Potentially Toxic Elements Contamination in Surface Sediment and Indigenous Aquatic Macrophytes of the Bahmanshir River, Iran: Appraisal of Phytoremediation Capability

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Abstract

To determine the status and sources of contamination and phytoremediation capability of *Typha latifolia L.* in the Bahmanshir River of Iran, the concentration of eight potentially toxic elements (As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn) in sediment and plant tissues from ten sampling sites were measured. Mean concentrations of Cd, Cr, Cu, Pb, and Zn in the sediment exceeded those of local background. PCA-MLR receptor analysis suggested that the sediment contamination was due to municipal wastewater/vehicular pollutions and weathering/industrial/agricultural activities, with contributions of 66% and 34%, respectively. Average enrichment factor (EF) and modified hazard quotient (mHQ) for Pb and Cu were categorized as moderate. Modified pollution index (MPI) and modified ecological risk index (MRI) values suggested moderate to heavy pollution and low ecological risk, respectively. The values of sediment quality guidelines (SQGs), ecological contamination index (ECI), contamination severity index (CSI), and toxic risk index (TRI) were all similar, reflecting low to moderate contamination and toxicity. *Typha latifolia L.* showed good phytostabilization capability for Cd, Cu, and Pb, and phytoextraction capacity for Zn. Using the metal accumulation index (MAI) and the comprehensive bioconcentration index (CBCI*)*, *Typha latifolia L.* was shown to have acceptable performance in the accumulation of Cd, Cu, Pb, and Zn and thus, can be considered a good candidate for bioaccumulation of these elements in the study area. Overall, this study suggests that phytoremediation using *Typha latifolia L.* could be a practical method for uptake and remove of potentially toxic elements from aquatic environments.

Keywords: Potentially toxic elements, Sediment contamination, PCA-MLR, Phytoremediation, *Typha latifolia L.*

1. Introduction

Contamination of aquatic environments and fluvial ecosystems has become a public concern due to the non-degradability, accumulation, and toxicity of several potentially toxic elements (Li *et al.* 2019b). With rapid urbanization, industrialization, and increases in human populations, rivers receive large quantities of these elements which in turn degrade environmental quality (Setia *et al*. 2020). Among freshwater environments, rivers are the most susceptible to contamination. Potentially toxic elements in aquatic ecosystems can enter the food chain and accumulate in the blood, fatty tissues, hair, nails, and teeth of humans living along rivers, and ultimately cause diseases such as cancers. Potentially toxic elements are derived from natural sources including volcanoes and weathering of rocks, and from anthropogenic sources such as discharges of untreated municipal sewage, industrial emissions and effluents, traffic-related pollution, mining activities, and application of pesticides and inorganic fertilizers (Singh *et al.* 2017; Kumar *et al.* 2020a). These sources release potentially toxic elements into river water, resulting in elevating levels of bioaccumulation into aquatic organisms and degradation of water quality. In addition, these elements can be strongly sorbed to suspended sediments and rapidly deposited in bed sediments, causing detrimental effects on aquatic diversity. With changing pH, redox and temperature, these elements can be secondary contamination sources when they are released from sediments into the water column. Therefore, sediment can act as both sources and sinks of contaminants (Jia *et al.* 2018). Accordingly, bed sediments in aquatic environments relate to, and can be considered indicators of, the concentrations of contaminants in water. In this regard, indices for the assessment of sediment contamination, including Enrichment Factor (EF), Modified Pollution Index (MPI), Modified Ecological Risk (MRI), and, have been widely used to evaluate sediment contamination (Brady *et al.* 2015; Duodu *et al.* 2016; Pandey *et al.* 2019). In recent years, new indices for estimating contamination in river sediment have been developed. These include the Modified Hazard Quotient (mHQ), Ecological Contamination Index (ECI), Contamination Severity Index (CSI), and toxic risk index (TRI) (Peiman *et al.* 2015; Zhang *et al.* 2016; Benson *et al.* 2018).

Potentially toxic elements can be taken up from water and sediment and accumulated in aquatic macrophytes acting as a filter, in a process called phytoremediation (Parihar *et al.* 2021). Evaluation of potentially toxic element uptake in macrophytes can be an important tool for monitoring the levels of contamination in aquatic ecosystems and their bioaccumulation ability. Phytoremediation or 'green purification' can be considered as a cost-effective and environmentally friendly technology method in aquatic ecosystems. *Typha latifolia L.* (also known as Cattail) belongs to the *Typhaceae* family, and is a high-biomass aquatic macrophyte with a high capacity for taking up potentially toxic elements grown under various climatic conditions, especially in tropic and warm regions (Sasmaz *et al.* 2008; Varun *et al.* 2011). *Typha latifolia L.* accumulates potentially toxic elements in its tissues without serious physiological damage and can be considered a good candidate for evaluating the potential of phytoremediation (Klink *et al.* 2013).

River contamination associated with potentially toxic elements is an important problem globally and specifically in Iran due to rapid urbanization and industrialization. The Bahmanshir River is one of the major waterways located in Abadan City, Khuzestan Province, Iran, and is one of the tributaries of the Karoon River. Discharges of large amounts of untreated agricultural and industrial effluents and municipal sewages of Ahvaz and Abadan Cities have contaminated the Bahmanshir River with a range of potentially toxic elements (Haghnazar *et al.* 2021). Oil refinery and petrochemical emissions and effluents in Abadan City have also been suggested to be responsible for the deterioration of the quality of this river. *Typha latifolia L.* is an indigenous aquatic macrophyte and dominant plant growing along the Bahmanshir River, and therefore it may be a candidate for phytoremediation in the study area. The present study aims to evaluate the capability of *Typha latifolia L.* for remediation of the sediment contamination caused by potentially toxic elements. The main objectives were to 1) determine the concentration of As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn in surface sediments and *Typha latifolia L.*, 2) evaluate contaminant concentrations based on relevant indices, and 3) identify the main sources of contamination and their relative contributions using correlation analysis, principal component analysis (PCA), and multiple linear regression (MLR). The Bahmanshir River was used as the study site as it is representative of anthropogenically-impacted rivers in Iran.

2. Materials and Methods

2.1. Study area

The Bahmanshir River is located adjacent to Abadan City, a major industrial city of Khuzestan Province, south-west Iran, with 347,000 inhabitants in 2016. The river (30°25'53.52"N ~ 29°59'42.71"N and 48°43'13.16"E ~ 48°12'37.38"E) is a tributary of the Karoon River with a length of approximately 83 km, and it also receives drainage from the upstream part of the Karoon River via a canal (Fig. 1). It flows through Abadan City to the Persian Gulf. The basin has an arid climate with a very hot summer (August) and a very mild winter (February) and annual precipitation of 157 mm year^{-1}. Recorded annual maximum and minimum temperatures are –2.2 °C and 52.3 °C, respectively. The Bahmanshir River is also the main water supply for irrigation regions in a 1 to 3 km wide strip covering about 7000 ha on both sides of the river which is cultivated with agricultural products such as palm-groves and vegetables. Oil refinery and petrochemical activities, agricultural effluents, and sewage from Abadan City affect Bahmanshir River. Moreover, significant amounts of contaminants flow to the Bahmanshir River due to discharging of urban and rural sewage into the upstream

Karoon River. As shown in Fig. 1, all sampling sites can be related to agricultural activities. The effects of oil refinery emissions that were transported in the prevailing wind are reflected in the downstream sites. Municipal wastewater and vehicular emissions have affected all sampling sites, but in Abadan City they are discharged mainly in the middle portion of the sampling section. The highest concentration of traffic in the city is located between sampling sites 4 and 6 which are also in this midstream area.

2.2.Sample collection and analysis

Ten sites were established for sampling and a total of 30 samples (i.e., 10 samples for sediment, 10 samples for roots and 10 samples for stems) were collected in September 2020 from upstream to downstream on the Bahmanshir River. All samples were obtained in triplicate from three sub-sites of each sampling location. Composite soil samples of ~ 1 kg were collected at 10 cm depth at each sub-site using a Van Veen grab sampler. After removing impurities, each sample was packed in a sterilized self-lock polyethylene bag and shipped to the laboratory for further analysis. The samples were oven-dried at 80 °C, crushed to < 4 mm, ground and sieved through a 200-mesh polyethylene sieve. Approximately 1 g of each sample was digested using HF-$HClO_4$-HNO_3 mixtures in a microwave digestion system (Perkin Elmer Titan Microwave) at 160 °C for 6 h. Finally, the solutions were filtered and diluted with deionized water to make a volume of 25 ml. Samples of root and stem of the indigenous aquatic macrophyte *Typha latifolia L.* were collected from each sampling site. Root samples were collected between 10 ~ 20 cm below the sediment surface. The roots and stems were washed with tap and distilled waters and oven-dried at 80 °C for 24 h. After grinding the dried samples into fine sized powders using a pestle and mortar, 5 g of each sample was digested in a mixture solution of H_2SO_4–HNO_3–H_2O_2 using a microwave digestion system (Perkin Elmer Titan Microwave) at 70 °C. When white fumes were observed, the digestion process was continued until a clear solution was obtained. This solution was cooled and diluted with distilled water to 25 ml.

Fig 1. Location of the Bahmanshir River and sampling points (Photos from www.isna.ir).

As, Cd, Cr, Cu, Pb, Ni, and Zn were detected using inductively coupled plasma mass spectroscopy (ICP-MS). In this study, Claritas PPT® Grade ICP-MS Multi-Element Solution Standards Set (CLMS-SET, SPEX CertiPrep) were used as the certified reference materials (CRMs). These, together with duplicate samples (10% of the total samples) and reagent blanks, were used to assess the data quality. Percentage recoveries of samples ranged from 92% to 105%. Relative standard deviations (RSD) for the duplicate samples were found to be less than 5%. The values of the limits of determinations (LOD) for the potentially toxic elements in sediment and plant are given in Table S1.

2.3. Contamination assessment of sediment

To evaluate sediment contamination in the Bahmanshir River, an index-based approach was conducted by using major and novel indices including enrichment factor (EF), Modified Pollution Index (MPI), Modified Ecological Risk (MRI), Sediment Quality Guidelines (SQGs), Modified Hazard Quotient (mHQ), Ecological Contamination Index (ECI), Contamination Severity Index (CSI), and Toxic Risk Index (TRI). Descriptions of these indices are presented in Table S2.

2.3.1. Enrichment factor (EF)

To differentiate between natural and anthropogenic sources, a normalization technique, the Enrichment Factor (EF), that is applied commonly for pollution assessment of sediments was used. This was computed using the following equation:

$$EF = \frac{\left[C_n / C_{ref} \right]_{sample}}{\left[C_n / C_{ref} \right]_{background}} \tag{1}$$

where $[C_n/C_{ref}]$ represents the ratio of elements concentration to the relevant reference value. In this study, local background concentrations reported by Mokhtarzadeh *et al.* (2020) were used as the reference values. In this study, Fe was selected as a reference element for geochemical normalization due to its uniform natural concentration and natural abundance in the Earth's crust. (Li *et al.* 2019a; Faměra *et al.* 2021). An EF value of < 1.5 reflects the regional rock composition and suggests elements originate by natural sources, whereas an EF > 1.5 more indicates anthropogenic sources of potentially toxic elements (Pandey *et al.* 2019).

2.3.2. Modified pollution index (MPI)

The Modified Pollution Index (MPI) (Brady *et al.* 2015) can be used to estimate the overall status of contamination in a particular area. The MPI index is considered to be a more reliable index than others because it takes into account the background concentrations and gives more accurate qualification of sediment contamination (Mokhtarzadeh *et al.* 2020). The MPI is defined as:

$$MPI = \sqrt{\frac{\left(EF_{average}\right)^2 + \left(EF_{max}\right)^2}{2}} \tag{2}$$

where $EF_{average}$ and EF_{max} represent average and maximum enrichment factors, respectively.

2.3.3. Modified ecological risk (MRI)

In order to assess the ecological risk of the sediment, the modified ecological risk (MRI) was employed. The MRI quantifies the adverse ecological effects of potentially toxic elements by taking into account the lithogenic and sedimentary inputs. MRI is calculated by using the following formula (Duodu *et al.* 2016):

$$E_r^i = T_r^i \times EF^i \ , \qquad MRI = \sum_{i=1}^{i=n} E_r^i \tag{3}$$

where T_r^i and EF^i are the toxic-response factor and the enrichment factor for the element *i*. The values of the toxic-response factors of As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn are 10, 30, 2, 5, 1, 5, 5, and 1, respectively (Hakanson, 1980).

2.3.4. Sediment quality guidelines (SQGs)

Sediment quality guidelines (SQGs) represent the concentration limits of contaminants and help to evaluate the adverse biological effects of potentially toxic elements on the living of organisms in sediment. Two sets of SQGs have been developed as (a) the effect range low (ERL)/effect range median (ERM), and (b) the threshold effect level (TEL)/probable effect level (PEL). The ERL and TEL indicate the conditions where adverse biological effects are infrequently observed, whereas the ERM and PEL suggest whether or not detrimental biological effects would be likely to occur. To determine the possible ecological and biological effects of multiple toxic elements, the mean Effect Range Median quotient (mERM-Q) and the mean probable effect level quotient (mPEL–Q) were calculated using the following equations (El-Alfy *et al.* 2020):

$$mPEL - Q = \frac{\sum_{i=1}^{i=n} C_{sample} / PEL}{n} \tag{4}$$

$$mERM-Q=\frac{\sum_{i=1}^{i=n} C_{sample}/ERM}{n} \tag{5}$$

where C_{sample} is the concentration of toxic element *i* in the sediment, *n* refers to the number of toxic metals in the study. The values of ERM and PEL for the elements are given in Table S3.

2.3.5. Modified hazard quotient (mHQ) and Ecological contamination index (ECI)

The risk of each potentially toxic element to aquatic environments was estimated using the modified hazard quotient (mHQ) proposed by Benson *et al.* (2018). This index is calculated by comparing the values of potentially toxic elements with three threshold values as follows:

$$mHQ=\left[C_i\left(\frac{1}{TEL_i}+\frac{1}{PEL_i}+\frac{1}{SEL_i}\right)\right]^{0.5} \tag{6}$$

where C_i, is the measured concentration of toxic element i, TEL, PEL, and SEL are the threshold effect level, the probable effect level, and the severe effect level of toxic element i, respectively (Table S3).

The accumulative ecological risk of the aquatic ecosystem was determined using the ecological contamination index (ECI) which is associated with the derived factors of principal component analysis (PCA). The values of ECI is calculated using the following equation developed by Benson *et al.* (2018):

$$ECI=B_n\sum_{i=1}^{i=n} mHQ_i \tag{7}$$

where B_i represents the reciprocal of the derived eigenvalue of toxic element concentrations.

2.3.6. Contamination severity index (CSI)

The contamination severity index (CSI) (Peiman *et al.* 2015) was used to assess the ecotoxicological risk of the river sediment based on the effect range low (ERL) and effect range median (ERM) presented in Table S3. The CSI value was computed as follows:

$$W_t = \frac{\left(L_{fi} \times E_v\right)}{\sum_{i=1}^{i=n}\left(L_{fi} \times E_v\right)} \tag{8}$$

$$CSI = \sum_{i=1}^{i=n} W_i \left[\left(\frac{C_i}{ERL_i}\right)^{0.5} + \left(\frac{C_i}{ERM_i}\right)^{2}\right] \tag{9}$$

where W_t is the weighted value for each toxic element, L_{fi} and E_v indicate factor loading and eigenvalue of each toxic element, respectively, which are derived from PCA, and C_i shows the measured concentration of toxic element *i*.

2.3.7. Toxic risk index (TRI)

The toxic risk index (TRI) was employed to assess the toxicity of the ecosystem. The TRI is calculated based on the comparison between the concentration of toxic elements, the threshold effect level (TEL) and probable effect level (PEL) by using the following formula (Zhang *et al.* 2016):

$$TRI = \sum_{i=1}^{i=n} TRI_i = \left[0.5\left(\left(\frac{C_i}{TEL_i}\right)^2 + \left(\frac{C_i}{PEL_i}\right)^2\right)\right]^{0.5} \tag{10}$$

where TRI_i and C_i demonstrate the toxic risk index and measured concentration for toxic element i.

2.4. Phytoaccumulation assessment

2.4.1. Bioconcentration factor (BCF) and Translocation factor (TF)

The capability of the macrophytes to uptake and accumulate potentially toxic elements from sediment can be described by the bioconcentration factor (BCF). The BCF is determined by the ratio between toxic element concentrations in the dry mass of the macrophyte roots and those in sediment. The translocation factor (TF) is defined as the ability of macrophytes to transfer potentially toxic elements from the roots to the upper parts of the plant. In this study, the *TF* value was estimated as the ratio of the concentration of potentially toxic elements in the macrophyte stems to those in the roots. The BCF and TF values are calculated using the following equations:

$$BCF = C_{roots} / C_{sediment} \tag{11}$$

$$TF = C_{stems} / C_{roots} \tag{12}$$

where $C_{sediment}$ refers to the concentration of potentially toxic elements in the river sediment and C_{roots}, and C_{stems} are the same potentially toxic elements concentration in the roots and stems of the macrophyte, respectively. A BCF of < 1 indicates that the macrophyte has limited accumulation capability, whereas a BCF of > 1 demonstrates that the macrophyte has bioaccumulation potential. According to Nematollahi *et al.* (2020), bioaccumulation can be assessed using the BCF into the following categories: 0.001 < BCF < 0.01, very weak absorption; 0.01 < BCF < 0.1, weak absorption, 0.1 < BCF < 1, intermediate absorption; 1 < BAC < 10, strong absorption; and 10 < BCF < 100, intensive absorption. A TF value of > 1 indicates a good transfer system and phytoextraction capability (Parihar *et al.* 2021). A BCF > 1 and TF > 1 show the ability of phytoextraction while a BCF > 1 and TF < 1 can be only a candidate for phytostabilization (phytoimmobilization) capability.

2.4.2. Metal accumulation index (MAI)

The ability of plants to accumulate potentially toxic elements is estimated using the metal accumulation index (MAI) (Safari *et al.* 2018). In this study, the MAI was used to compare the accumulation ability of the root of the indigenous macrophytes with the results of other studies. The value of MAI is estimated as follows:

$$MAI = \left(\frac{1}{n}\right)\sum_{j=1}^{j=n} I_j \tag{13}$$

where n is the total number of potentially toxic elements and Ij represents the sub-index of the element j by the deviation of the mean concentration (x) on the standard deviation (Δx) of the element j.

2.4.3. Comprehensive bio-concentration index (CBCI)

The comprehensive bio-concentration index was applied to assess the bioaccumulation ability of macrophytes by considering the effects of the toxic elements on them. By comparing the CBCI value of tissues, the overall accumulation abilities of the macrophyte can be evaluated. The CBCI is based on a fuzzy synthetic evaluation developed by Zhao *et al.* (2014):

$$CBCI = \frac{\sum_{i=1}^{i=n} \mu_i}{n} \tag{14}$$

$$\mu_i = \begin{cases} 0 & BCF = BCF_{\min} \\ \dfrac{BCF - BCF_{\min}}{BCF_{\max} - BCF_{\min}} & BCF_{\min} < BCF < BCF_{\max} \\ 1 & BCF = BCF_{\max} \end{cases} \tag{15}$$

where μ_i is referred to the fuzzy membership function of element *i*.

2.5. Statistical analysis

The normality of the data distribution was assessed with the Kolmogorov–Smirnov (K–S) test (Mehraein *et al.* 2020). Pearson's correlation analysis was used to determine the degree of correlation of the potentially toxic elements in the Bahmanshir River sediment samples. Principal component analysis (PCA) was also conducted to determine possible relationships between particular elements and sources of contamination. The Kaiser-Meyer-Olkin (KMO value > 0.5) and Bartlett sphericity tests ($p < 0.001$) were carried out to examine the applicability and validity of the PCA results. The contribution of each source was assessed using multiple linear regression (MLR) applied to the results of the PCA analysis. All multivariate statistical analysis was performed using SPSS 26 (SPSS Inc., USA) software.

3. Result and discussion

3.1. Concentration of potentially toxic elements in the surface sediments

Descriptive statistical data of the sediments, together with average concentrations of the potentially toxic elements for upper continental crust (UCC) (Hu and Gao, 2008 and Taylor and McLennan, 1995) and local background values (Mokhtarzadeh *et al.* 2020), are summarized in Table 1. Mean concentrations decreased in the order Mn > Cr > Zn > Cu > Ni > Pb > As > Cd. Mean values of As and Mn were lower than those in the UCC, but mean concentrations of Cd, Cr, Cu, Ni, Pb, and Zn were 3.7, 1.5, 3.2, 2.5, 1.4, and 1.5 times higher than their respective UCC values. Mean concentrations of As, Mn, and Ni were lower than background concentrations. In contrast, Cd, Cr, Cu, Pb, and Zn concentrations were 1.2, 1.8, 4, 4, and 2.5 times higher, respectively, than local background concentrations. Coefficients of variation (CV) for Cr (9.3%) and Mn (10.1%) were below 15%, indicating low variation and uniform dispersion in the sampling sites (Sangsefidi *et al.* 2017).

The CV values of Ni (16%), Pb (15%), and Zn (27%) showed medium variation and distribution with 15% < CV < 36%. CV values of As (64%), Cu (60%) and Cd (475) were all

> 36%, which characterized them as having non-uniform spatial distribution. Generally, a high CV value (> 20%), together with an average concentration higher than the corresponding background concentration, may reveal significant impact of human activity on the spatial variation of the particular element. Therefore, the concentrations of Cd, Cu, and Zn may have been affected by anthropogenic activities. The spatial distributions of potentially toxic elements in the surface sediments of the Bahmanshir River are presented in Fig. 2. The results indicated a homogeneity in the spatial distribution of Cr, Mn, Ni, and Pb, confirming the results of the coefficient of variation (CV < or ~ 15%). High concentrations of As were observed upstream at sites 2 and 3, and concentrations of Cd, Ni, and Zn (sites 6) were highest in the middle of the Bahmanshir River.

Fig 2. Spatial distribution of potentially toxic elements in the surface sediments

The concentration of Cu increased dramatically and Pb increased gradually in the downstream direction with highest concentrations in the samples from sites 10 and 8 (at the end of the urban area), respectively, suggesting common sources. All sampling sites were contaminated with Cd, Cr, Cu, Ni, and Pb with respect to their respective UCCs. Exceedances of UCC values were also detected in 10% and 90% of the sampling sites for As and Zn, respectively. Concentrations of Cr, Cu, Pb, and Zn were higher than their respective local background values in all sampling sites. However, in 20%, 70%, 20% of the sampling sites, the concentrations of As, Cd, and Ni, respectively, exceeded their respective local background values.

3.2. Sources of potentially toxic elements in the sediments

Principal component analysis (PCA) and Pearson's correlation analysis were employed to identify the potential sources of potentially toxic elements in the Bahmanshir River sediments. The PCA results with eigenvalues > 1 and the correlation analysis results are given in Table S4 and Fig. 3a, respectively. The Kaiser-Meyer-Olkin (KMO = 0.502) and Bartlett's sphericity tests (ρ = 0.001) demonstrated the suitability of data for PCA. Two principal components were extracted for the river sediments, describing 73.99% of the total variance (Table S4). The first component (PC1) explained 45.42% of the total variance and was specified by Cd, Cr, Mn, Ni, and Zn. Significant correlations were observed between Cr and Ni (ρ = 0.942), Cr and Zn (ρ = 0.783), and Zn and Ni (ρ = 0.916). Cadmium and Zn (ρ = 0.514), Cr and Mn (ρ = 0.599), Mn and Ni (ρ = 0.646), and Mn and Zn (ρ = 0.619) were moderately correlated. The toxic elements identified in PC1 may have been derived from municipal wastewater and traffic-related sources. This is confirmed by previous research that showed that Cd, Cr, Ni, and Zn can be released from municipal wastewater, tire and brake abrasion, combustion of lubricant oils, and vehicle exhaust fumes (Doudo *et al.* 2016; Ustaoğlu and Islam, 2020). Manganese may also be released from Mn-containing additives such as MMT in gasoline (Giri and Singh, 2014). According to Ghadiri (2016), about 19 million m^3/year of municipal wastewater in Abadan City discharges to the Bahmanshir River, resulting in deterioration of water quality and contamination of river sediments by potentially toxic elements (in particular Cd and Cr). The presence of high traffic zone in the middle part of the Bahmanshir River may have led to the elevated element concentrations in PC1 in this area.

The second component (PC2) comprises As, Cu, and Pb, and accounts for 28.57% of the total variance. Lead exhibited a strong correlation with Cu (ρ = 0.698), whereas As was not correlated with the other elements (Fig. 3a).

Fig 3. a) Correlation plot of the potentially toxic elements analyzed in this study, and b) Loading factors with vectors of PCA for Bahmanshir River sediment.

As may have been derived from natural sources such as weathering of parent materials (e.g., pyrite oxidation) (Hamidian *et al*. 2016), but agricultural activities in the area where samples 1 and 2 were taken may have contributed As through use of insecticides, herbicides, and pesticides (Ustaoğlu and Islam, 2020). As described above, Cu and Pb may have been derived from oil refinery and petrochemical emissions, together with agricultural effluents (Al-Dabbas *et al.* 2015; Haghnazar *et al.,* 2021). The street dust and soil in the south-east of the urban areas in Abadan City are contaminated by oil refinery and petrochemical emissions due the dominance of the northwestern wind (Shamal wind) (Ghanavati *et al.,* 2019; Mokhtarzadeh *et al*. 2020). Abadan City is entirely covered with 10 to 50 m-thick alluvial deposits. Due to the low vertical permeability and high groundwater table, atmospherically-deposited elements may have been mobilized to the river via surface runoff (Ghadiri, 2016). In addition, the river may have been contaminated by Pb and Cu due to tidal irrigation in the study area and the use of chemical pesticides and fertilizers in the agricultural soils.

The PCA loading factors are presented in Fig. 3b. The longest vectors are shown by Cr, Ni, and Zn, suggesting strong loading factors which touch the edge of the circle (R=1). Chromium and Mn have moderate loading factors and the same direction as Cr, Ni, and Zn. These elements were all directed towards the longitudinal axis in the direction of PC1. Conversely, the vectors Cu-Pb and As indicated strong and moderate loading factors, were inclined toward the transverse axis and were attributed to PC2. The opposite direction of the As vector suggests different contamination sources for it compared to those of the other elements.

Multi linear regression (MLR) was applied to the results of PCA to determine the contributions of the different contaminant sources. The values of PCR factors for each sampling sites are used as X_i in the MLR equation (Eq.16). The standardized normal deviates of ΣPTEs for each sampling sites were used in the right hand side of this equation. Therefore, the normalized sums of the potentially toxic elements and the factors from PCA are considered as dependent and independent variables, respectively. The regression equation is expressed as follows (Wang *et al.* 2020):

$$z = \sum_{i=1}^{i=N} B_i X_i \tag{16}$$

where Z is normalized summation of toxic elements, N is the number of factors (sources), B_i and X_i are the regression coefficient and factor scores respectively. By use of regression in SPSS software, the value of the coefficient (B_i) was obtained. Finally, the contribution of each source was calculated by the following equation:

$$\text{Contribution of source i } (\%) = {B_i}\big/{\sum B_i} \times 100 \tag{17}$$

As discussed above, factors 1 and 2 represent domestic sewage/vehicular pollution and parent materials/industrial emission/agricultural effluent sources, respectively. The equation of regression was:

$$z = 0.803 X_1 + 0.420 X_2 \tag{18}$$

Municipal wastewater and vehicular pollution represented 66% of the contribution, whereas oil refinery emissions, combined with agricultural effluents and parent materials, accounted for the remaining 34%.

3.3. Evaluation of sediment contamination

Enrichment factors (EF) were calculated to determine the extent of potentially toxic element contamination of the sediments (Fig. S1). Mean values of EF decreased in the order Cu (3.3) > Pb (3.2) > Zn (1.9) > Cr (1.4) > Cd (1) > Ni (0.7) > Mn (0.6) > As (0.5). The average values of EF for Cu and Pb fell within the moderate enrichment category, whereas those for the other elements were found to be less than 2, indicating deficiency to minimal enrichment. High levels of Cu enrichment (5 < EF < 20) in 30% of the sampling sites. Average values of EF for Cu, Pb, and Zn were > 1.5, suggesting anthropogenic sources for these elements.

The results of the modified pollution index (MPI) and the modified ecological risk (MRI) are presented in Fig. 4a. The MPI values increased downstream. Sites 1-7 were moderately polluted whereas the remaining sites were moderately to heavily polluted. The MRI values also showed increases from upstream to downstream, suggesting a low ecological risk. High values of MRI in sites 6 and 8 were spatially associated with municipal wastewater discharge, vehicular pollution and industrial emissions. Sediment quality guidelines were used to calculate the mean effect range median quotient (mERM-Q) and mean probable effects level quotient (mPEL-Q). The spatial distributions of mERM-Q and mPEL-Q exhibited similar trends (Fig. 4b), with increases from upstream to midstream and decreases from midstream to downstream. This is likely due to the fact that the value of mERM-Q and mPEL-Q are directly related to the concentration of the elements in the sampling sites. Concentrations of Cd, Cr, Mn, Ni, and Zn were highest in the middle portion of the river, probably because the mERM-Q and mPEL-Q equations are based on the average ratio of concentration/standard. All sampling sites had medium priority and medium-low degrees of contamination, with site 6 having the highest value (21% probability) for both mERM-Q and mPEL-Q.

Another useful method for clarifying the level of contamination in the aquatic environment is the modified hazard quotient (mHQ). The spatial distributions of the mHQ values are presented in Fig. 4c. Mean values of mHQ ranked in the order Cr (2.3) > Ni (2.12) > Cu (1.83) > Pb (1.58) > Zn (1.18) > As (0.89) > Cd (0.66). Moderate severity of contamination was exhibited by Cu and Pb, whereas Zn and As/Cd were included in the low and very low severity of contamination classes, respectively. All of the sampling sites were classified as having considerable severity of contamination of Cr. In addition, 70 % and 40 % of sampling sites were at the considerable severity of contamination range for Ni and Cu, respectively. The highest values of mHQ were exhibited by Cu in site 10 (mHQ = 2.7) and site 8 (mHQ = 2.54), indicating considerable severity of Cu contamination in the downstream portion of the river.

The results of the ecological contamination index (ECI), contamination severity index (CSI), and toxic risk index (TRI) calculations are shown in Fig. 4d. The values of ECI ranged from 3 to 4, indicating slight changes along the river. All sampling sites were included in the slightly to moderately contaminated class (3 < ECI < 4). The values of CSI increased from upstream to midstream, and decreased from midstream to downstream. This trend is associated with the direct impact of the element concentrations and factor loadings which are obtained by PCA. The highest value of CSI was recorded in site 6 (1.95), demonstrating low to moderately severity in the midstream. In sites 1, 2, and 10, the values of CSI varied from 1.1 to 1.4, indicating low severity, whereas sites 3-9 ranged between 1.5 and 1.96, revealing low to moderately severity. The TRI values increased from upstream to downstream. The values of TRI ranged from 6 to 10, with minimum and maximum values in sites 1 and 8, respectively. This is likely due to the effects of the concentration of Cu and Pb and their relevant TEL and PEL values. With the exception of sites 8, which was classified as having a moderate toxic risk, all sampling sites fell within in the low toxic risk level.

Fig 4. Spatial distributions of pollution indices a) MPI and MRI, b) mERM-Q and mPEL-Q, c) mHQ, and d) ECI, CSI, and TRI

3.4. Concentration of potentially toxic elements in *Typha latifolia L.*

Aquatic macrophytes have been shown to be effective for bioremediation of aquatic environments impacted by potentially toxic elements (Rana and Maiti, 2018). Accordingly, the phytoremediation potential of the indigenous aquatic macrophyte community was analyzed in this study. Descriptive statistics of potentially toxic elements in the tissues of *Typha latifolia L.* grown in the bank and floodplain of the Bahmanshir River are given in Table 2. Mean concentrations of As, Cd, Cr, Cu, Mn, Ni, Pb, and Zn were 1.77, 0.19, 10.9, 96.9, 123, 56.5, 38, and 117 mg/kg in roots, respectively, and 0.94, 0.04, 5.09, 30.5, 73.2, 7.77, 18.1, and 128 mg/kg in stems, respectively. Manganese and Zn exhibited the highest concentrations in roots and stems. The mean concentrations of As, Cd, Mn, and Zn for both root and stem were below the toxicity threshold in plant tissues. As and Cd are non-essential potentially toxic elements for plants with detrimental effects on nutrient uptake, photosynthesis system, root elongation, and oxidative stress, whereas Mn and Zn are required for activation of enzymes and resistance against stresses (Guo and Chi, 2014). However, high concentrations of these elements can lead to harmful effects. Maximum accumulations of Cd, Mn, and Zn in the roots were determined in the midstream samples, whereas concentration of As was higher in the upstream samples. Contrary to As, Cd, and Mn, the values of Zn in the roots in most of the sites were higher than those in the stem. This suggested that *Typha latifolia L.* translocated Zn from root to shoot effectively. The mean contents of root and stem Cr and Cu, and root Ni and Pb, exceeded the threshold level of toxicity. Chromium is considered to be a toxic element with high detrimental consequences on plants such as affecting protein formation and plant growth (Sudarshan *et al.* 2020). However, Ni is an essential element for plants in terms of urease activation (Van Der Ent *et al.* 2018). Regarding the trend of Ni concentrations in downstream direction, due to the high density urban areas and increasing discharge of municipal wastewater and urban runoff in midstream to downstream, the accessibility of root to Ni has increased which is led to increase the concentration of Ni in root samples. According to He *et al.* 2012, the presence of toxic elements such as Zn and Cu has directly adverse effects on the uptake of Ni to aboveground tissues due to the competitive nature. According to Table 2, the concentration of Cu in root samples increased considerably from upstream (36.6 mg/kg) to downstream (233 mg/kg). The increasing of Cu concentrations from site 1 to 10 together with the presence of Zn concentrations in root samples result in the reduction of the uptake capacity of Ni in stems in the downstream direction. Mean concentrations of Cr in the sediment were approximately ten-fold higher than those in the roots, suggesting low capacity for bioaccumulation. Due to its major role in photosynthesis, Cu is a necessary element in plants, but high quantity of Cu may pose adverse effects on the plant survival and production (Kumar *et al*. 2020b). Lead is also a toxic and non-essential metal for plant metabolism, even at very low concentrations. High concentrations of Cu and Pb were recorded in the roots of downstream *Typha latifolia L.*, suggesting that this macrophyte might be a good candidate for bioaccumulation of these elements.

Table 2. Potentially toxic element concentrations (mg/kg) in *Typha latifolia L.* tissues.

To find the relationship between the concentrations of potentially toxic elements in sediment and root samples, their spatial variations were plotted (Fig S2). Concentrations of sediment- and root-borne Cr, Cu, Mn, Pb, and Zn had the same trends. By contrast, there were no relationships between sediment and root As, Cd, and Ni concentrations. This may be due to the fact that these elements originated from non-uniform contamination sources. To evaluate this further, spatial variations in total element sediment and root concentrations were plotted (Fig. S3). Similar trends were observed, suggesting that the concentrations of potentially toxic elements in the roots were dependent on those in the sediments in which they grew.

3.5.Phytoremediation assessment of *Typha latifolia L.*

The phytoremediation capability of *Typha latifolia L.* was determined using the bioconcentration factor (BCF), translocation factor (TF), metal accumulation index (MAI), and comprehensive bioconcentration index (CBCI). Mean values of BCF and TF for individual toxic elements are depicted in Fig. 5a. The mean values of BCF in the macrophyte decreased in the order Pb (1.26) > Cd (1.12) > Zn (1.07) > Cu (1.04) > As (0.76) > Ni (0.67) > Mn (0.28) > Cr (0.09). Strong absorption (BCF > 1) was detected in the macrophytes for Pb, Cd, Zn, and Cu based on the classification reported by Nematollahi *et al.* (2020). The macrophytes showed intermediate absorption (0.1 < BCF < 1) for As, Ni, and Mn, whereas Cr, with a 0.01 < BCF < 0.1, was classified as having weak absorption. The results suggest that *Typha latifolia L.* may be a phytoaccumulator of Pb, Cd, Zn, and Cu (BCF > 1) in the study area, which is in agreement with the results reported by Sasmaz *et al*. (2008) and Klink (2017). Strong absorption has also been determined for *Typha latifolia L.* for Zn (Varun *et al.* 2011) and Cd/Cu (Rana and Maiti, 2018). The highest value of TF was calculated for Zn (1.11), suggesting high translocation Zn capability from root to stem for *Typha latifolia L.* The other elements exhibited TF < 1, indicating ineffective translocation. The lowest value of TF was recorded for Ni (0.19), similar to the result obtained by Azizi *et al*. (2020). With the exception of Zn, the results of TF demonstrated that *Typha latifolia L.* in the study area is considered as an excluder species with low capability for translocation. Klink *et al*. (2013) has shown that this macrophyte has a well-developed metal tolerance strategy with a high root retention capacity. According to Bonanno (2013), the values of potentially toxic elements in different parts of Typha species follow in the order of root > stem > leaf, revealing an ineffective system for transporting potentially toxic elements to aboveground parts.

The values of BCF and TF in each sampling site are shown in Fig.5b and 5c. They fell within BCF < 1 and TF < 1, indicating low ability of *Typha latifolia L.* to take up potentially toxic elements from sediment and mobilize them towards the stem. Arsenic, Cd, Cu, Ni, and Pb had BCF > 1 and TF < 1 in 30%, 40%, 60%, 20%, and 50% of the sampling sites, respectively, suggesting high potential of *Typha latifolia L.* for phytostabilization of these elements.

Considering the mean values of BCF and TF in toxic elements, *Typha latifolia L.* may be able to remediate Cd, Cu and Pb contamination by phytostabilization. Values of BCF > 1 and TF > 1 for Zn were found in 60% of the sampling sites, suggesting that *Typha latifolia L.* could be employed for phytoextraction of Zn. High bioaccumulation and translocation of Zn was also observed in the experimental study on *Typha latifolia L.* reported by Hejna *et al*. (2020), which aligns with the results of the present study.

Fig 5. a) Values of BCF and TF in *Typha latifolia L.* (The values above the dashed horizontal line indicate good phytostabilization or phytoextraction capability), b) Mixed scatter graph of BCF for As, Cd, Cr, and Cu, and c) Mixed scatter graph of BCF for Mn, Ni, Pb, and Zn.

Values of the metal accumulation index (MAI) and the comprehensive bioconcentration index (CBCI) for the present and previous studies were computed to evaluate the ability of macrophytes to uptake multiple toxic elements. In order to have unification in the elements and meaningful comparison with the results of previous studies, As was not considered in the calculation of MAI. The calculated value for MAI of 4.82 for this study was observed to be 56% and 74% higher than those that calculated in Sasmaz *et al*. (2008) and Klink *et al*. (2013) (MAI = 3.08 and 2.76), respectively. However, the values of MAI values obtained in this study were 70% less than those in the Bonanno *et al*. (2018) study (MAI = 8.21). The results of the present study and those of Varun *et al.* (2011) with (MAI = 4.51) are similar. Thus, *Typha latifolia L.* showed an acceptable performance in the accumulation of potentially toxic elements in the study area. The mean value of CBCI in the present study (0.46) was greater than the value obtained by Varun *et al*. (2011) (0.42) and Sasmaz *et al*. (2008) (0.38). The high CBCI in the present study reflects the multi-element accumulation ability of *Typha latifolia L.* in the Bahmanshir River. The spatial distribution of CBCI is depicted using a radar graph in Fig. S4. High values of the CBCI were detected in site 10 and 9 (CBCI = 0.63), and in site 1 (CBCI = 0.51). All of the results suggest that *Typha latifolia L.* could be employed as a phytoremediation tool for removing potentially toxic elements from surface sediments in the Bahmanshir River.

4. Conclusion

Contamination of surface sediment of the Bahmanshir River in south-west Iran, and the phytoremediation capability of *Typha latifolia L.* grown in this sediment, were investigated. Mean concentrations of As, Mn, and Ni in the river sediment were less than their respective local background concentrations, while mean concentrations of Cd, Cr, Cu, Pb, and Zn exceeded their respective local background concentrations. High concentrations of Cd, Cr, Ni, and Zn in the middle part of the river were ascribed to municipal wastewater discharge and vehicular pollution. Concentrations of Cu and Pb increased downstream due to oil refinery and petrochemical emissions, and agricultural pollution. Average values of *EF* indicated moderate enrichment for Cu and Pb and deficiency to minimal enrichment for the other elements. The *MPI* index revealed moderate to heavy pollution from upstream to downstream. Overall, the river had low ecological risk, with the results of the pollution assessment with the sediment quality guidelines demonstrating a 21% probability of toxicity. In all sampling sites, considerable severity of contamination was observed for Cr and Ni using the *mHQ* index. Slight to moderate contamination, low to moderate severity of contamination, and low toxic risk level were detected for most sampling sites based on the *ECI*, *CSI*, and *TRI* indices, respectively. In terms of phytoremediation capability, BCF >1 and TF <1 were calculated for Cd, Cu and Pb in 40%, 60%, and 50% of the sampling sites, indicating phytostabilization ability. According to the results, *Typha latifolia L.* can act well as a phytoextractor of Zn. Values of CBCI were highest downstream, suggesting this area had the highest potential for bioaccumulation of toxic elements. Overall, the results of the study suggest that *Typha latifolia L.* is a good candidate for remediation of Cd-, Cu-, Pb- and Zn-contaminated river sediment in the Bahmanshir River, and may be useful in other similarly-affected areas with similar climatic conditions.

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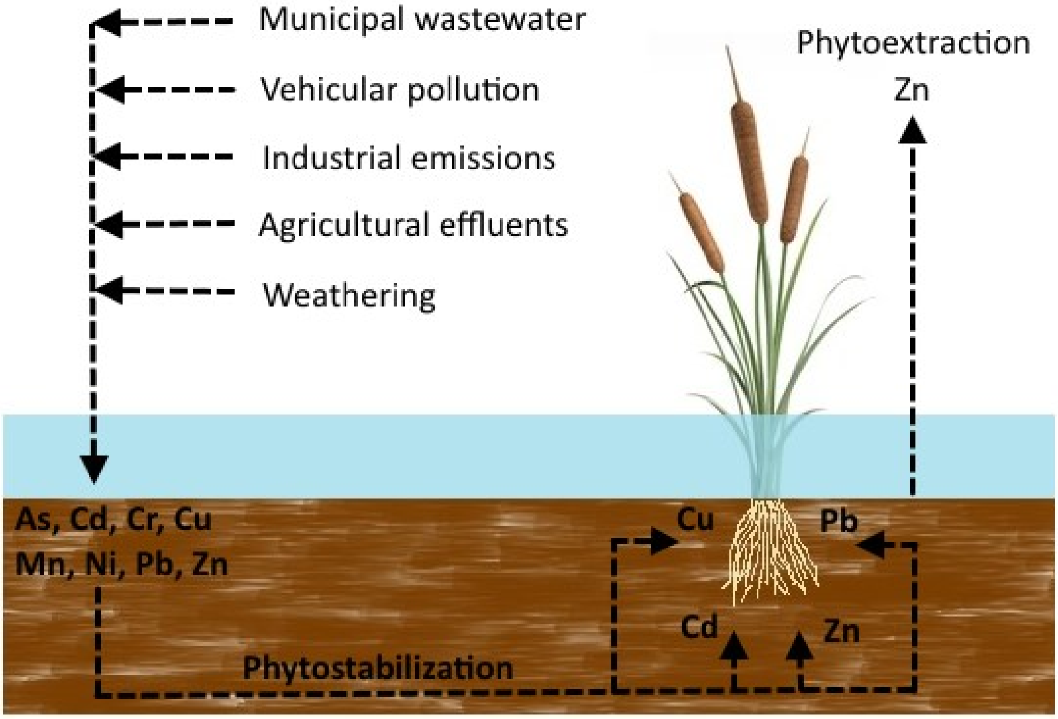
Highlights:

- Mean concentrations of Cd, Cr, Cu, Pb, and Zn exceeded the local background concentration.
- Moderated level of enrichment was observed for Cu and Pb.
- Index-based approach for the overall assessment of the sediment quality indicated moderate contamination and toxicity.
- Municipal wastewater and vehicular pollution were found as the main sources of pollution.
- *Typha latifolia L.* represented phytoremediation capability for Cd, Cu, Pb, and Zn


Municipal wastewater
Vehicular pollution
Industrial emissions
Agricultural effluents
Weathering
Phytoextraction
Zn
As, Cd, Cr, Cu
Mn, Ni, Pb, Zn
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Cd
Zn
Phytostabilization

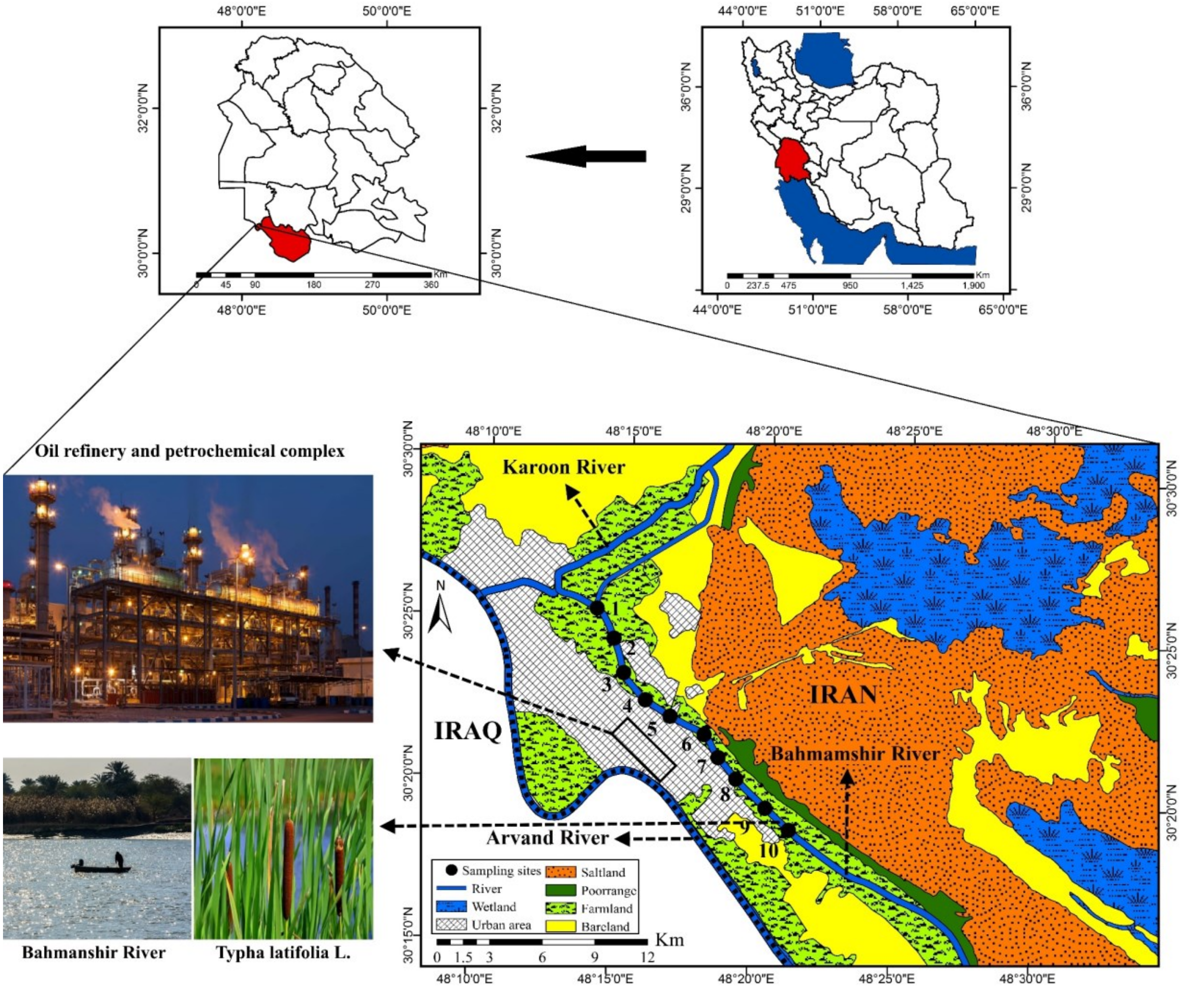


Fig 1. Location of the Bahmanshir River and sampling points (Photos from www.isna.ir).

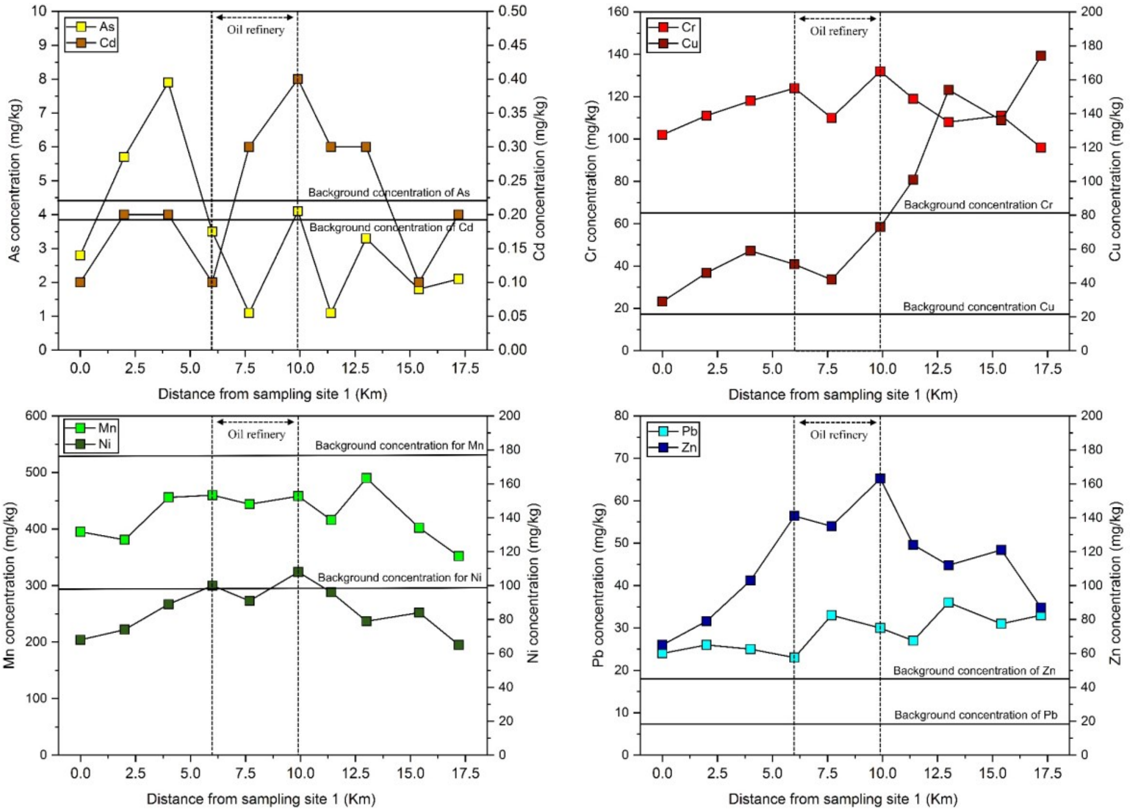
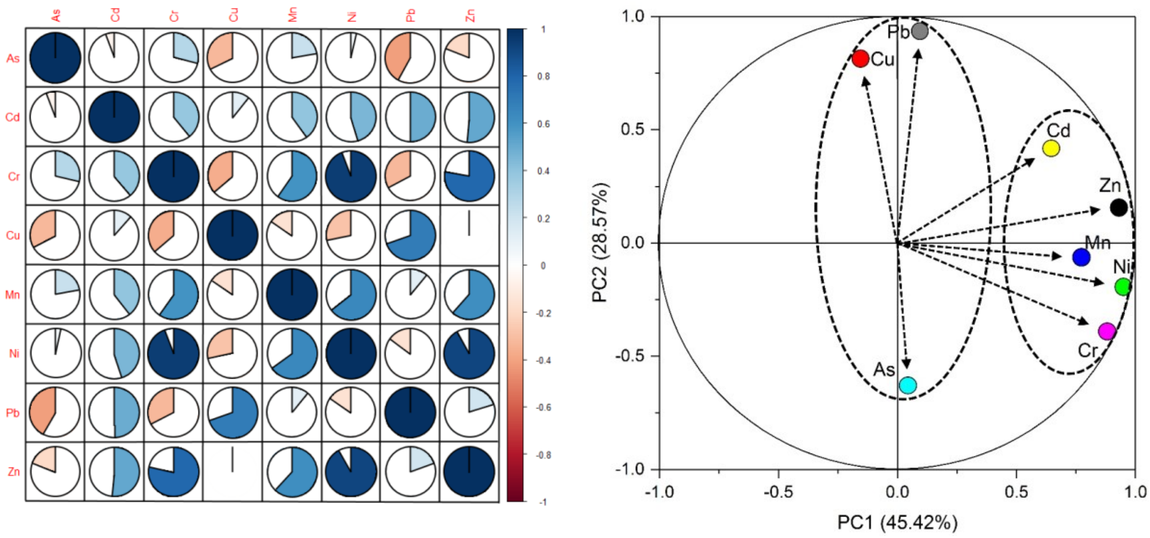
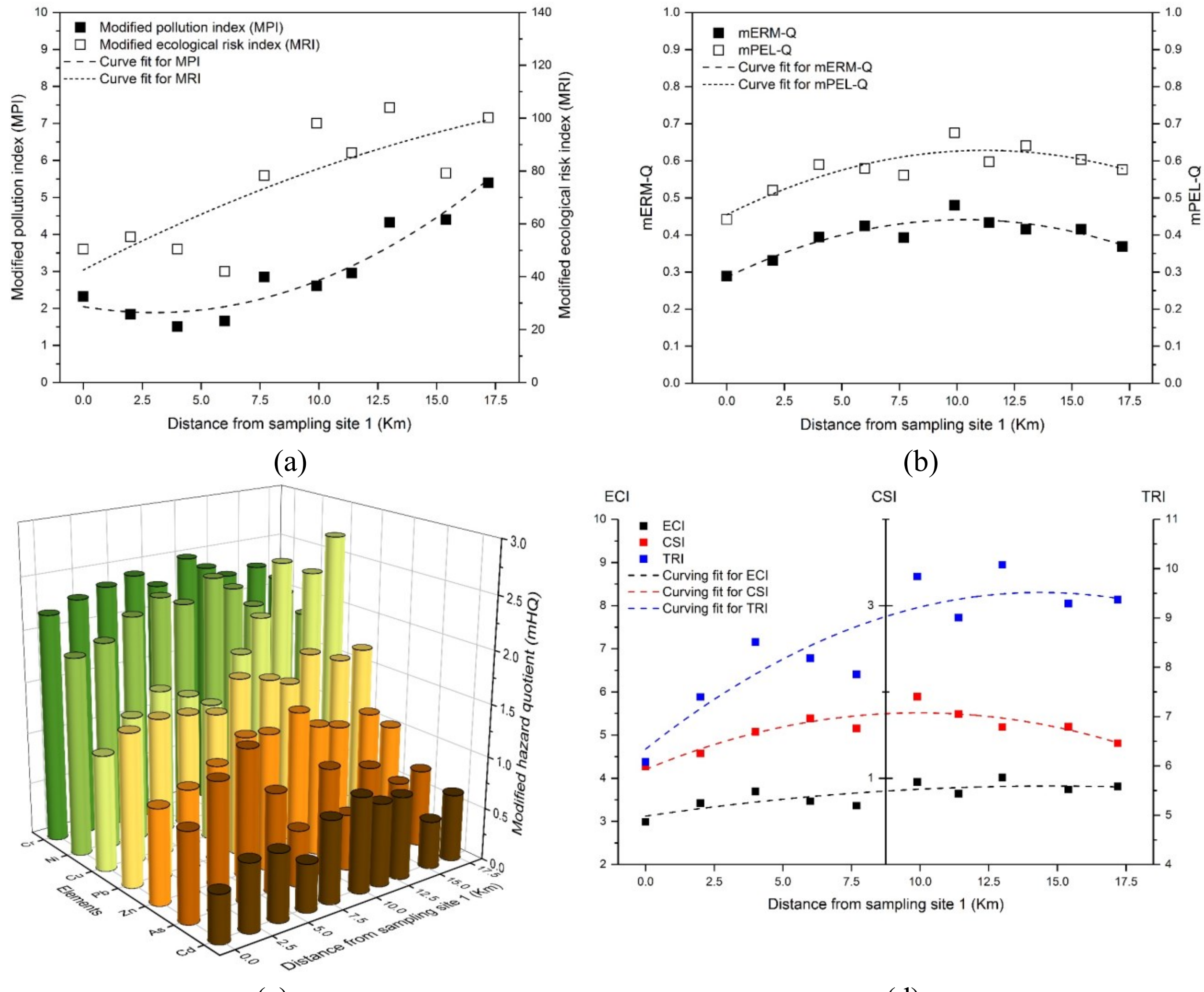


Fig 2. Spatial distribution of potentially toxic elements in the surface sediments



(a) (b)

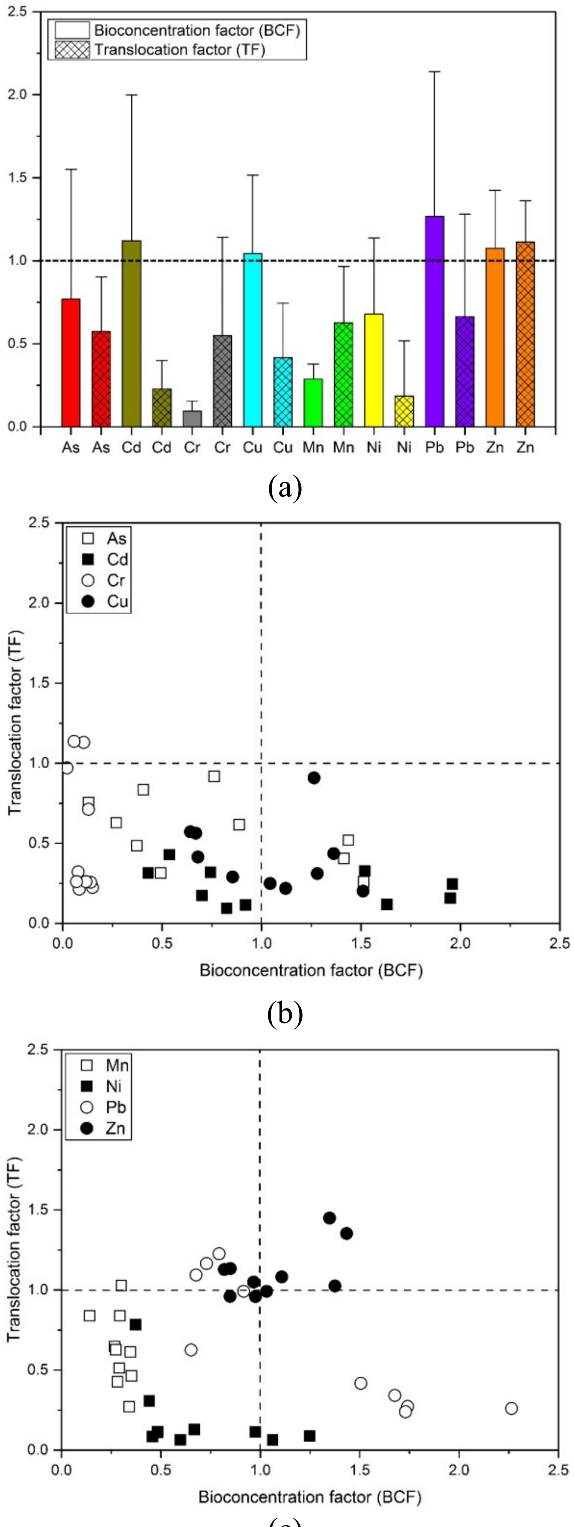
Fig 3. a) Correlation plot of the potentially toxic elements, and b) Loading factors with vectors of PCA for the surface sediment of the Bahmanshir River



(a) (b)

(c) (d)

Fig 4. The spatial distribution of pollution indices a) MPI and MRI, b) mERM-Q and mPEL-Q, c) mHQ, and d) ECI, CSI, and TRI



(a)

(b)

(c)

Fig 5. a) Values of BCF and TF in Typha latifolia L. (The values above the dashed horizontal line indicate good phytostabilization or phytoextraction capability), b) Mixed scatter graph of BCF for As, Cd, Cr, and Cu, and c) Mixed scatter graph of BCF for Mn, Ni, Pb, and Zn.

Table 1. Descriptive statistics of potentially toxic elements in the surface sediments of the Bahmanshir River

Elements	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Mean (mg/kg)	3.34	0.22	113	86.5	425	85.4	28.8	113
SD (mg/kg)	2.1	0.1	10.5	51.6	43	14	4.4	30.1
Minimum (mg/kg)	1.1	0.1	96	29	352	65	23	65
Maximum (mg/kg)	7.9	0.4	132	174	490	108	36	163
CV (%)	64	47	9	60	10	16	15	27
Upper continental crust	5.7 [a]	0.06 [a]	73 [a]	27 [a]	600 [b]	34 [a]	20 [b]	75 [a]
Local background [c]	4.4	0.18	64	21.5	532	99	7.1	45

[a] Hu and Gao (2008)

[b] Taylor and McLennan (1995)

[c] Mokhtarzadeh et al. (2020)

Table 2. Potentially toxic elements concentrations (mg/kg) in *Typha latifolia L.* tissues

	Sites	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Root	1	3.96	0.19	10.7	36.6	56	25.3	22	93.2
	2	2.12	0.18	14.3	62.6	132	32.6	19	106
	3	1.03	0.16	6.74	40.1	122	40.7	17	142
	4	1.72	0.15	10.3	34.1	162	48.2	18.2	136
	5	1.66	0.16	16.5	26.9	151	54.4	21.5	132
	6	1.10	0.17	18.5	62.3	129	52.2	52.2	138
	7	1.58	0.22	9.2	105	121	64.2	40.6	105
	8	1.34	0.21	12.5	173	134	77	62.2	124
	9	1.59	0.19	7.74	205	118	89.2	52	99.1
	10	1.60	0.32	2.07	223	106	81.1	74.7	89.7
	Mean	1.77	0.19	10.8	96.9	123	56.5	38	117
Stem	1	1.60	0.03	12.1	33.2	47	19.8	21.8	126
	2	1.03	0.02	10.2	27.3	81	10	22.1	154
	3	0.78	0.01	7.66	16.6	79	3.42	18.5	145
	4	0.54	0.04	2.19	19.2	75	5.36	22.3	143
	5	0.43	0.06	3.70	15.4	41	3.49	13.4	126
	6	0.69	0.05	4.75	18.1	55	5.96	14.2	133
	7	0.82	0.07	2.96	26.2	62	8.24	17	119
	8	1.12	0.03	3.28	37.7	84	8.71	15	134
	9	0.98	0.04	2.01	41.4	99	5.65	17.7	112
	10	1.47	0.03	0.79	69.3	109	7.09	19.4	89.1
	Mean	0.94	0.04	4.97	30.5	73.2	7.77	18.1	128
Toxicity threshold [a]		20	5-10	1-2	15-20	170-2000	20-30	10-20	150-200

[a] Vamerali *et al*. (2010)

Supplementary material

Table S1. Limit of determinations (LOD) for the elements in sediment and plant (mg/kg)

Elements	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Sediment	0.1	0.1	1	1	5	1	1	1
Plant	0.01	0.01	0.01	1	1	0.01	0.01	1

Table S2. Classification and information for sediment pollution indices

Index	Grading	Status	References
EF	< 2	Deficiency to minimal enrichment	Sutherland (2000)
	2 ~ 5	Moderate enrichment	
	5 ~ 20	Significant enrichment	
	20 ~ 40	Very high enrichment	
	> 40	Extremely high enrichment	
MPI	< 1	Unpolluted	Brady *et al.* (2015)
	1 ~ 2	Slightly Polluted	
	2 ~ 3	Moderately polluted	
	3 ~ 5	Moderately-heavily polluted	
	5 ~ 10	Heavily polluted	
	> 10	Severely polluted	
MRI	< 150	Low risk	Duodu *et al.* (2016)
	150 ~ 300	Moderate risk	
	300 ~ 600	Considerable risk	
	> 600	Very high risk	
mERM-Q	< 0.1	Low priority (9% probability)	Long *et al.* (2000)
	0.1 ~ 0.5	Medium-low priority (21% probability)	
	0.5 ~ 1.5	High-medium priority (49% probability)	
	> 1.5	High priority (76% probability)	
mPEL-Q	< 0.1	Low degree of contamination (8% probability)	Long *et al.* (2006)
	0.11 ~ 1.5	Medium-low degree of contamination (21% probability)	
	1.51 ~ 2.3	High-medium degree of contamination (49% probability)	
	> 2.3	High degree of contamination (73% probability)	
mQH	< 0.5	Nil to very low severity of contamination	Benson *et al.* (2018)
	0.5 ~ 1	Very low severity of contamination	
	1 ~ 1.5	Low severity of contamination	
	1.5 ~ 2	Moderate severity of contamination	
	2 ~ 2.5	Considerable severity of contamination	
	2.5 ~ 3	High severity of contamination	
	3 ~ 3.5	Very high severity of contamination	
	> 3.5	Extreme severity of contamination	
ECI	< 2	Uncontaminated	Benson *et al.* (2018)
	2 ~ 3	Uncontaminated to slightly contaminated	
	3 ~ 4	Slightly to moderately contaminated	
	4 ~ 5	Moderately to considerably contaminated	
	5 ~ 6	Considerably to highly contaminated	
	6 ~ 7	Highly contaminated	
	> 7	Extremely contaminated	
CSI	< 0.5	Uncontaminated	Pejman *et al.* (2015)
	0.5 ~ 1	Very low severity	
	1 ~ 1.5	Low severity	
	1.5 ~ 2	Low to moderate severity	
	2 ~ 2.5	Moderate Severity	
	2.5 ~ 3	Moderate to high severity	
	3 ~ 4	High severity	
	4 ~ 5	Very high severity	
	> 5	Ultra-high severity	
TRI	< 5	no toxic risk	Zhang *et al.* (2016)
	5 ~ 10	low toxic risk	
	10 ~ 15	Moderate toxic risk	
	15 ~ 20	considerable toxic risk	
	> 20	Very high toxic risk	

Table S3. Values of sediment quality guidelines (SQGs) for selected potentially toxic elements

Elements	As	Cd	Cr	Cu	Mn	Ni	Pb	Zn
ERL[a]	8.2	1.2	81	34	–	20.9	46.7	150
ERM[a]	70	9.6	370	270	–	51.6	218	410
TEL[b]	5.9	0.596	37.3	35.7	–	35	18	123
PEL[b]	17	3.53	90	197	–	91.3	36	315
SEL[b]	33	10	110	110	–	75	250	820

[a] Long *et al.* 1995

[b] MacDonald *et al.* 2000

Table S4. Principal component loadings of the toxic elements

	PC1	PC2
As	0.044	– 0.629
Cd	0.647	0.418
Cr	0.881	– 0.390
Cu	– 0.155	0.813
Mn	0.772	– 0.063
Ni	0.949	– 0.194
Pb	0.093	0.936
Zn	0.931	0.156
Eigenvalue	3.63	2.28
% Total variance	45.42	28.57
Cumulative %	45.42	73.99

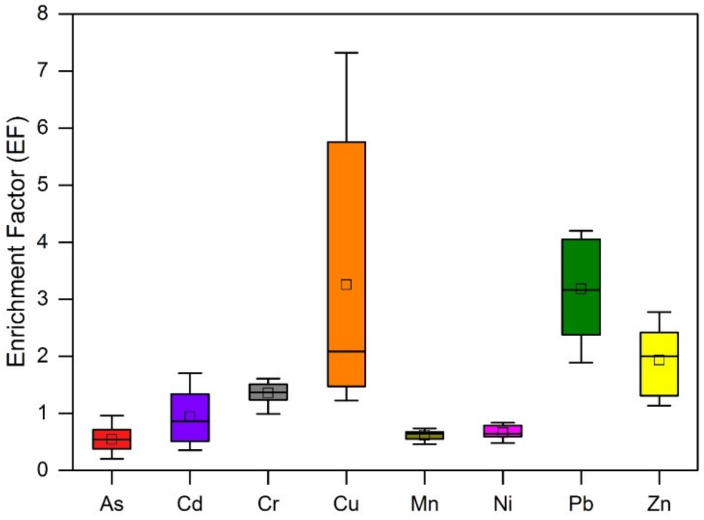


Fig S1. Box and whisker plots of EF in the surface sediments

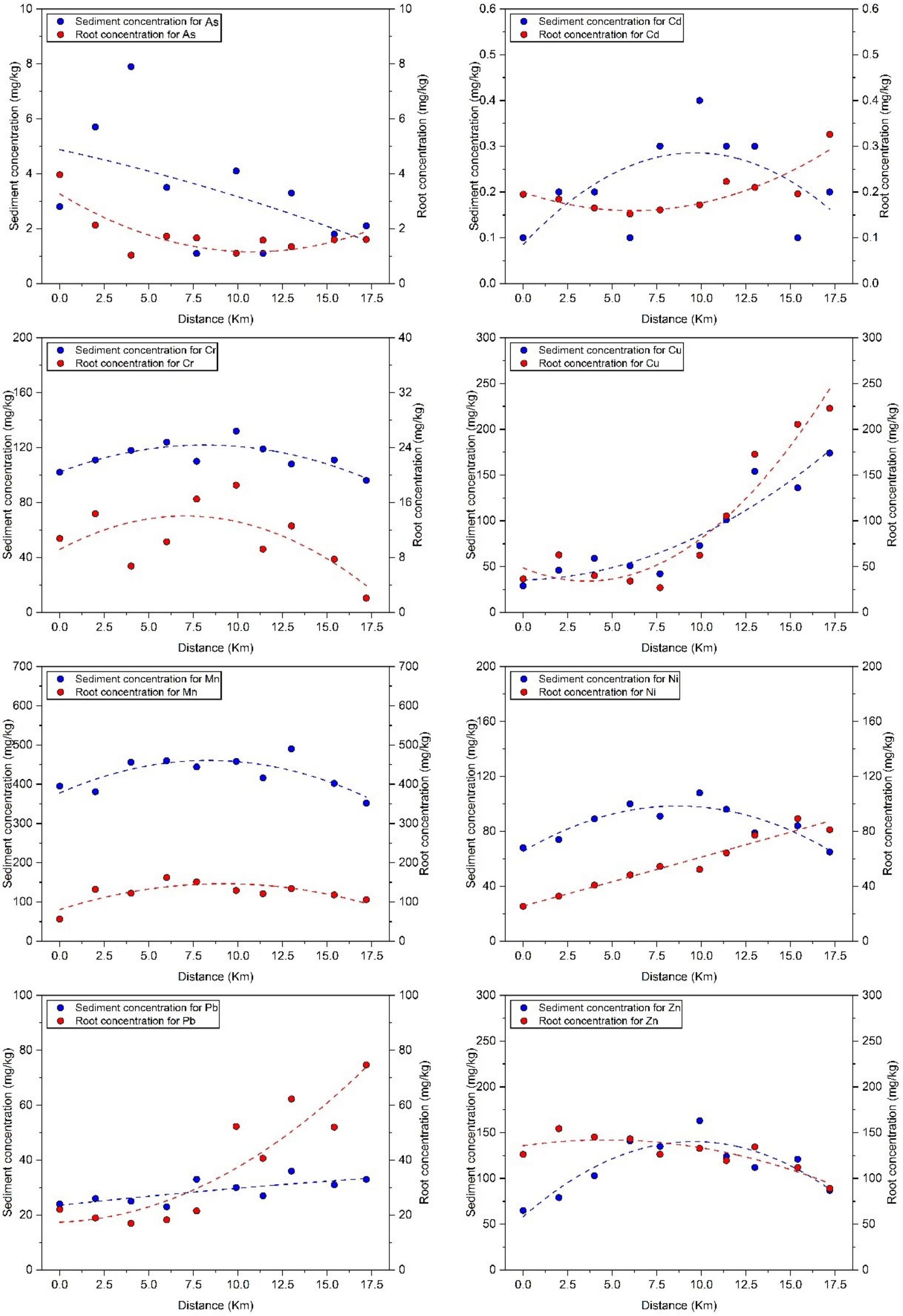


Fig S2. Spatial distribution of the elements concentrations in sediment and root.

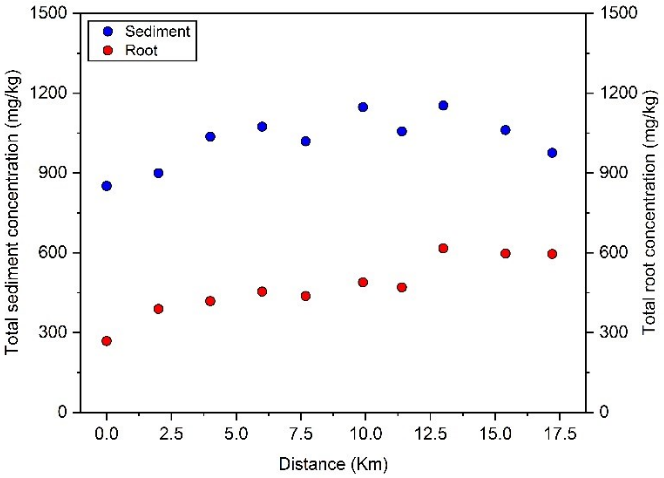


Fig S3. Spatial distribution of the total element concentrations in sediment and root.

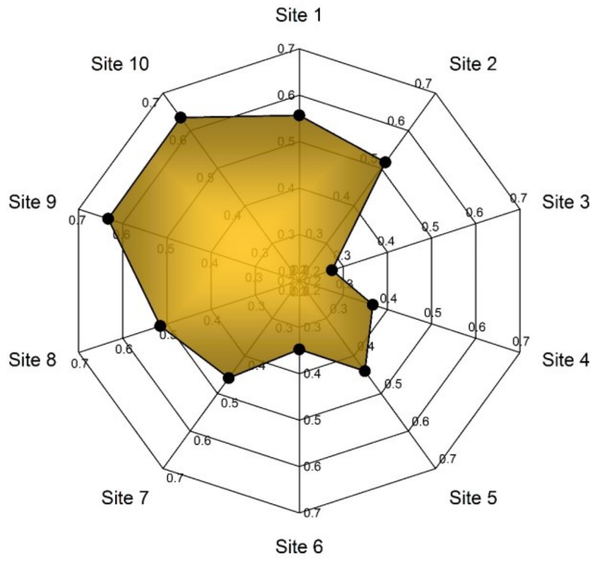


Fig S4. The spatial distribution of CBCI for *Typha latifolia L.*