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# Exploring the canal environment in terms of water, bed sediments and vegetation in a reclaimed floodplain of Northern Italy

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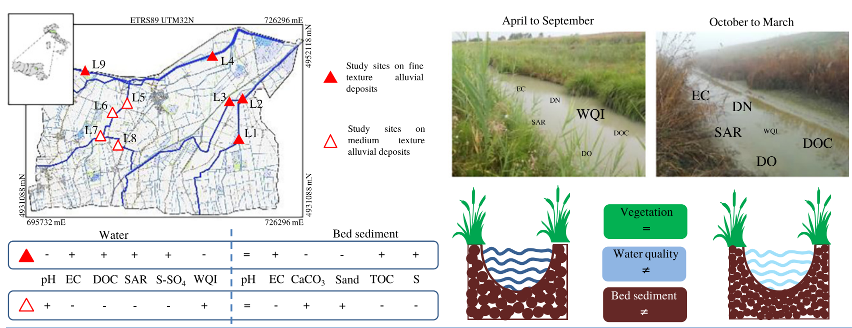
## HIGHLIGHTS

- Water, bed sediments and vegetation of artificial canals in floodplain were studied.
- Water quality worsened with lowering of water flow within canals.
- Water and bed sediment physicochemical properties were mainly affected by lithology.
- Plant diversity was affected by agricultural landscape rather than by edaphic factors.

## GRAPHICAL ABSTRACT




TOC total organic carbon; WQI water quality index; SAR sodium adsorption ratio; EC electrical conductivity; DO dissolved oxygen; DOC dissolved organic carbon; DN dissolved nitrogen

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## ABSTRACT

The Po plain (Italy) is one of the largest floodplains in Europe that needs environmental restoration. To achieve this goal, the knowledge of the 'environment' (water, bed sediments and vegetation) of the canals crossing such floodplain is necessary. The water flow of the canals was kept low for hydraulic safety purposes from October to March (NIR), and high for irrigation purposes from April to September (IR). Within this framework, this study aimed to assess in 9 sites of the east part of Po plain 1) the canals' environment quality in terms of vegetation diversity, and water and bed sediment physicochemical properties; and 2) how these features are influenced by canal managements and landscape properties. Water was monthly sampled both in NIR and IR periods, the bed sediments were sampled in summer and winter periods, while the vegetation was recorded in spring and autumn. The low water flow during NIR worsened the water quality by increasing the concentrations of nutrients and salts. A higher salt and nutrient concentrations were observed both in water and bed sediments of canals crossing areas with fine texture alluvial deposits than in those flowing through medium texture alluvial deposits. Further, higher nutrient and salt concentrations were observed for the canals used as collectors of the water coming from other canals. Despite the differences observed for the bed sediments and water quality, the vegetation type and biodiversity did not show differences among the study sites probably because affected by the land use of the surrounding landscape. Indeed, the canals cross agricultural land which limit the developments of natural vegetation and do not promote plant biodiversity. Overall, the present study found out the key role of landscape properties and canal managements on 'canal environment' quality which need to be considered to perform an appropriate reclamation of such environments.

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## 1. Introduction

Floodplains are a very important integral part of river systems, main to exchange of water masses and matter between river and terrestrial ecosystems (Kiedrzyńska et al., 2008; Mitsch et al., 2008; Castillo et al., 2020). The interrelationships occurring among the floodplain resources (e.g., soil, water, watercourses' bed sediments and vegetation) are crucial for maintaining the function and integrity of floodplain systems (Thoms, 2003). In the past, both to increase cultivable land and to provide area for urbanization, floodplains have been modified by channelization and reclamation activities (Scholten et al., 2005), and the water flow of watercourses was also regulated, building high embankments like hanging and straight rivers (Brandolini and Cremaschi, 2018).

The floodplain ecosystems degradation is very important threat in Europe (Nilsson and Jansson, 1995; Tockner and Stanford, 2002; Tockner et al., 2009), due to a reduction and fragmentation of aquatic landscape (Buldrini et al., 2013) and reduction of wetlands extend. Such human–made alterations reduce the ecosystem services provided by floodplains through the reduction in suitable habitats for plants, biodiversity, and nutrient cycling (Hupp et al., 2009; Dorotovičová, 2013).

The agricultural land-use is considered the major driver factor of worsening of watercourses' water quality (Buck et al., 2004). In many studies it is reported that the fertilization practices carried out on agricultural soils increase nutrient loadings in watercourses (e.g., Renwick et al., 2008; McDowell et al., 2010; Billy et al., 2013) promoting eutrophication phenomena (Hilton et al., 2006). In addition, the frequent crop's vegetation removal promotes soil erosion processes (Ni et al., 2021) which further promote nutrient accumulation both in water and in bed sediments (Rickson, 2014; Singh et al., 2018). Also, riparian vegetation and its management on the banks can influence the bank erosion and deposition control (e.g., Cotton et al., 2006; Heppell et al., 2009) which, in turn, affect biodiversity and ecosystem functioning (Richardson et al., 2007; Forio et al., 2020; Popescu et al., 2021). On the other hand, riparian vegetation is affected both by water quality and sediment characteristics (Kočić et al., 2008; Asaeda and Rashid, 2012; Alemu et al., 2018). Up to date, several are the studies that investigated the effect of vegetation on the water bodies (e.g., Ghermandi et al., 2009; Dosskey et al., 2010; Västilä and Järvelä, 2018; Dunea et al., 2021) but accurate studies addressed to find a relationship between quality of both water and bed sediments, and riparian vegetation are missing.

The Po plain is one of the largest (74,500 $km^2$) alluvial plains in Europe (Amorosi et al., 2016). Po plain is filled by sediments eroded from the Alp and the Apennine chains which have been transported and deposited by the Po River and its tributaries (Amorosi et al., 2002; Bianchini et al., 2002, 2012, 2014; Garzanti et al., 2012). The Po plain has a long-standing connection with human settlements for its suitability to agriculture. Human communities settled in the Po plain modified such landscape, which was almost entirely marshland, through reclamation activities like the construction of embankments, drainages, and dams, and channelisation works (Brandolini et al., 2019). In the last century, fluvial dynamics of the Po plain were largely altered by the action of the land-reclamation boards which, together with intensive agriculture and urbanization, caused degradation processes (e.g., Marchetti, 2002; Di Giuseppe et al., 2014; Bolpagni et al., 2020). The hydraulic system of the Po plain, modified by both reclamation and the construction of artificial reclamation canals, provides several benefits: a) hydraulic safety of the reclaimed areas, b) collection of drainage water from soils of the various hydraulic sectors and c) water source for irrigation purposes. On the other hand, the construction of the artificial canals changed the amount and speed of the water flow negatively affecting the riparian vegetation diversity (Fraaije et al., 2019) and promoting the accumulation of nutrients in water (Ferronato et al., 2015; Khatri and Tyagi, 2015).

Consequently, it is urgent to provide current and detailed information regarding the artificial canal environment in terms of vegetation diversity, water and bed sediment physicochemical properties within the east part of Po plain area, to apply effectiveness interventions in attaining environmental improvements. In this view, the key innovation of the present study is to assist practitioners and policy makers to target such interventions through the provisioning of the insights about both the properties of the studied ecosystem and the underlying processes. Further, the present study attempts to give insights through a holistic approach based on the designated use of the canals (i.e., habitat for wildlife and plants, water supply for agriculture, hydraulic safety), land use and landscape morphology.

The specific objectives of the present study were to assess 1) the canals' environment quality in terms of vegetation diversity, and water and bed sediment physicochemical properties; and 2) how these features are influenced by canal managements and landscape properties.

The present work was conducted within the Life Green4Blue project which planned to create both stepping stones and wetlands areas addressed to improve the function of the artificial canals as ecological corridors.

## 2. Materials and methods

### 2.1. Study area

The study area was extended for 40,730 ha. This area was bounded at North-East and South-East by Reno and Sillaro rivers, respectively, and at North-West and South-West by Navile and Emiliano Romagnolo canals, respectively (Fig. 1a). The study area is crossed by Idice river and by a complex network of artificial canals managed by Renana Remediation Consortium (RRC).

The canals are used for different purposes: a) hydraulic safety and flood-risk mitigation, b) irrigation supporting, c) draining of urban and industrial settlements wastewater and agricultural area. Within the study area, the water flow is controlled by a detailed hydraulic scheme with pumps and gates. Further, floodplain wetlands are preserved in order to store flood waters during high runoff events. Each year, from April to September (irrigation period, IR) the water flow of the canals is kept high for irrigation purpose, while from October to March (no–irrigation period, NIR) the canals are kept with a limited water flow to prevent flooding risks due to the abundant and frequent rainfalls occurring in autumn and winter seasons. The riparian vegetation is mowed twice per year, specifically at the end of spring and summer seasons. The investigated area includes six sites Natura 2000 with high interest for biodiversity (Fig. 1a), arable lands, and urbanized and industrial areas with productive and commercial settlements.

Key feature of the investigation area was the presence of soils with medium-size and fine-size textures (Fig. 1b). The medium-size texture soils fall close to the paleoriver of Reno, and to Savena, Idice and Sillaro rivers (yellow area of Fig. 1b). While fine-size texture soils fall in morphologically depressed areas which correspond to the ancient marsh valleys (purple area of Fig. 1b). The soils (Fig. 1c) are mostly Cambisols (IUSS Working Group WRB, 2015) with low soil forming processes due to the recent plain formation, and Vertisols (IUSS Working Group WRB, 2015) with large amount of clay. Less frequent are Calcisols, Fluvisols and Arenosols (IUSS Working Group WRB, 2015).

The area lies in temperate climate zone with a mean annual air temperature of 14.5 °C and a mean cumulative annual rainfall of 575 mm, with fall season as the wettest one.

Within the investigation area, nine study sites for the creation of stepping stones or wetland areas were chosen (Fig. 1). The canals of each study site were characterized by different dimensions (length, width, and depth) and bank slope (Table 1), but all of them had natural bed with vegetated banks.

### 2.2. Sampling and analysis

In each study site, water samples were monthly collected from May 2020 till February 2022, stored in Pyrex glasses, and placed in cooler bags. In field, temperature (T) and dissolved oxygen (DO, Electrode Hack-Lange) were detected. Once in lab, an aliquot of each water sample was used for determining electrical conductivity (EC, Orion, Germany) and pH

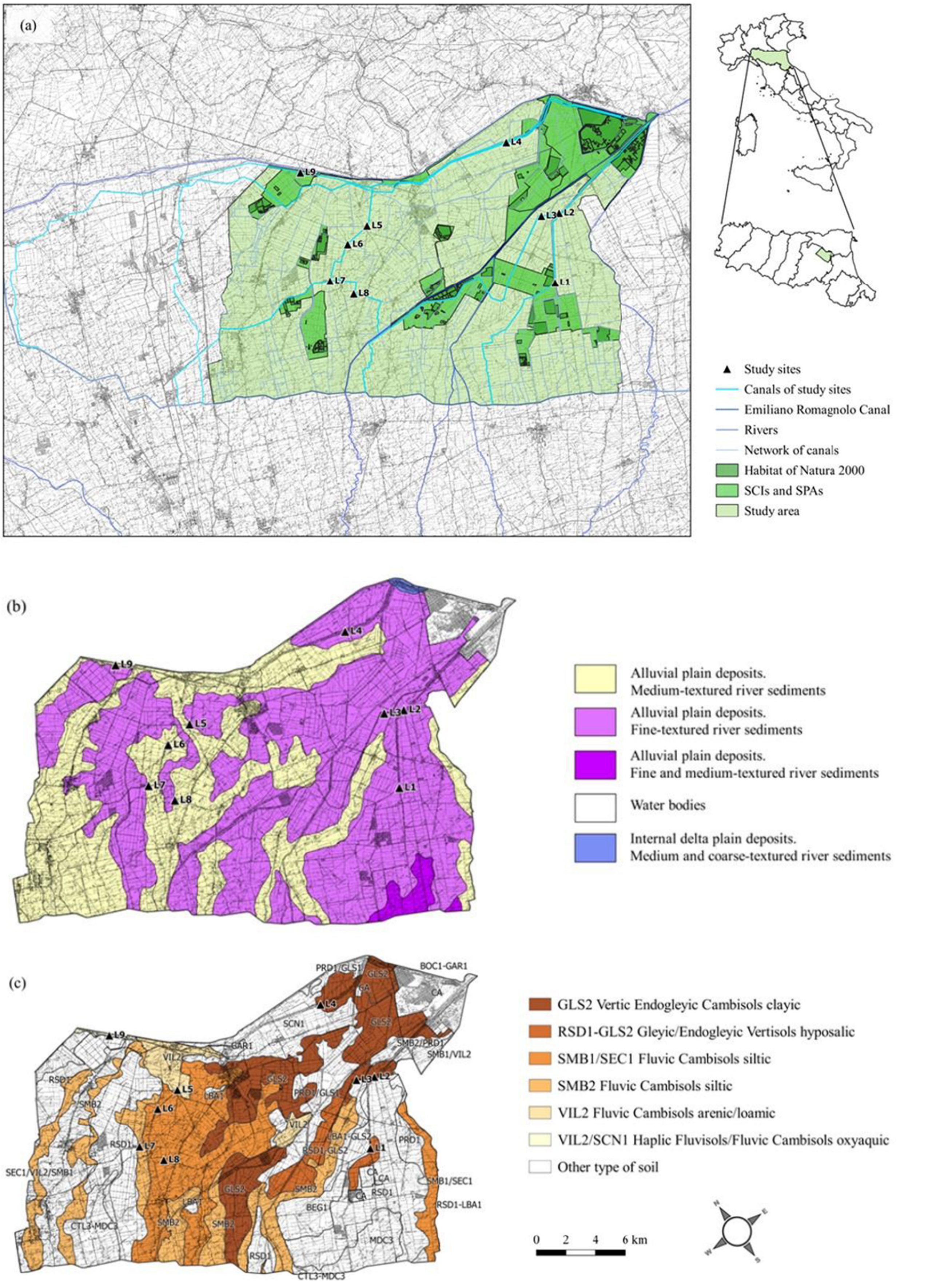


**Fig. 1.** Technical (a), lithological (b) and soil (c) maps of the study area. Coordinate reference system: ETRS89 UTM 32 N. SCIs = Sites of Community Importance (Habitats Directive); SPAs = Special Protection Areas (Birds Directive).

(pH meter, Crison, Germany). Another aliquot was filtered with Whatman 42 filter paper in order to determine dissolved organic carbon (DOC) and dissolved nitrogen (DN) concentrations using TOC-V CPN analyser (Shimadzu, Japan), ammonium ($N\text{-}NH_4$) and nitrate ($N\text{-}NO_3$) nitrogen concentrations using flow injection auto-analyser (AA3, Bran Luebbe, Germany). Further, the filtered water samples were analysed for the concentration of total Ca, Cu, Fe, K, Mg, Na, P, S and Zn using inductive coupled plasma optical emission spectrometry (ICP-OES, Germany, Ameteck Spectro) after acidification with high-purity $HNO_3$ (Suprapur, Merck, Germany).

Surface bed sediment (0–5 cm) samples, hereafter called sediment, were collected on February, July, and November 2020, and in July and December 2021. The sediment samples were oven–dried at 60 °C and sieved through 2 mm sieve. The electrical conductivity (EC, Orion, Germany) and pH (pH meter, Crison, Germany) were measured on a 1:2.5 ratio *w/v* with distilled water. The amount of sand, silt and clay was determined by pipette method (Gee and Bauder, 1986). Carbonate content ($CaCO_3$) was calculated by volumetric method (Loeppert and Suarez, 1996). Total organic carbon (TOC) and total nitrogen (TN) concentrations were detected by CHN elemental analyser (CN Elemental Analyser 1110, Thermo Scientific GmbH, Dreieich, DE) with pre-treatment with hydrochloric acid to dissolve carbonates. The relative abundance of C and N stable isotopes was determined by continuous flow–isotope ratio mass spectrometry (CF–IRMS) using an isotopic mass spectrometer Delta V advantage (Thermo-Finnigam, DE). The values were then expressed as $\delta^{13}C$ and $\delta^{15}N$, as the deviation in parts per thousand compared with the universal standard as a reference. The total amounts of Al, Ca, Cu, Fe, K, Mg, Na, P, S and Zn were determined by ICP-OES after microwave digestion (Milestone 1200, USA) with aqua regia (suprapure HCl and $HNO_3$ 3:1 *w*/w) according to Ferronato et al. (2015).

Vegetation survey was performed in spring season (SS) 2020 and 2021 (from May to June) and fall season (FS) 2020 and 2021 (from October to November). At each study site, 4 plots 1 × 5 m wide and spaced 5 m apart were sampled on one side of the canals. Plots were arranged along 40 m long transects and running parallel to the canals' edge. Within each plot, plant species were identified, and their cover was estimated according to the Braun-Blanquet method (Damgaard, 2014). The identified species that had a relative cover >5 % in at least one of the study sites were classified into five groups: aquatic and riparian, agricultural, ruderal, invasive, and pasture species. The plant species were considered aquatic when growing wholly or partly submerged in water. Riparian vegetation has been defined as the complex of plant communities growing in the transitional region between aquatic and terrestrial ecosystems (García and Jáuregui, 2020). We classified as agricultural species those herbaceous plants commonly cultivated in the investigated floodplain; for ruderal species we considered those plants adapted to survive in disturbed environments (Brun et al., 2003); the plants were classified as invasive species when they were non-native (or alien) to the floodplain under consideration; the pasture species were plants, including grasses, legumes and herbs, that tend to be perennial, meaning they grow all year round. The plant species with a relative coverage lower than 5 % in all study sites were classified as "others".

### 2.3. Index calculation and statistical analyses

To evaluate the water quality, sodium adsorption ratio (SAR) (Richards, 1954) commonly used to estimate the sodium hazard of irrigation water, and water quality index (WQI) (Pesce and Wunderlin, 2000) were calculated as follow:

$$SAR = \frac{|Na|}{\sqrt{|Ca| + |Mg|}} \tag{1}$$

where Na, Ca, Mg are the concentrations of these elements (Richards, 1954).

$$WQI = \frac{\Sigma_{i=1}^{n} C_i \times W_i}{\Sigma_{i=1}^{n} W_i} \tag{2}$$

where $C_i$ is quality rating of the *i*th water quality parameter (pH, EC, DO, TC, TN, $N\text{-}NO_3$, $N\text{-}NH_4$, P, Ca, Mg, $SO_4$), $W_i$ is the unit weight for the *i*th parameter. C and W were based on Pesce and Wunderlin (2000).

Shannon index (H) was calculated to quantify the diversity of species in plants' communities:

$$H = -\Sigma_{i=1}^{n} p_i \times \ln(p_i) \tag{3}$$

where $p_i$ is the proportional abundance of each species (i) within the total number of species identified on study site (n) (Shannon, 1948).

A cluster analysis (CA) was performed considering the physicochemical properties dataset of (1) water samples of both IR and NIR periods ($CA_{tw}$), (2) water samples of IR ($CA_{IR}$) and (3) sediment samples ($CA_{sed}$). To perform the clustering, the data were scaled and Ward's method was used on Euclidean distances. The number of clusters identified were two for $CA_{tw}$ and $CA_{sed}$, and three for $CA_{IR}$. Such groups were selected according to silhouette method.

A principal component analysis ($PCA_{tw}$) was performed on the dataset used for $CA_{tw}$ and its outputs were categorized according to the cluster results.

Since $CA_{tw}$ showed differences mainly due to IR and NIR (see Results section, Paragraph 3.1), a Kruskal-Wallis test was performed on water physicochemical parameters separated by the two periods ($KW_{tw}$). While, concerning $CA_{IR}$ and $CA_{sed}$ results, the Kruskal-Wallis test was performed to identify significant differences for the physicochemical parameters of irrigation water ($KW_{IR}$) and sediment ($KW_{sed}$) between the study sites grouped into the clusters. $KW_{IR}$ compared three groups consist of sites (W1) L5, L6, L7, and L8, (W2) L1, L2, and L3 and (W3) L4 and L9. $KW_{sed}$ compared sites (S1) L1, L2, L3, L4, and L9 and (S2) L5, L6, L7, and L8.

All statistical analysis were performed with RStudio software ver. 2022.07.0 + 548 of R Core Team 4.1.2.

**Table 1**
Coordinates of the study sites and morphological features, main using purposes and water sources of the canals.

| Study site | Coordinates ETRS89 UTM 32 N | | Canal morphology | | | Main using purpose | Water source |
|---|---|---|---|---|---|---|---|
| | mE | mN | Width | Depth | Bank slope | | |
| | | | m | m | % | | |
| L1 | 716,217.97 | 4,935,376.96 | 4.5 | 0.6 | 37 | Irrigation canal | Emiliano Romagnolo canal |
| L2 | 719,067.43 | 4,938,858.78 | 8.5 | 0.6 | 62 | Irrigation canal | Emiliano Romagnolo canal |
| L3 | 717,988.87 | 4,939,398.06 | 8.3 | 0.9 | 85 | Irrigation canal | Emiliano Romagnolo canal |
| L4 | 718,772.62 | 4,944,617.21 | 33.0 | 1.4 | 47 | Collector of water | Emiliano Romagnolo canal, Bologna-Navile wastewater treatment plant |
| L5 | 708,654.01 | 4,945,490.61 | 22.4 | 1.5 | 48 | Collector of water | Emiliano Romagnolo canal, Bologna-Navile wastewater treatment plant |
| L6 | 706,870.11 | 4,945,253.73 | 17.6 | 1.5 | 46 | Irrigation canal | Emiliano Romagnolo canal, Bologna-Navile wastewater treatment plant |
| L7 | 704,570.00 | 4,944,005.67 | 19.6 | 1.6 | 44 | Irrigation canal | Emiliano Romagnolo canal, Bologna-Navile wastewater treatment plant |
| L8 | 705,294.88 | 4,942,423.30 | 5.2 | 1.0 | 49 | Irrigation canal | Emiliano Romagnolo canal |
| L9 | 707,006.46 | 4,950,853.06 | 12.0 | 1.6 | 75 | Collector of water | Emiliano Romagnolo canal |

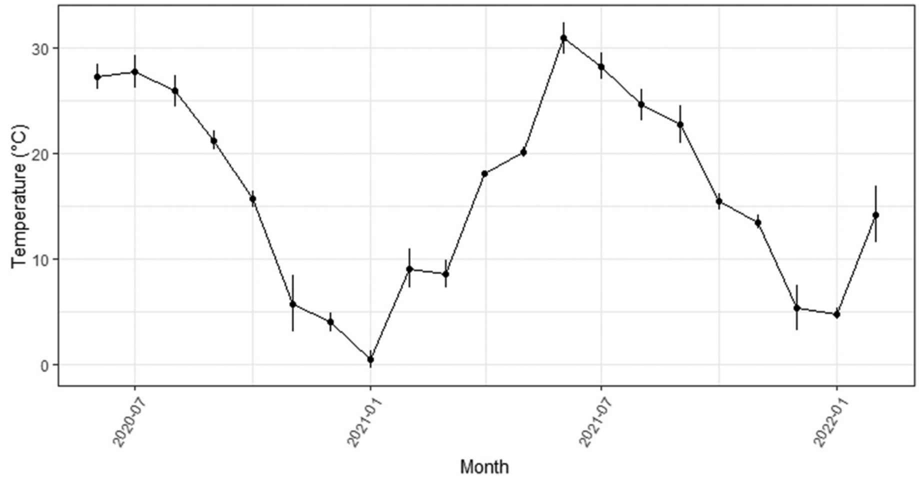


**Fig. 2.** Mean monthly canals' water temperature. The error bars are the standard deviations.

## 3. Results

### 3.1. Water quality

The water temperature of the investigated canals (Fig. 2) showed lower values during NIR (9 °C, on average) compared to IR (25 °C, on average).

The output of $CA_{tw}$ distinguished two clusters where samples of IR and NIR were almost totally divided in cluster 1 (C1) and cluster 2 (C2), respectively (See Table S1 of the Supplementary materials for the absolute frequencies).

According to the Varimax rotation results of $PCA_{tw}$ (Fig. 3), the first (Dim1) and the second (Dim2) principal component explained together 54.9 % of the total variance. Most of the total variance was explained by Dim1 which showed a positive loading for SAR and EC values, and for the concentrations of DN, N-$NO_3$, Ca, K, Mg, Na, P and S, a negative loading for WQI. The biplot resulting from the $PCA_{tw}$ showed that mostly (80 %) of C1 were within the I and III quadrants, while C2 within the II and IV quadrants, indicating a greater nutrient load in water sampled during NIR than IR.

In fact, as shown by Kruskal-Wallis test all parameters were higher in NIR than IR, except for WQI which was higher in IR, and Fe, Cu e Zn concentrations which did not show significant differences (Table 2 and Fig. 4).

The output of $CA_{IR}$ grouped samples into three clusters (See Fig. S1 of the Supplementary materials): cluster A mainly represented by sites L5, L6, L7 and L8, cluster B by sites L1, L2 and L3, and cluster C by sites L4 and L9 (See Table S2 of the Supplementary materials for the absolute frequencies). The cluster C is separated from the others at 32 % of distance, while cluster A and B at 20 %.

As shown by Kruskal-Wallis test, sites L4 and L9 (W3) were enriched by salts and nutrients, showing the highest values of EC and SAR, and the lowest WQI values (Table 3 and Fig. 5). Conversely the sites L5, L6, L7, and L8 (W1) were characterized by the lowest values of EC and SAR, and the lowest concentrations of DOC, N-$NH_4$, K, Mg and S-$SO_4$. Further, W1 showed the highest values of pH, DO and WQI. Sites L1, L2, and L3 (W2) showed values of SAR, K, Na, S-$SO_4$ and WQI in between of those observed for W1 and W3 (Table 3 and Fig. 5). Further, W2 showed similar Ca, P, and Zn concentrations to W3, similar pH, DO, DOC, N-$NH_4$, and Mg concentrations to W1, and the lowest values of DN and N-$NO_3$ (Table 3 and Fig. 5).

### 3.2. Sediments

No contamination in sediments was found according to Italian legislative threshold (Legislative Decree 2006/152/ITA, 2006) except for Zn concentration. The Zn concentration threshold (150 mg $kg^{-1}$) was exceeded on February, July, and November 2020, and July and December 2021 (161.9, 169.1, 179.3, 161.7, and 172.3 mg $kg^{-1}$, respectively) for site L9, on July 2020 (448.6 mg $kg^{-1}$), on February 2020 (161.4 mg $kg^{-1}$) and on July 2021 (154.0 mg $kg^{-1}$) for sites L6, L4 and L1, respectively.

The output of $CA_{sed}$ grouped samples into two clusters (See Fig. S2 of the Supplementary materials): cluster I was composed by 23 statistical units, including sites L1, L2, L3, L4, and L9, while cluster II by 22 statistical units, mainly represented by sites L5, L6, L7, and L8 (See Table S3 of the Supplementary materials for the absolute frequencies).

Sites L1, L2, L3, L4, and L9 (S1) had higher values of EC, silt, nutrients and total elements than those found in sites L5, L6, L7, and L8 (S2), except for Ca, $CaCO_3$ and sand contents, and $\delta^{13}C$ values (Table 4).

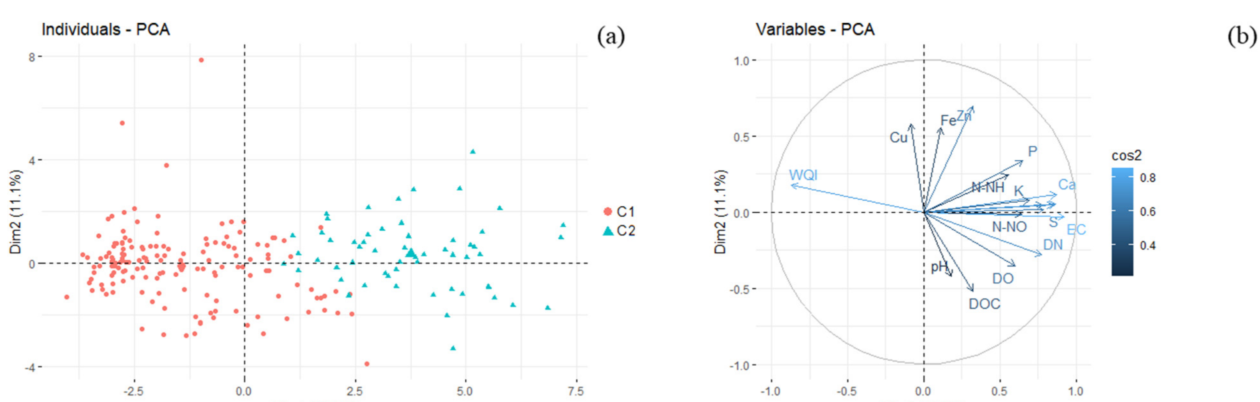


**Fig. 3.** Principal component analysis (PCA) biplot (a) of water samples collected during the irrigation and no-irrigation period, showing the two cluster groups (C1 and C2) of cluster analysis. Eigenvectors of variables (b) gradually coloured according to their eigenvalues.

**Table 2**
Mean and standard error (se) of water chemical properties during irrigation (IR) and no-irrigation (NIR) periods. Different letters within each column indicate significant differences between the periods ($p < 0.05$).

| Period | | pH | EC | DO | DOC | DN | N-$NO_3$ | N-$NH_4$ | Ca | K | Mg | Na | P-$PO_4$ | S-$SO_4$ | Fe | Cu | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS $cm^{-1}$ | mg $L^{-1}$ | | | | | | | | | | | | μg $L^{-1}$ | |
| IR | mean | 7.80 b | 0.49 b | 8.03 b | 6.55 b | 1.11 b | 1.00 b | 0.65 b | 58.89 b | 7.55 b | 15.03 b | 27.91 b | 0.07 b | 17.98 b | 0.05 | 8.24 | 6.12 |
| | se | 0.03 | 0.02 | 0.15 | 0.29 | 0.07 | 0.08 | 0.04 | 1.20 | 0.44 | 0.35 | 1.47 | 0.01 | 0.64 | 0.01 | 0.69 | 0.65 |
| NIR | mean | 8.04 a | 0.88 a | 11.37 a | 12.83 a | 3.83 a | 3.94 a | 1.31 a | 85.57 a | 12.18 a | 25.85 a | 61.43 a | 0.19 a | 31.10 a | 0.05 | 6.46 | 8.05 |
| | se | 0.03 | 0.02 | 0.20 | 0.85 | 0.26 | 0.49 | 0.11 | 2.54 | 0.47 | 1.02 | 2.78 | 0.02 | 1.55 | 0.01 | 0.24 | 0.76 |

EC electrical conductivity; DO dissolved oxygen; DOC dissolved organic carbon; DN dissolved nitrogen.

### 3.3. Plant species composition

A total of 210 plant species were identified within the study sites (data not shown), but only 20 of them had a relative cover greater of 5 % in at least one of the study sites (Table 5). The most abundant plant species comprised 14 plant families mostly belonging to aquatic and ruderal species (Table 5). *Carex riparia* C. and *Phragmites australis* (Cav.) Trin. ex Steud were the most abundant and shared by the nine study sites and they showed higher relative cover compared to the other identified species. Specifically, *P. australis* showed the highest relative cover within L6 (50 and 76 % in SS and FS, respectively), while it was scarce or lacking within L2. *C. riparia* grew abundantly in sites L1 and L2 (on average 32 and 55 % in SS and FS, respectively), but it was scarcely detected or absent within L5, L6 and L9.

*Urtica dioica* L. and *Rubus fruticosus* L. were the most abundant ruderal species in the study sites. The maximum cover for *U. dioica* was recorded in site 9 (29 % in both periods), while *R. fruticosus* showed the highest relative cover during FS in L8 (39%).

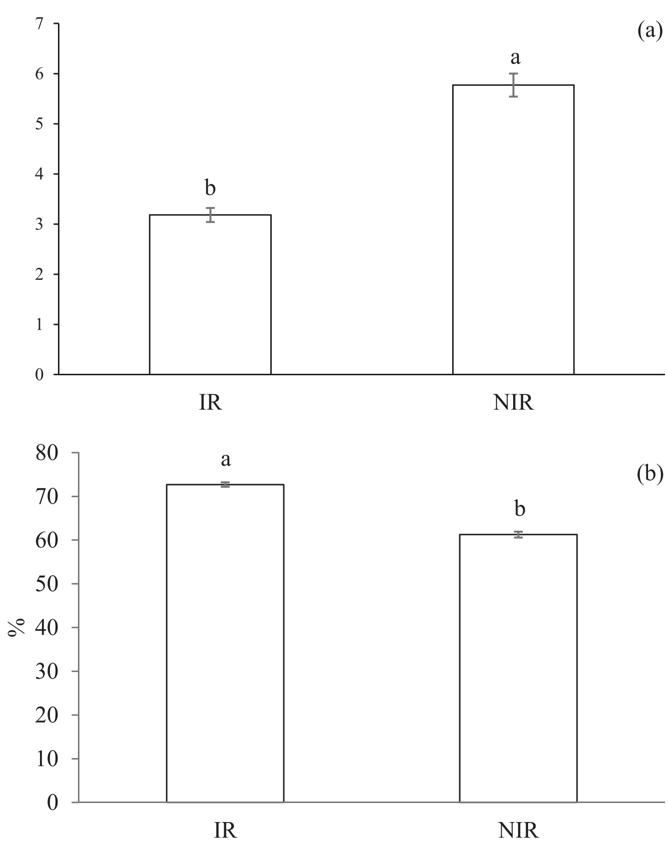


**Fig. 4.** Sodium adsorption ratio (a) and water quality index (b) of water sampled during the irrigation (IR) and no–irrigation (NIR) period. Error bars are the standard errors. Different letters above the bars indicate significant differences ($p < 0.05$).

The study sites showed to be weakly colonized by invasive plant species, in fact we identified only the *Amorpha fruticosa* L. with a cover higher than 5 % which was more abundantly within site L9 (relative coverage of 10 and 32 % in SS and FS, respectively).

Similar to invasive species, pasture plant species were scarcely distributed among the study sites. In fact, *Brachypodium phoenicoides* (L.) Roem & Schult. was the only pasture plant with a cover higher than 5 %. It was mainly found within site L7 with a relative cover of 1 and 9 % in SS and FS, respectively.

Despite the study sites were surrounded by agricultural fields, the presence of agricultural plant species resulted to be scarce, and they were represented by *Avena sterilis* L. and *Elymus repens* (L.) Gould. The highest relative coverage for *A. sterilis* was found during SS period within sites L3 (15%), *E. repens* was mainly identified within L4 with a relative coverage of 9 and 16 % in SS and FS periods, respectively.

Taking into consideration the plant diversity calculated through the Shannon index (Table 6), most of the investigated sites had a low diversity (Fernando, 1998; Baliton et al., 2020). A moderate diversity was observed within L2 (2.70) and L7 (2.65) for the SS period and within L4 (2.52) and L7 (2.69) for FS period. A high diversity was reached during SS period within L3 (3.25).

## 4. Discussion

### 4.1. Seasonal change of water quality

The present investigation showed a significant change of the water physicochemical parameters between IR and NIR. Such findings are in accordance with previous studies which recorded seasonal changes on water quality and nutrient loads into watercourses due to the change of water flow (Markou et al., 2007; Yeşilırmak, 2010; Deng et al., 2018; Bisimwa et al., 2022).

WQI values showed the water quality worsening during NIR (Fig. 4) caused by an increase in nutrient concentrations (Table 2). The higher load of nutrients in NIR compared to IR might be due to both the higher nutrient leaching from soils resulting from the higher rainfalls (Arias-Estévez et al., 2008; Papadakis et al., 2015; Rashmi et al., 2017), and the lower water flow which prevented a 'dilution effect' (Yeşilırmak, 2010; Liu et al., 2011; Deng et al., 2018). In this sense, it is important to mention that, conversely to IR, during NIR no water supply from the Emiliano-Romagnolo canal was carried–out. Therefore, during NIR, the main sources of water for the canals are the wastewater treatment plants and the drainage through the cultivated fields.

Since the water of NIR was sampled close to canals' sediment due to the low water flow, this fact could further explain the higher nutrient concentrations in NIR compared to IR. In fact, in a study conducted in a Mediterranean coastal lagoon located in Northern Greece by Markou et al. (2007), a higher exchange rate of nutrients and trace elements was recorded between the bed sediments and the bottom water than that flowing in the surface part of the watercourses. Further, the release of nutrients from sediments is strongest under low-flow conditions because of both the relatively long contact time between the water column and the sediment, and the high ratio between the sediment surface area and water volume. However, since the sediments can act either as a nutrient source or sink for the

**Table 3**
Mean and standard error (se) of chemical properties of water sampled during the irrigation period from canals of sites L5, L6, L7 and L8 (W1), sites L1, L2, and L3 (W2), and sites L4 and L9 (W3). Different letters indicate significant differences within each column ($p < 0.05$).

| | | pH | EC | DO | DOC | DN | $N\text{-}NO_3$ | $N\text{-}NH_4$ | Ca | K | Mg | Na | $P\text{-}PO_4$ | $S\text{-}SO_4$ | Fe | Cu | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $mS\ cm^{-1}$ | $mg\ L^{-1}$ | | | | | | | | | $\mu g\ L^{-1}$ | $mg\ L^{-1}$ | $\mu g\ L^{-1}$ | | |
| W1 | mean | 7.98 a | 0.41 c | 8.63 a | 5.07 b | 1.07 b | 1.10 a | 0.50 b | 54.23 b | 3.94 c | 12.82 b | 18.43 c | 40.64 b | 14.38 c | 39.63 | 8.69 | 4.91 b |
| | se | 0.05 | 0.02 | 0.23 | 0.33 | 0.10 | 0.11 | 0.06 | 1.40 | 0.14 | 0.33 | 0.86 | 2.90 | 0.32 | 7.48 | 1.22 | 0.66 |
| W2 | mean | 7.62 b | 0.49 b | 7.48 b | 7.86 a | 1.01 c | 0.77 b | 0.68 a | 57.84 b | 9.79 b | 17.43 a | 26.21 b | 45.60 b | 20.54 b | 65.57 | 8.71 | 6.48 b |
| | se | 0.05 | 0.02 | 0.22 | 0.59 | 0.16 | 0.16 | 0.07 | 1.69 | 0.76 | 0.59 | 1.55 | 4.10 | 1.49 | 16.78 | 1.14 | 1.54 |
| W3 | mean | 7.72 b | 0.67 a | 7.68 b | 7.56 a | 1.35 a | 1.13 a | 0.90 a | 69.80 a | 11.42 a | 15.86 a | 49.43 a | 172.63 a | 21.32 a | 35.75 | 6.66 | 7.97 a |
| | se | 0.05 | 0.03 | 0.26 | 0.45 | 0.11 | 0.14 | 0.11 | 2.93 | 0.72 | 0.73 | 2.96 | 18.22 | 0.99 | 5.06 | 0.91 | 1.18 |

EC electrical conductivity; DO dissolved oxygen; DOC dissolved organic carbon; DN dissolved nitrogen.

watercourse systems (Jones and Holmes, 1996; Dahm et al., 1998), it is important to note that in our case we do not know the dominant nutrient exchange direction occurring between the sediments and water.

The reduced flow regime of water together with the increased in nutrient concentrations occurring in NIR (Table 2) might promote eutrophication phenomena (Paerl, 2006) resulting in negative impacts on benthic organisms. In fact, there is a common acceptance that large amount of nutrients (i.e., N and P) promote an excessive growth of plants, mainly in the form of algae, in waterbodies (Dodds and Smith, 2016) which are recognized to reduce the DO concentration in waterbodies (Chaudhury et al., 1998; Chislock et al., 2013). Then, the microbial breakdown of that biomass in eutrophic canals can result in a further low dissolved oxygen concentration. However, in our study the algal biomass was not determined. The higher DO content in NIR than IR can be due to the major influence of temperature on DO (Sabater et al., 2000).

The worsening of water quality during NIR was confirmed by the higher SAR values compared to IR (Fig. 4), indicating a larger risk of salinity.

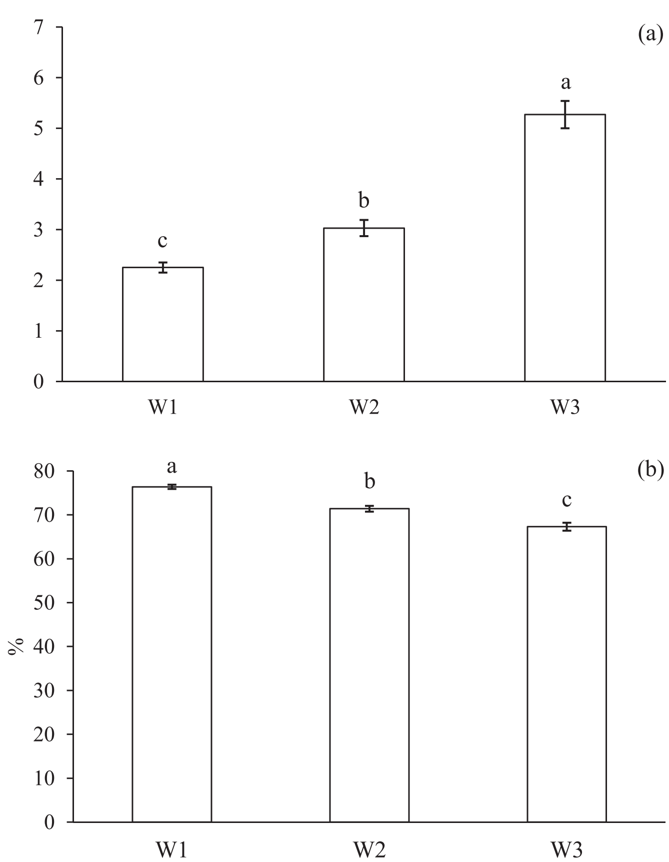


**Fig. 5.** Sodium adsorption ratio (a) and water quality index (b) of water sampled during the irrigation period from canals of sites L5, L6, L7 and L8 (W1), sites L1, L2, and L3 (W2), and sites L4 and L9 (W3). Error bars are the standard errors. Different letters above the bars indicate significant differences ($p < 0.05$).

Though during NIR the water of the canals is not used for agricultural purposes, the salinization could modify the growth, the activity, and the survival of a wide range of living organisms associated to the watercourses (Hintz and Relyea, 2017; Olson and Hawkins, 2017; Velasco et al., 2019), threatening the function of canals as ecological corridors. In addition, salt–enriched water infiltration into the banks could promote soil salinization, which is currently a severe soil threat in north–eastern part of Italy (Vittori et al., 2020).

### *4.2. Spatial differences of water quality among the study sites*

The findings got from IR showed some differences among the study sites despite the high amount of water from CER introduced within the canals whose chemical parameters are monitored along the entire watercourse. Therefore, differences among the study sites would indicate the influence of the agricultural and industrial activities that occur within the territory on water of the canals (Turner et al., 2003; Duan et al., 2007; Conley et al., 2009; Liu et al., 2011; Bu et al., 2016).

The higher EC values and nutrients concentration in sites L4 and L9 than in other studied canals (Table 3) could be attributed to their function as collector canals of the whole plain area and the proximity of sampling sites to hydrographic basin closure. Our results are consistent with previous studies which observed an increase of nutrients from upstream to downstream of watercourses flowing through agricultural, urban, or industrial land (Bisimwa et al., 2022; Ferronato et al., 2013). In fact, the study sites L4 and L9 were located 39 and 30 km far from CER, respectively, while the water of the other study sites flowed for no >22 km before to be sampled.

The differences occurring between the water samples collected from sites L1, L2, and L3 and those collected from sites L5, L6, L7, and L8 (Table 3) could be mainly attributed to the geomorphological features of the land that the canals cross. In fact, such canals had similar function and managements, but canals L1, L2, and L3 cross alluvial plain deposits with fine-texture river sediments, while canals L5, L6, L7 and L8 cross alluvial plain deposits with medium-texture river sediments (Fig. 1b). Specifically, a higher EC, SAR and nutrients concentration (Table 3 and Fig. 5) were found in water samples of canals flowing through soil with fine texture than in those flowing through soils with medium texture. Although the leaching of salts and nutrients is lower in fine texture soils than in coarse ones (Nguyen et al., 2020; Kasper et al., 2019), in our case the higher values of EC, SAR and nutrients in canals L1, L2 and L3 could be attributed to run-off processes. In particular, the lower water infiltration capacity of fine texture soils (Jarvis and Messing, 1995; Wesseling et al., 2009) could promote run-off processes during rainfall events with consequent transport of clay particles (rich of exchangeable nutrients around their surface) within the canals (Braskerud, 2003; Lado and Ben-Hur, 2004; Lowe et al., 2021). The delivery of fine soil particles from the surround land into the canals could promote nutrients enrichment in water (Haygarth et al., 2005; Savic et al., 2021) because of their desorption from the soil particle surfaces.

### *4.3. Influence of lithology on sediments*

The distinction between sediment samples of sites S2 and sites S1 could be attributed to the different lithology that characterize the study sites

**Table 4**
Mean and standard errors (se) of physicochemical parameters of sediment sampled from canals of sites L1, L2, L3, L4, and L9 (S1), and sites L5, L6, L7, and L8 (S2). Different letters indicate significant differences within each column ($p < 0.05$).

| Group | | pH | EC | $CaCO_3$ | sand | silt | clay | TOC | TN | $\delta^{13}C$ | $\delta^{15}N$ | Al | Ca | Fe | K | Mg | Na | P | S | Cu | Zn |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | mS cm$^{-1}$ | g kg$^{-1}$ | | | | % | | ‰ | | g kg$^{-1}$ | | | | | | | | mg kg$^{-1}$ | |
| S1 | mean | 7.79 | 0.60 | 169 | 66 | 655 | 280 | 2.07 | 0.26 | −27.9 | 6.68 | 46.0 | 54.0 | 28.6 | 11.6 | 11.0 | 0.83 | 1.09 | 1.23 | 56.5 | 120.7 |
| | | | a | b | b | a | a | a | a | b | a | a | b | a | a | a | a | | a | a | |
| | se | 0.04 | 0.03 | 5.82 | 11 | 16 | 13 | 0.11 | 0.01 | 0.10 | 0.20 | 1.17 | 1.49 | 0.86 | 0.35 | 0.27 | 0.03 | 0.10 | 0.09 | 2.63 | 6.37 |
| S2 | mean | 7.88 | 0.37 | 194 | 388 | 425 | 192 | 1.22 | 0.15 | −27.4 | 5.73 | 26.6 | 62.8 | 19.6 | 7.3 | 7.9 | 0.58 | 0.73 | 0.65 | 33.4 | 114.4 |
| | | | b | a | a | b | b | b | b | a | b | b | a | b | b | b | b | | b | b | |
| | se | 0.05 | 0.03 | 4.38 | 47 | 39 | 18 | 0.10 | 0.01 | 0.08 | 0.17 | 1.86 | 1.02 | 0.99 | 0.50 | 0.36 | 0.04 | 0.05 | 0.08 | 2.77 | 18.24 |

EC electrical conductivity; TOC total organic carbon; TN total nitrogen.

(Fig. 1b). Indeed, S2 were within the lithological unit with medium-texture river sediments which had a large amount of sand. In S1, instead, a higher amount of silt and clay were recorded because they were located on the lithological unit with fine-texture river sediments.

Sites S2 differed from other sites by lower load of nutrients and heavy metals concentration, except for Ca concentration which was higher for the abundance of carbonates. The distinction occurring between S1 and S2 was likely due to the different sediments' particle size distribution. Fine-grained particles in sediment are known to have higher retention of organic matter and heavy metal due to high surface area and ionic attraction capacity (Ferronato et al., 2013; Ferronato et al., 2015). In fact, in our study sediment samples with less load of nutrients and heavy metals (S2) had higher amount of sand compared to others (S1), which had higher silt and clay contents (Table 4). In this sense, the similar clustering observed for sediments and water of IR, including their chemical properties, would suggest the pivotal role of exchange of matter between them (Maazouzi et al., 2013).

Moreover, the higher Al, Fe, and Mg concentrations in sediment samples of S1, which had lower amount of sand and significant differences in C isotopes compared to samples of S2 (Table 4), may depended on the deposition of different parent material along the canals of the two clusters. Mineralogy and geochemistry composition of soil and sediment are known to have a strong correlation (Bremner and Willis, 1993; Salonen and Korkka-Niemi, 2007).

Noteworthy, in IR period, the sites L4 and L9 differ from sites L1, L2, and L3 for water quality although they had similar lithology. As previously reported (Paragraph 4.2), canals L4 and L9 had a poorer water quality compared to other sites due to their function as collectors of water flowing through the whole plain area. This would highlight that the influence of canal hydraulic management on watercourse quality is greater than the lithological factor.

Zinc threshold exceeding in sediment of site L1, L4, L6, and L9 likely due to agricultural practice and/or deposition of contaminated soil erosion. As reported by Ferronato et al. (2015), Zn concentration often exceed the legislative threshold on surface sediments of this plain area channels, because Zn, but also Cu, are frequent soil pollutants in agricultural land (García-Carmona et al., 2019).

### 4.4. The canals' vegetation

In general, the plant species composition found through the present investigation was similar to those observed by Montanari et al. (2020) within the same study area, and similarities were observed among the considered study sites. Although the literature reports that plant species composition and distribution along watercourses and floodplains are affected by water quality (Kočić et al., 2008; Alemu et al., 2018) and pedoclimatic factors (Michaud et al., 2012; Vidotto et al., 2016), the similar vegetation type among the investigated sites would suggest that other factors affect the composition of the studied plant communities. In fact, in our case the plant communities did not mirror the differences observed for water and sediments.

The most abundant plants are stress tolerant ruderal plants therefore they can withstand mowing (Montanari et al., 2020). It is important to highlight the predominance of *Phragmites australis* (Cav.) Trin. ex Steud

**Table 5**
Relative cover of plant species identified within the study sites (L1, L2…L9) in spring (SS) and the fall (FS) seasons.

| Group | Species | | Plant family | L1 | | L2 | | L3 | | L4 | | L5 | | L6 | | L7 | | L8 | | L9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | SS | FS | SS | FS | SS | FS | SS | FS | SS | FS | SS | FS | SS | FS | SS | FS | SS | FS |
| Aquatic and riparian species | *Althaea* | *cannabina* | Malvaceae | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 8 | 0 | 0 | 0 | 0 |
| | *Althaea* | *officinalis* | Malvaceae | 5 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 7 | 0 | 0 | 0 | 0 |
| | *Carex* | *acuta* | Cyperaceae | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 12 | 0 | 0 | 0 | 0 |
| | *Carex* | *riparia* | Cyperaceae | 37 | 40 | 26 | 70 | 1 | 11 | 0 | 12 | 1 | 0 | 0 | 0 | 9 | 14 | 14 | 6 | 1 | 1 |
| | *Cornus* | *sanguinea* | Cornaceae | 0 | 0 | 0 | 0 | 1 | 11 | 0 | 1 | 1 | 35 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | *Equisetum* | *telmateia* | Equisetaceae | 9 | 1 | 0 | 1 | 1 | 2 | 1 | 1 | 1 | 0 | 0 | 0 | 22 | 1 | 0 | 0 | 0 | 0 |
| | *Humulus* | *lupulus* | Cannabaceae | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 13 |
| | *Iris* | *pseudacorus* | Iridaceae | 9 | 3 | 1 | 3 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 4 | 1 | 1 | 0 | 1 |
| | *Phragmites* | *australis* | Poaceae | 23 | 29 | 1 | 0 | 30 | 38 | 36 | 23 | 47 | 39 | 50 | 76 | 22 | 15 | 56 | 23 | 39 | 3 |
| | *Populus* | *alba* | Salicaceae | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 17 | 2 | 0 | 0 | 0 | 0 |
| Agricultural species | *Avena* | *sterilis* | Poaceae | 0 | 0 | 1 | 0 | 15 | 0 | 0 | 0 | 1 | 0 | 4 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| | *Elymus* | *repens* | Poaceae | 0 | 1 | 1 | 0 | 3 | 11 | 9 | 16 | 12 | 0 | 0 | 0 | 1 | 0 | 5 | 6 | 0 | 0 |
| Ruderal species | *Bromus* | *sterilis* | Poaceae | 0 | 0 | 11 | 0 | 1 | 0 | 9 | 0 | 12 | 0 | 8 | 0 | 1 | 0 | 5 | 0 | 0 | 0 |
| | *Cephalaria* | *transsylvanica* | Dipsacaceae | 1 | 0 | 1 | 5 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | *Crepis* | *pulchra* | Asteraceae | 1 | 0 | 1 | 0 | 1 | 0 | 14 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| | *Galium* | *aparine* | Rubiaceae | 1 | 2 | 11 | 0 | 1 | 0 | 1 | 9 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 2 | 0 | 1 |
| | *Rubus* | *fruticosus coll.* | Rosaceae | 0 | 0 | 11 | 5 | 1 | 4 | 1 | 4 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 39 | 0 | 1 |
| | *Urtica* | *dioica* | Urticaceae | 5 | 5 | 11 | 0 | 1 | 1 | 0 | 9 | 1 | 0 | 13 | 6 | 1 | 9 | 1 | 5 | 29 | 29 |
| Invasive species | *Amorpha* | *fruticosa* | Fabaceae | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 32 |
| Pasture species | *Brachypodium* | *phoenicoides* | Poaceae | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 9 | 0 | 0 | 0 | 0 |
| Others | | | | 10 | 18 | 24 | 14 | 45 | 19 | 29 | 17 | 22 | 22 | 22 | 17 | 22 | 19 | 18 | 19 | 7 | 19 |

Others includes the plant species with a relative cover lower than 5 % in all study sites.

**Table 6**
Shannon diversity index of vegetation growing on the study sites (L1, L2, L3….L9) in spring (SS) and fall (FS) seasons.

| Season | L1 | L2 | L3 | L4 | L5 | L6 | L7 | L8 | L9 |
|---|---|---|---|---|---|---|---|---|---|
| SS | 2.03 | 2.70 | 3.25 | 2.38 | 2.24 | 1.98 | 2.65 | 1.81 | 1.59 |
| FS | 1.94 | 1.39 | 2.20 | 2.52 | 1.78 | 1.10 | 2.69 | 2.12 | 2.14 |

and *Carex riparia* C., which are recognized to be efficient catch plants and, therefore, can be crucial to keep low the nutrient loads in watercourses (Schulz et al., 2011). Although human activity may facilitate growth of invasive plant populations by modifying environmental conditions and introducing new sources of propagules (Hobbs, 2000; Foxcroft et al., 2007, 2008a, 2008b), in our case the invasive plants were limited. The scarce spreading of invasive plants can be attributed to the abundancy of *P. australis* and *C. riparia* which promptly uptake nutrients (Schulz et al., 2011; Ladislas et al., 2013) that otherwise can be assimilated by the invasive plants. Further, *P.s australis* is considered invasive in North America (Pengra et al., 2007; Rohal et al., 2021) indicating its ability to control other plant species.

The plant diversity was rather similar among the study sites. It resulted low, consistent with previous studies conducted in wetlands or areas close to rivers (e.g., Mligo, 2017; Rubio et al., 2022). The similar plant diversity among the study sites might be associated to the similar landscape surrounding such sites (Ives et al., 2011; Rooney and Bayley, 2011). Whilst the generally low plant diversity might be attributed to the fact that the investigated canals are within agricultural lands and they are mowed every year, which both negatively affect the growth and developments of "natural" plant species (Krause et al., 2011; Harvolk et al., 2015).

### *4.5. Future perspectives for Po plain canal ecosystems*

The occurrence of water quality worsening of the canals during the NIR period, the poor water quality within the collector canals (i.e., L4 and L9) and the low flora diversity would highlight the needing of solutions to improve the features of the studied environments.

The findings of the present study would suggest to keep an high water level during NIR to ensure a good quality of water. However, this fact must face with the hydraulic safety function of the studied canals especially in a climate change scenario where extreme flood risks and sediment deposition within the canals will rise (Kiedrzyńska et al., 2015; Nayak and Shukla, 2023). Sediments' deposition on the bed of the canals reduces both the capacity of the canals and the quality of the water that flow within them (Maazouzi et al., 2013). Several are the studies that report ambitious practices for planning floodplains capable of improving water quality retaining sediments and nutrients (Kiedrzyńska et al., 2008, 2015; Zalewski et al., 2021). In our case, the sediment dredging can be a suitable technique for removing excess sediment from canal beds (Gurmu et al., 2022) which could be used as soil amendment on the surrounding lands (Crocetti et al., 2022).

The lower water quality in terms of EC values and nutrient concentrations of the collector canals highlights the necessity to perform strategies able to reduce salinization and eutrophication risks. In this sense, nature–based solutions like the establishment of flow-through wetlands, shallow lakes and backwaters close to such canals might improve the water quality (Golden et al., 2019; Hansen et al., 2018; Cheng et al., 2020).

The flora survey performed for the present investigation pointed out the low flora diversity. Because of the importance of flora diversity for canal ecosystems providing habitat for biological communities and mitigating harmful environmental impacts on water (Rowiński et al., 2018), such diversity might be increased through the creation of meanders and plantation actions (Seer et al., 2018).

## 5. Conclusion

The present study showed that the aquatic environment of the studied canals is influenced by multiple factors, such as hydrological conditions, landscape features and canal utilization. In particular, the reduction of the water flow within the canals worsened the water quality. In fact, the reduced water inflow from CER together with the higher water leaching processes from the surrounding soils caused by the rainfalls occurring in NIR increased the amount of nutrients in water. Therefore, although the water flow within the canals is kept low during NIR to guarantee hydraulic safety, this could cause eutrophication and salinization phenomena. To avoid the worsening of the canals' water quality, the present study would suggest sediment removal from the canals' bed which would allow to increase canals' capacity and, in turn, to keep both a high water level within the canals and the hydraulic safety.

The differences observed for water of L4 and L9 sites would highlight the influence of the using purpose of the canals on water quality. We observed a poorer water quality in L4 and L9 compared to the others because of their utilization as collector canals. The water quality of these canals can be improved through the creation of flow-through wetlands, shallow lakes and backwaters close to such canals.

Noteworthy was the key role of lithological features of the areas crossed by the canals on both water and sediments. In fact, we observed a clear distinction of both water and sediment physicochemical properties according to the alluvial deposits type which would suggest how water and sediments are strongly related to the edaphic factors. In this sense we hypothesized that sediments developed from the alluvial deposits strongly interact with water.

Conversely to water, plants growing close to the canals did not show any relationship with the edaphic factors. This fact could be attributed to the agricultural landscape that the canals cross which does not allow the development of a biodiverse plant population. Therefore, in a view of improvement of the Po plain environment, the creation of meanders and plantation actions can be helpful for flora diversity rise.

Finally, in a view of reclamation of the investigated sites we would suggest keeping a higher water flow during NIR compared to the present to avoid the risk of eutrophication and salinization. Also, the introduction of plant species able to promptly uptake nutrients can be promoted to reduce the amount of nutrients within the canals located on fine texture deposits.

As a whole, the present study would highlight the importance of landscape and canal managements on canal environment and a marked relationship of water and bed sediments with edaphic factors. Because of these interactions and the presence of similar floodplain systems worldwide, our findings would highlight how the multiscale (vegetation, water and bed sediment) approach for the study of these ecosystems at global scale should be considered priority for floodplain managements addressed to keep their ecosystem functions. Therefore, it is expected that the approach used in the present study will contribute to reach the environmental targets set by the authorities and help to reconcile farming and environmental conservation.

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## CRediT authorship contribution statement

**Chiara Poesio:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Mauro De Feudis:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Andrea Morsolin:** Writing – review & editing. **Carla Lambertini:** Investigation, Writing – review & editing. **Alessandra Zambonelli:** Investigation, Writing – review & editing. **Gloria Falsone:** Methodology, Writing – review & editing. **Livia Vittori Antisari:** Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Data availability

Data will be made available on request.

## 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.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.161953.

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