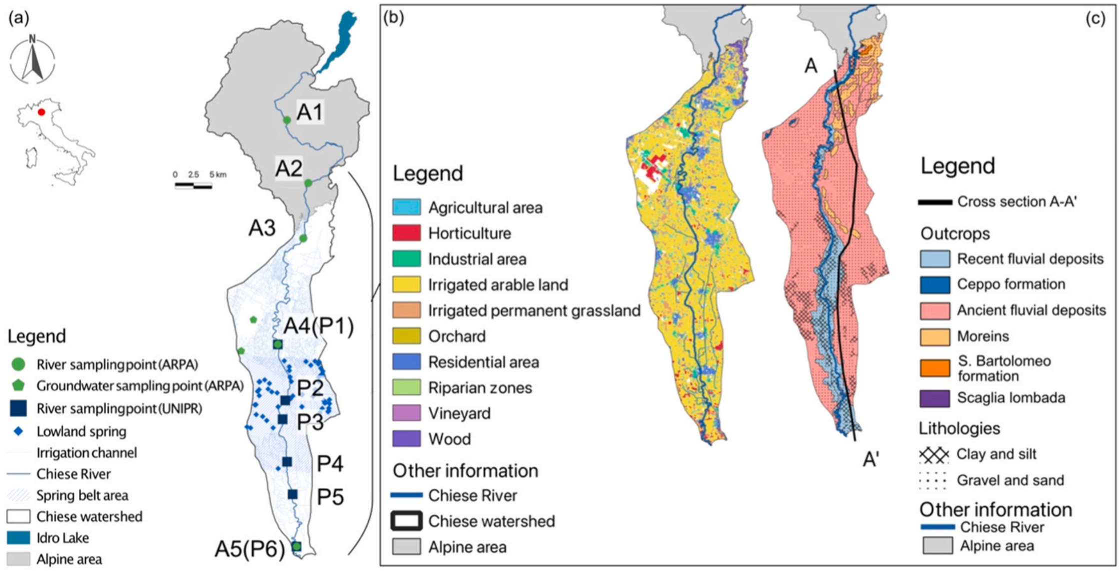

Fig. 1. (a) The Chiese River watershed, the sampling stations are named as in the map. Stations of the Regional Environmental Agency (ARPA) for surface and groundwater quality are highlighted in green, whereas the additional ones used for this manuscript are in blue; (b) land use in the Chiese River watershed; (c) outcrops in the investigated area. The cross-section A-A′ is reported in the Supplementary Material (Fig. A1).

2.2. Datasets of river NO_3^- concentration and discharge

Historical data of the Chiese River and surrounding aquifer N concentration for the period 2000–2020 were downloaded from the Lombardy Regional Environmental Protection Agency (ARPA Lombardia - https://www.arpalombardia.it, accessed 10 October 2022). The sampling stations are reported in Fig. 1a (A1-A5). Based on these data, a more detailed sampling was performed by Parma University (UNIPR) during the period 2021–2022 in the area where the NO_3^- increase in the river water was observed. The samplings were carried out 20 times in 24 months at the UNIPR sampling stations, with the stations P1 and P6 corresponding to A4 and A5, respectively (Fig. 1a). The Chiese River stage levels and discharge in the sampling station P5 for the period 2012–2019 were downloaded from the ARPA Lombardia website. The river discharge was measured at the UNIPR sampling stations (Fig. 1a) in July and August 2022 (irrigation period) and in October 2022 (non-irrigation period).

The R software (R Core Team, 2022) was used for the statistical tests. The package lme4 (Bates et al., 2015) was used to perform linear mixed effect analyses of the relationship between NO_3^- concentrations and the irrigation period. Non-parametric tests (Mann-Kendall and Sens's slope) were used to detect significant trends in water quality, main N inputs to agricultural land and N surplus.

2.3. Soil system budget

A comprehensive input–output N balance across the Utilised Agricultural Area (UAA) for the years 2000, 2008, 2010, 2014, and 2018, was calculated by using locally derived official census data on agricultural activity. Data on livestock density, irrigation volumes, and agricultural areas were extracted from the data warehouse of the National Institute of Statistics (Agricultural Census, http://dati-censimentoagricoltura.istat.it, accessed 8 November 2022) and the Agricultural Information System of the Lombardy Region (https://dati.lombardia.it/, accessed 14 October 2022), while data on crop yields and synthetic fertilizer use were obtained from the Annals of Agrarian Statistics (http://dati.istat.it, accessed 14 October 2022). Nitrogen balance across the UAA was calculated as the difference between inputs (livestock manure, synthetic fertilizers, biological N-fixation, atmospheric deposition) and outputs terms (crop harvest, ammonia volatilization, and denitrification in soils), according to the Soil System Budget approach. Such approach was previously adapted and applied to the Po River system and some of its sub-basins (Pinardi et al., 2022; Soana et al., 2011; Viaroli et al., 2018), proving to be a reliable proxy of N use efficiency at the basin scale and of the risk of diffuse N pollution to both surface and groundwaters.

All calculations are detailed in (Pinardi et al., 2022). The budget calculations were based on equations converting the census data into N fluxes using site-specific agronomic coefficients. The difference between nutrient inputs and outputs results in a net, i.e., a state of equilibrium, surplus, or deficit of N across the UAA. As such, it is an indicator of the N use efficiency of agroecosystems and a proxy of the potential risk of surface and groundwater diffuse pollution. N surplus indicates that the N inputs exceed crops uptake and losses to the atmosphere, resulting in transient N accumulation in the soil.

The N budget was first calculated at the municipality level, i.e., the administrative scale at which official agricultural statistics are usually available, and then aggregated at the basin scale by weighted for the percentage of each municipality area included in the study area through GIS analysis (QGIS software, version 3.16; https://www.qgis.org/it/site/). To characterise the agricultural pressures, the different magnitudes of agriculture and animal farming were tested dividing the watershed in three zones (mountain, hill, and plain) and contrasting differences in livestock units (LSU) abundances and areas of maize and hay cultivation. These differences were tested using the multivariate analysis of variance (MANOVA) and linear discriminant analysis (LDA) as post hoc test.

3. Results

3.1. Water management under traditional agricultural practices

The UAA accounts for 82% of the watershed's plain area (~730 km^2), mainly devoted to the cultivation of maize (38%) and fodder (21%). Most of the agricultural and animal farming activity is concentrated in the plain portion of the watershed according to the MANOVA results ($F(6,64)= 7.123$, $p < 0.001$) and the output of the LDA. The UAA is mostly irrigated through flood irrigation (66% of the cultivated surface, with an estimated water volume of 1.25×10^8 m^3) and sprinklers (31% of the surface, with an estimated water volume of

5.87×10^7 m^3). No exhaustive maps nor data are available on the irrigation wells position, characteristics, and groundwater head variations but, farmers report that almost every land parcel has a well for irrigation where groundwater heads are lower during the irrigation period. This agrees with the groundwater surface variation (up to 2.5 m, Fig. A1) which characterises the regional potentiometric maps reconstructed in May and September (lower groundwater table). Despite the change in the hydraulic heads, the groundwater flowpath is constant between September and May. As remarked in Fig. 2a, the Chiese River is almost drained during the irrigation period (April-September). On both sides of the river, there are small tributaries that are reported as "diffusively fed by groundwater" by Lombardy Region (Water Protection Plan (PTA), annex 5, https://www.regione.lombardia.it/). In the spring belt area (Fig. 2b) and downstream it, during the irrigation period a diffuse input from groundwater (and groundwater-fed channels) to the river was quantified as the difference between the downstream and upstream discharge, with106 L km^{-1} and 131 L km^{-1} in July and August, respectively. In October, after the end of the irrigation period, the diffuse input increased to 360 L km^{-1}, without any influence of precipitation. The change in groundwater inputs to the river agree with the hypothesized lower groundwater heads in summer than the rest of the year. These results also spatially agree with the potentiometric map (Fig. 2b) where a strong interaction between.

groundwater in the phreatic aquifer and the Chiese River is highlighted between the sampling stations P3 and P5. Downstream station P5, the river flows in low-permeability layers (silt and clay) and does not interact with groundwater (Fig. 1c and A1). The diffuse input from groundwater was also confirmed by the temperature decrease. During summer, when the water input is lowest but the temperature gradient between river and groundwater is the highest, downstream the sampling station of P2 the temperature was ~ 3.7 °C lower than upstream (June-September average: 24.6 °C).

3.2. N surplus in agricultural land and NO_3^- contamination in surface and groundwater

The N budget calculation showed a N surplus in the agricultural areas of the Chiese River basin in all five years studied and in all municipalities included in the watershed (Fig. 3a), ranging from a minimum average value of 132 kg N ha^{-1} y^{-1} in 2018 and a maximum of 235 kg N ha^{-1} y^{-1} in 2008 (Tab. A1).

Total N inputs to agricultural land were sustained mostly by livestock manure (56–65%) and by synthetic fertilizers (16–30%) (Tab. A1) with N from livestock manure exceeding N from synthetic fertilizers in 67–94% of the municipalities in the basin. In ten years (from 2008 to 2018), the N surplus declined significantly with a reduction of 43% at the basin level, mostly due to a decline in synthetic fertilizer distribution ($p < 0.001$, Tab. A1; Tab. A.2).

The dataset from ARPA Lombardia (2000–2020) points stable NO_3^- concentration from the Idro Lake to sampling station A4 (Fig. 3c) averaging 3.91 ± 0.87 mg NO_3^- L^{-1} (average ± standard deviation) till a maximum value of 6.39 mg NO_3^- L^{-1}. From here, it increases significantly till station A5, where concentrations average 16.49 ± 4.9 mg NO_3^- L^{-1} and includes a peak of 48.7 mg NO_3^- L^{-1} in 2017. This tendency was consistent for the period 2000–2020 and no statistically significant difference among years was detected ($p > 0.1$, Tab. A1). In the two shallow wells, the N concentrations were stable in the period 2011–2020 ($p > 0.05$, Tab. A1), averaging 67.09 ± 15.31 mg NO_3^- L^{-1} and peaking at 98.03 mg NO_3^- L^{-1} (Fig. 3b). Similarly, oxygen saturation had a constant value of 71.6 ± 11.4% over the period 2016–2021. The river stretch between stations A4 and A5, where N concentrations rapidly increase, was investigated in detail during the period 2021–2022 in twenty different samplings (Fig. 4). During both irrigation and non-irrigation periods, the N concentration increase between stations A4 and P2 was relatively small (3.6 ± 3.6 mg NO_3^- L^{-1}). During the non-irrigation period, the N concentration downstream increased at a low but consistent rate till the river closing section, just before the Chiese River flows into the Oglio River. During these months, this river stretch had a mean nitrate concentration of 9.36 ± 3.16 mg NO_3^- L^{-1} with a peak of 17.8 mg NO_3^- L^{-1}. In the same river stretch, during the irrigation period, the mean N concentration increased to 14.01 ± 5.02 mg NO_3^- L^{-1} with a peak of 32.18 mg NO_3^- L^{-1}. This increase in NO_3^- concentrations was proved to be positively related to the irrigation period, according to the linear mixed effects model results (F(1)= 30.97, $p < 0.001$) and it occurred in the area where the Chiese River gains water from the aquifer, i.e., from the sampling station P2 to P5 (Figs. 2c and 4b).

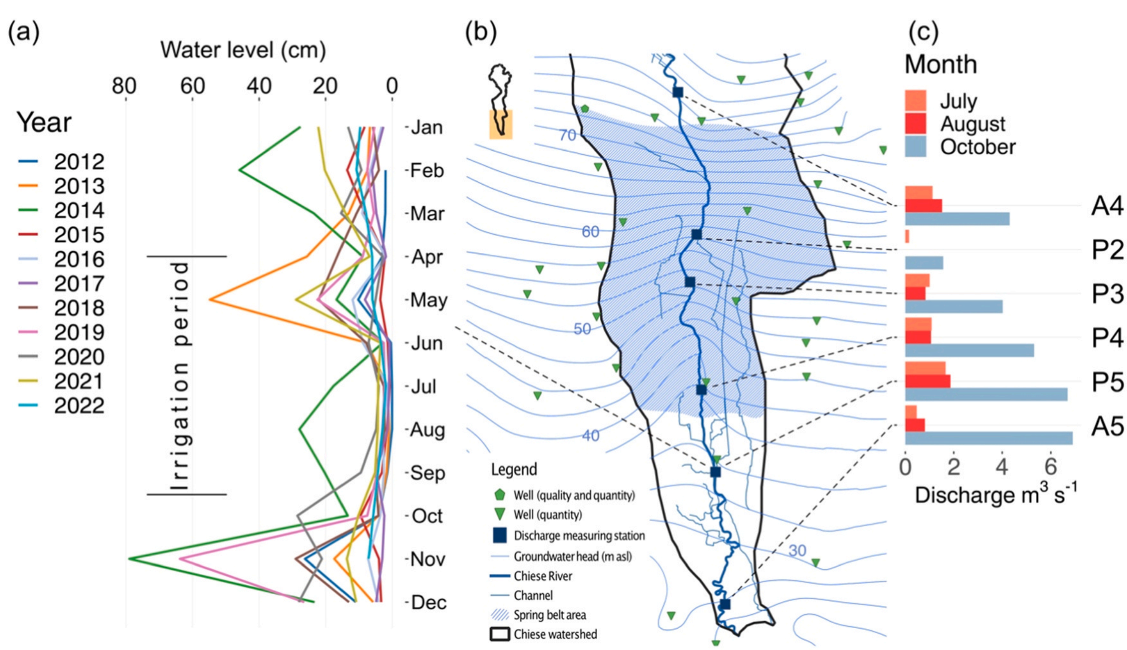

Fig. 2. (a) Water level in the station P5; (b) Location of wells used for the potentiometric map and the sampling stations where discharge measurements were performed; (c) Discharge in the Chiese River in 2022.

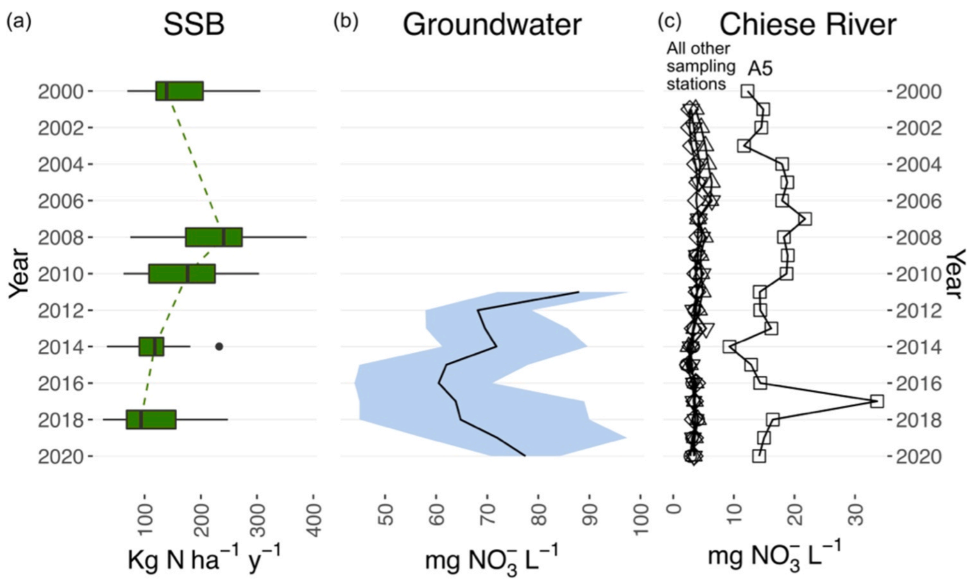

Fig. 3. (a) SSB surplus; (b) Groundwater NO_3^- concentration, the blue shaded area reports the minimum and maximum concentrations measured; (c) Chiese River NO_3^- concentration in the ARPA sampling stations reported in Fig. 1. A5 is the last sampling station along the river course.

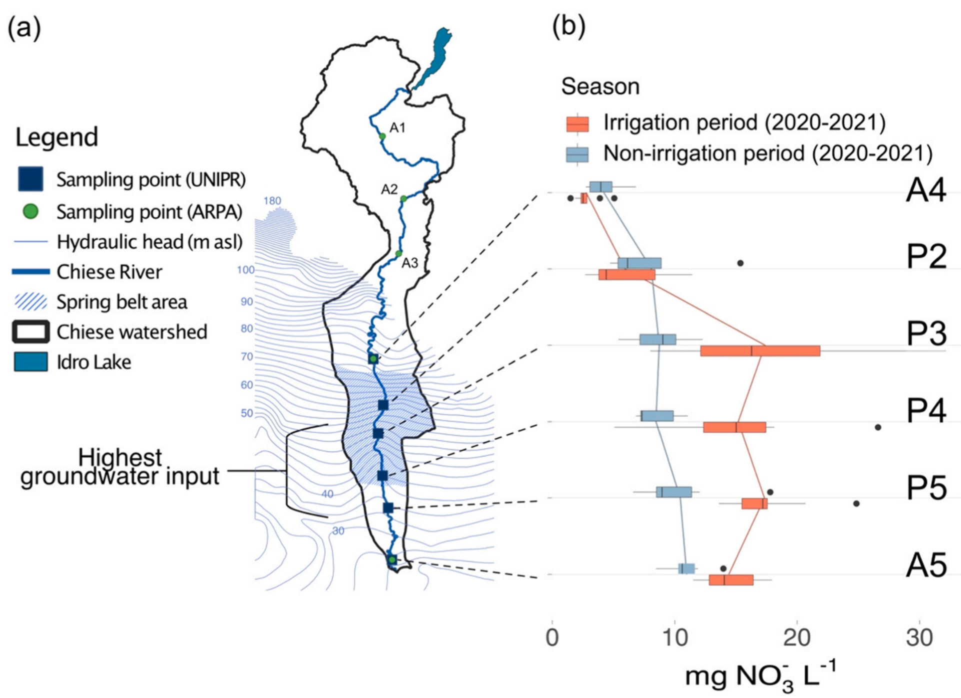

Fig. 4. (a) The sampling points in the Chiese River and potentiometric map of the investigated area; (b) NO_3^- concentrations for the period 2021–2022.

4. Discussion

4.1. Nutrients inputs reduction unpaired to water contamination

The N concentration in the Chiese River was constant for the past 20 years. From the Idro Lake to the sampling station A4, the river showed low NO_3^- concentration (Fig. 3c). This was an expected result, as these sampling stations are in a mountain portion of the watershed where agriculture and animal farming are not intensive, according to the outputs of MANOVA and LDA, with consequent small nutrient inputs to the watershed. Groundwater in the mountain portion is also less vulnerable to contamination from agricultural activities (Flavio et al., 1990). It is only in the last stretch of the river (Fig. 3c) that the N concentration can 5-fold increase. Such rapid change in N concentration is due to the diffuse input of groundwater to the river, which showed for the past 10 years high and constant N concentrations (Fig. 3b, c), despite a significant decrease in the N surplus (−43%) along the last two decades.

This fact is explained by the fast groundwater circulation (Rotiroti et al., 2019; Severini et al., 2022, 2020), the close timing between fertilization and rivers export (Pinardi et al., 2022), and the fast circulation among soil, groundwater, and surface waters (Balestrini et al., 2021; Laini et al., 2012; Racchetti et al., 2019; Severini et al., 2022; Taherisoudejani et al., 2018). In the Chiese watershed, the SSB has produced interesting results, well-capturing changes in agricultural practices such as the designation of the Nitrate Vulnerable Zones (Legislative Decree n. 152/2006). Nevertheless, the limitation to fertilization was unexpectedly unpaired with the constant N concentrations of the Chiese River, pointing out the presence of hidden mechanisms affecting nutrient concentrations in both surface and groundwater. We speculate that these mechanisms are supported by the recent, increasing dependency of flood irrigation on wells and therefore on nitrate-rich groundwater, which is peculiar to this watershed due to low river discharge and different from all the others reported above where the SSB technique was applied (Racchetti et al., 2019).

4.2. Surface and groundwater abstraction as positive feedback to contamination

The increase in the demand for agricultural products and production facilities has brought about an equivalent increase in water usage. In this region, agricultural production has shifted from perennial grasslands to intensive maize agriculture (Viaroli et al., 2018), which is known for its commercial value and for its high water (and nitrogen) demand. Given the total amount of irrigation water used in the plain area of the watershed (reported as m^3 ha^{-1} in each municipality), the required volumes are ~4.2 times the total volume discharged by the Chiese River during the irrigation period (average 2012–2019, data from the regional hydrologic monitoring system, https://idro.arpalombardia.it, accessed 8 November 2022). As a result, farmers almost completely drain the course of the Chiese River with several branches and take the remaining volumes from an extensive network of wells in the watershed. These wells are usually homemade and drilled into the shallow aquifer, as was reported also in nearby watersheds with similar features and agricultural practices (Severini et al., 2021). These areas have never dismissed the traditional, and inefficient, flood irrigation practices due to the large amounts of available water coming from the Italian Alps and farmers only recently started adopting sprinkler irrigation.

In the Southern Europe context, the climate models forecast faster and more severe droughts during the summer coupled with flash floods in the other seasons (Sperna Weiland et al., 2021). In areas like the Chiese watershed, this projection will translate into extended dry periods during the crop season, resulting in amplified demands for irrigation water from both rivers and aquifers. There is the potential for these changes to negatively impact soil fertility, fostering the percolation of nutrients far from the root zone and to the deeper part of the aquifer. Such conditions were experienced in the investigated watershed in 2022 and will became more common in the future (Bonaldo et al., 2023). During 2022, the total annual precipitation was 28% lower than the average of the precedent 18 years average (i.e., 556 versus 768 mm) and in the most critical months (July and August), 54% of the abundant precipitation (154 mm) occurred within a span of two consecutive days. This concentration of rainfall, while substantial, proved inadequate to alleviate the crisis in the agricultural sector. During this period the Chiese River downstream of the P2 sampling station, where a dam guided its diversion into an irrigation channel, experienced a drying-up phase (Fig. 2). Given the low discharge of the Chiese River in comparison with the volumes required for flood and sprinkler irrigation, farmers rely on groundwater extraction for irrigation, thereby contributing to the lowering of the groundwater table. This aligns with the lowering of 0.96 m in the groundwater head of a well close to the P2 station, spanning from March to July 2022 (unpublished data). Furthermore, the groundwater input to the river is ~ 3 times higher in October than in July and August. This difference was attributed to the higher groundwater table and hydraulic gradient after the end of the irrigation period. The major input of groundwater to the river is localised at the station P2, where the river was let dry in July and the downstream flow was supported only by groundwater. Due to this input of groundwater with high NO_3^- concentration, the NO_3 concentration of Chiese River showed a 5-fold increase.

4.3. The irrigation loop

The abstraction of groundwater for irrigation and its subsequent percolation to the aquifer and the river represent a vicious loop that produce positive feedback to the N contamination. The N surplus calculated through the SSB showed at present an average N excess of about 130 kg N ha^{-1} y^{-1} which is expected to accumulate temporarily in the soil as manure-associated organic N, and to be rapidly mineralised to NO_3^- (Xin et al., 2019). The continuous percolation of the same water promotes the dissolution of the produced NO_3^- and its transport from the vadose zone to groundwater, where a continuous increase of N concentration along the groundwater flow path directed to the Chiese River occurs. In the aquifer surrounding the Chiese River, the continuous use of large groundwater volumes to irrigate fosters the percolation of the N stored in the vadose zone and hinders the denitrification processes due to 1) continuous extraction from the aquifer and introduction of groundwater with higher O_2 concentration and 2) the uninterrupted percolation of N from the vadose zone to groundwater. This leads to high and stable N concentration in groundwater for the investigated period (Tab. A1). A conceptual model of this loop is reported in Fig. 5. When the river is dried out and only groundwater downstream the dams support its discharge, the effects of the irrigation loop on surface water are maximised. Although flood irrigation is a widely used practice in the Lombardy region, the results are particularly dramatic in the Chiese River as compared with other large rivers flowing from the Alps (Fig. 5b). Racchetti et al. (2019) evaluated the effect of flood irrigation on the main rivers of Lombardy region (except the Chiese River). The authors found the same dynamics with constant and low N concentrations in the northern river sections, rapidly increasing downstream the river-groundwater interaction area (gaining rivers along the spring belt area). Nevertheless, the river discharges are usually higher (up to several tens m^3 s^{-1}), hindering the effect of N input from groundwater due to large dilution. In these rivers the use of wells for irrigation is also not as plentiful as in the Chiese watershed. For example, in the adjacent Mincio River watershed, irrigation is mainly performed using water derived from the watercourses. This may explain lower O_2 and NO_3^- concentration in the groundwater of the Mincio as compared to the Chiese watersheds, also due to denitrification and hydrodynamic dispersion (Pinardi et al., 2022; Severini et al., 2020) (Fig. 5b). Ultimately, different water sources for irrigation practices in the two watersheds result in much lower N input to surface water in the Mincio compared to the Chiese River.

When the Chiese River receives little to no water from upstream, its discharge is entirely supported by groundwater characterised by N concentrations above the European directives thresholds (91/676/EEC, 2000/60/EC, and the EU/2020/2184) set at 50 mg NO_3^- L^{-1}. To deal with this diffuse violation, in February 2023 the European Commission sent a reasoned opinion to Italy (INFR(2018)2249) for failure to fully comply with the Nitrates Directive and better protect its waters from diffuse nitrate pollution from agricultural sources. During the irrigation period, temperatures of waters are the highest and the solubility of O_2 is the lowest. Algae and macrophyte communities have their maximum coverage and the river can undergo nocturnal hypoxia, with severe consequences for the fish community and a general degradation of the ecosystem in the sense of 2000/60/EC. In other stretches of the river where or when the river-groundwater interaction is less significant, the river can be also let dry, as happened at station P2 in August, with a significant annihilation of the riverine ecosystem.

5. Conclusions

The Chiese River case study clearly points out the combined effects on the agroecosystem of inefficient irrigation practices, excessive fertilization, and mismanagement of both surface and groundwater in a context of water scarcity. Similar issues are being investigated using numerical models and long-term simulations addressing worst-case

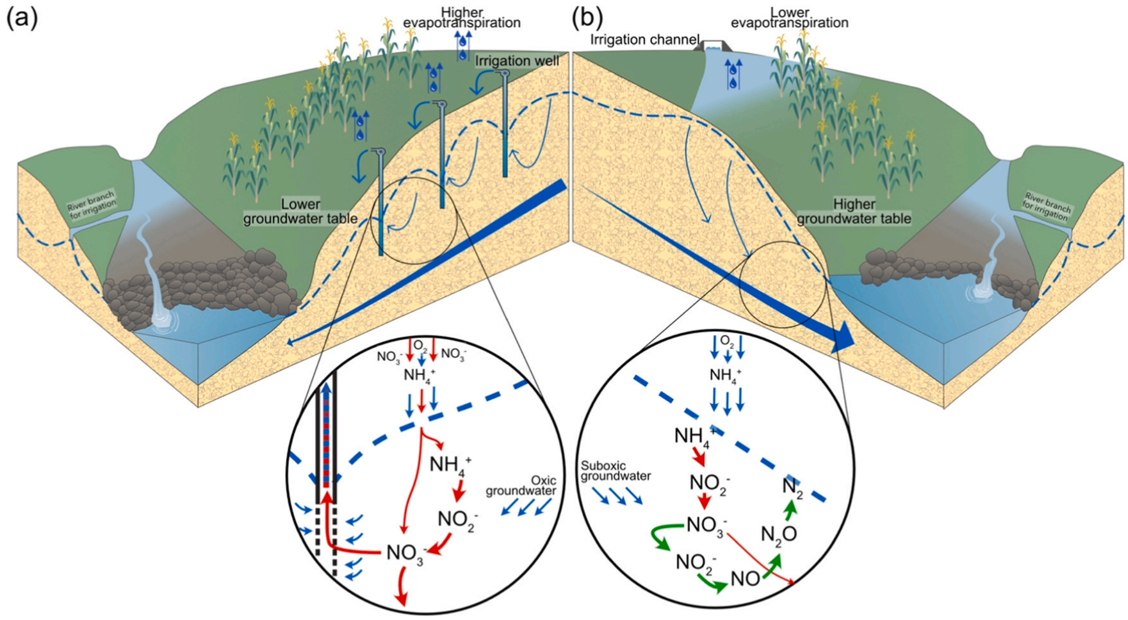

Fig. 5. The conceptual model illustrating the functioning of the irrigation loop in the river and aquifer of the Chiese watershed (a) and in a watershed with a lower dependency of irrigation on wells, like the Mincio (b), where irrigation is performed using irrigation channels (upper part of the figure).

climatic scenarios and their effects elsewhere, often using datasets with severe data gaps and an unsatisfactory level of process understanding (Erb et al., 2017). These effects lead to a significant worsening of the fluvial ecosystem, pointing out how the current water demand could undermine the past and present efforts to achieve the good ecological status of European rivers according to the WFD, especially considering future droughts driven by climate change. From a more agricultural perspective, it could further decrease the efficiency of organic fertilizers under traditional management practices, which are still widely performed in the Po Plain, one of the largest European N hotspots. This could lead to an increased application of manure or synthetic fertilizers, worsening the NO_3^- contamination in surface water and groundwater and increasing the production of nitrus oxide (N_2O), with positive feedback on climate change. Thus far, this is one of the few empirical examples of water scarcity impacts under not-optimised agricultural management of a watershed, where hydrogeological, ecological, and biogeochemical methods are now being used to understand the evolution of N contamination under these circumstances.

Adaptive strategies to climate change and decreasing water availability for irrigation are urgently needed to avoid environmentally, economically, and socially unsustainable agricultural practices. These include converting traditional irrigation practices such as flooding, which consume large amounts of water and displace large amounts of soluble mineral elements from soils to surface and groundwater, to other irrigation forms that consume less water. In precision agriculture, such transition can be supported using humidity sensors, satellite-derived information on photosynthetic performances of crops along the vegetative period or with the concurrent shift of crops, with maize replaced by less water-demanding cultivations. At present, such expected transitions are still embryonic and the business-as-usual approach, in dry summers like that of 2022, dries out the Chiese River nearly 20 km upstream the river closing section.

CRediT authorship contribution statement

Conceptualization and investigation by Edoardo Severini, Monia Magri, and Marco Bartoli. Formal analysis, validation, and data curation by Edoardo Severini, Monia Magri, Elisa Soana, and Marco Faggioli. Writing - Original Draft: Edoardo Severini, Monia Magri, and Marco Bartoli. Writing - Review & Editing: Edoardo Severini, Monia Magri, Marco Bartoli and Fulvio Celico. Project administration: Marco Bartoli.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108564.

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