




## Research Article

# Geochemical variability in the soils of Bangladesh as affected by sources of irrigation water and inundation land types



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Received: 19 September 2020 / Accepted: 21 January 2021 / Published online: 2 February 2021

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## Abstract

Paddy soils in Bangladesh experience extensive irrigation with groundwater and surface water, both having variable geochemical constituents. The soils also have topological variations across the landscape. To understand the geochemical variability in the soils as affected by the different sources of irrigation water and the topographical variability, cultivation zones of paddy soils irrigated with both groundwater ( $n = 904$ ) and surface water ( $n = 281$ ) across Bangladesh were sampled and analyzed for a suit of seventeen geochemical elements. This study also assessed the extent and distribution of arsenic and the other geochemical elements in the paddy soils ( $n = 1209$ ) as well as in a set of neighboring non-paddy soils ( $n = 235$ ) within the different inundation land types (highland, medium highland-1, medium highland-2, medium lowland, lowland and very lowland) of Bangladesh. The mean concentrations of aluminum (26,000 mg/kg), cobalt (13 mg/kg), copper (32 mg/kg), iron (28,250 mg/kg), lead (18 mg/kg), magnesium (8050 mg/kg), molybdenum (1.02 mg/kg), nickel (41 mg/kg), potassium (4870 mg/kg), sodium (750 mg/kg) and zinc (70 mg/kg) in the surface water-irrigated paddy soils were found to be significantly ( $0.001 \geq p \leq 0.05$ ) higher compared to the concentrations in the soils irrigated with groundwater (23,400; 12; 28; 25,650; 17; 7000; 0.96; 36; 4350; 600; and 62 mg/kg, respectively). Therefore, surface water used for paddy irrigation could increase the inputs of a number of toxic elements in the paddy soils having potential risk of crop contamination. Arsenic in the paddy and non-paddy soils varied significantly ( $F = 24.74$ ,  $p < 0.001$  and  $F = 3.42$ ,  $p < 0.01$ , respectively) within the inundation land types, the very lowland (9.95 and 6.72 mg/kg, respectively) and lowland (8.33 and 5.20 mg/kg, respectively) having the highest mean arsenic concentrations and the medium highland-1 (5.27 and 5.17 mg/kg, respectively) having the lowest. The concentrations of the other geochemical elements analyzed were also observed to be higher, in general, in the soils of very lowland and lowland. Since the low-level lands are predominantly used for paddy cultivation, higher concentrations of various toxic elements, particularly arsenic, in such soils pose an increased risk of rice toxicity in Bangladesh. The results of this study present an inimitable geochemical database for the surface soils across Bangladesh which can be used in any future studies on the geomorphologically variable agricultural and non-agricultural Bangladeshi soils, providing a basis for environmental pollution assessment and sustainable mitigation approaches.

**Keywords** Arsenic · Heavy metal · Paddy soil · Irrigation water · Inundation land types

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s42452-021-04269-1>.

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SN Applied Sciences (2021) 3:256 | <https://doi.org/10.1007/s42452-021-04269-1>

## 1 Introduction

Agriculture is a top priority sector in Bangladesh playing a vital role in the economic growth of the country [1]. Bangladesh ranks 4th in the world in terms of rice production, rice consumption and area under rice production [2]. Over 70 percent of the country's land area is currently under agricultural practices, of which 75 percent is under rice cultivation [2, 3]. About 40 percent of the net cultivable area is under irrigation and 60 percent of the total irrigation requirement is met by the groundwater, which in many places has elevated concentrations of arsenic [4]. The extensive use of the arsenic contaminated groundwater for paddy irrigation, particularly in the dry season, is potentially increasing arsenic load in the soils [4–7]. Thus, arsenic contamination of agricultural soils has become a major environmental problem in Bangladesh [8]. Despite the groundwater input of arsenic in the paddy field soils, other geochemical elements like, aluminum, calcium, iron, lead, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, sodium and zinc are also added to the soils through groundwater irrigation, although the magnitude and spatial distribution patterns are variable [9, 10]. Different mobilization processes in the aquifer sediments have been reported to induce different concentrations of elements in the groundwater of alluvial floodplains in Bangladesh and elsewhere [11, 12].

Along with the groundwater, surface water is also used for paddy irrigation in many areas of Bangladesh where abundant [8, 13]. Although the baseline concentrations of arsenic in surface water have been reported to be low, for example, river water contains arsenic in the range of 0.1–2 µg/l which is three orders of magnitude lower than arsenic rich groundwater [14], the surface water in Bangladesh is at risk of contamination with a variety of toxic heavy metals [4, 15–17]. Elevated levels of toxic elements in surface water can come from a range of sources, such as from the discharge of untreated or partially treated effluents from industries, indiscriminate use of toxic metal containing fertilizers and pesticides in agricultural lands and other anthropogenic activities [4, 16, 18, 19]. Thus, surface water can contribute to the inputs of toxic heavy metals into the irrigated paddies. This ultimately warrants further concern with respect to the toxic metal contamination of the agricultural lands followed by accumulation into crops. These can potentially affect the national food security as well as can pose a threat to the human health in Bangladesh. However, total metal concentrations in agricultural soils also reflect the soil's geological origin and mineral weathering besides the inputs from anthropogenic activities [12, 20–22].

The soils of Bangladesh are naturally variable in their geochemical fingerprints [7]. Bangladesh has a complex geological and geomorphological setting with an active sedimentary depositional history [8, 9]. Bangladesh has three major geomorphological units—hill, terrace and floodplain areas [4, 23]. The hills and the uplifted terraces are of Pleistocene age and the floodplains are of Holocene age. To understand and characterize the landforms and landscapes of the geomorphological areas, Bangladesh is divided into 20 main physiographic regions based on the parent material in which individual soil types were formed and the landscape on which the soils were developed [24]. These physiographical units are also characterized by land topography and age of the land formation through sediment deposition over time [23]. In Bangladesh, the topographic levels of land in relation to the normal depth and duration of seasonal flooding, known as the inundation/ depth-of-flooding land types, have been classified into highland (above flood level), medium highland-1 (normal flooding depth is up to 30 cm), medium highland-2 (normal flooding depth is 30–90 cm), medium lowland (normal flooding depth is 90–180 cm), lowland (normal flooding depth is 180–300 cm), very lowland (normal flooding depth is over 300 cm) and bottomland (depression sites which remain wet throughout the year) [24]. The diversity and complexity of soils in Bangladesh are influenced by variations in the flooding depth within the different inundation land types [25, 26].

The variability of arsenic in the paddy soils of Bangladesh is inherently high [7, 27, 28]. The dynamics of arsenic in soil vary due to variations in indigenous soil properties, particularly the ionic constituents of iron, manganese, aluminum, calcium, magnesium, phosphate, sulfate and carbonate, and pH, redox potential and texture of soil as well as the microbially mediated biogeochemical interactions that control the biogeochemical cycling of arsenic in soils [7, 29–34]. Temporal variability and spatial heterogeneity (both lateral and vertical) in the distribution of arsenic in the paddy soils have also been reported [35, 36]. Arsenic concentration in the topsoil increases during the irrigation period and remobilizes and decreases over the monsoon season particularly in the deeply flooded soils through monsoon flooding and the floodwater flows into rivers [35, 37–39]. However, as the paddy soils have, in general, a higher arsenic concentration compared to the adjacent non-paddy soils, the process of loss of arsenic from the soils by monsoonal floods is not sufficient to reduce the arsenic concentration in the paddy soils back to the non-paddy soil background concentration [7]. Thus, the accumulation and release of arsenic in soils vary within the toposequence of a landscape due to variations in relief. There is very limited data available to compare

the differences in arsenic concentrations at or within all the inundation land types in Bangladesh.

Enrichment and variabilities of a range of geochemical elements have been found in the geomorphologically different soils of Bangladesh, which may perhaps be explained by the differences in sedimentary depositional environments acting across the landscape of the country [7]. The changes in the river courses over time altered the regional sediment depositional patterns. It also reformed the regional topological features, drainage conditions as well as soil types [8]. The complex river systems in the country actively rework the sediment deposition and mobilization patterns that give rise to the variability in the indigenous soils [40–42]. The newer sediments re-deposit onto the less- or un-weathered older sediments as well as they also become mixed together. Thus, it alters the exposed surface soil sediments through lensing of the sediments redeposited and remobilized that may cause the variability in the soil sediments [43]. The complex interactions between soil properties, climate, agricultural management practices and land topographic variations in the paddy soil environment in Bangladesh can also enhance such variability in the inherent soil geochemical relationships [44].

In the present study, we examined the extent and distribution of arsenic and a range of other geochemical elements within the different inundation land types across Bangladesh as well as the extent and distribution of the geochemical elements in paddy soils irrigated with groundwater and surface water. Cultivation zones of paddy soils irrigated with both groundwater ( $n=904$ ) and surface water ( $n=281$ ) across Bangladesh, from latitude  $22^{\circ} 06'$  to  $24^{\circ} 53'$  and longitude  $88^{\circ} 20'$  to  $90^{\circ} 59'$  were sampled and analyzed for arsenic and a suite of 16 other elements: aluminum, calcium, cadmium, cobalt, chromium, copper, iron, lead, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, sodium and zinc. The paddy soils along with a subset of non-irrigated non-paddy soils ( $n=235$ ) were categorized according to the 6 inundation land types of Bangladesh: highland, medium highland-1, medium highland-2, medium lowland, lowland and very lowland. The data were used to determine whether the sources of irrigation water impact on the concentrations of the geochemical elements in paddy soils, and to assess the spatial heterogeneity of the geochemical constituents in the soils, both paddy and non-paddy, within the inundation land types. By examining the concentrations of arsenic and other geochemical elements in the soils, we aimed to understand the impacts that paddy irrigation water and inundation land types have on soil elemental concentrations at a landscape scale. This study presents, so far, the largest geochemical database of Bangladeshi soils. It needs to be noted that the data presented here

were previously published in Chowdhury et al. [7], where the data were presented and discussed in relation to arsenic and the different physiographic regions of Bangladesh rather than inundation land types as here. While topology of the landscape is an important factor particularly considering the geochemical variability in an active sedimentary depositional environment like in Bangladesh, this further analysis adds additional insight into the elemental distribution in agricultural and non-agricultural soils as affected by the topographical variations across the landscape of the country.

## 2 Materials and methods

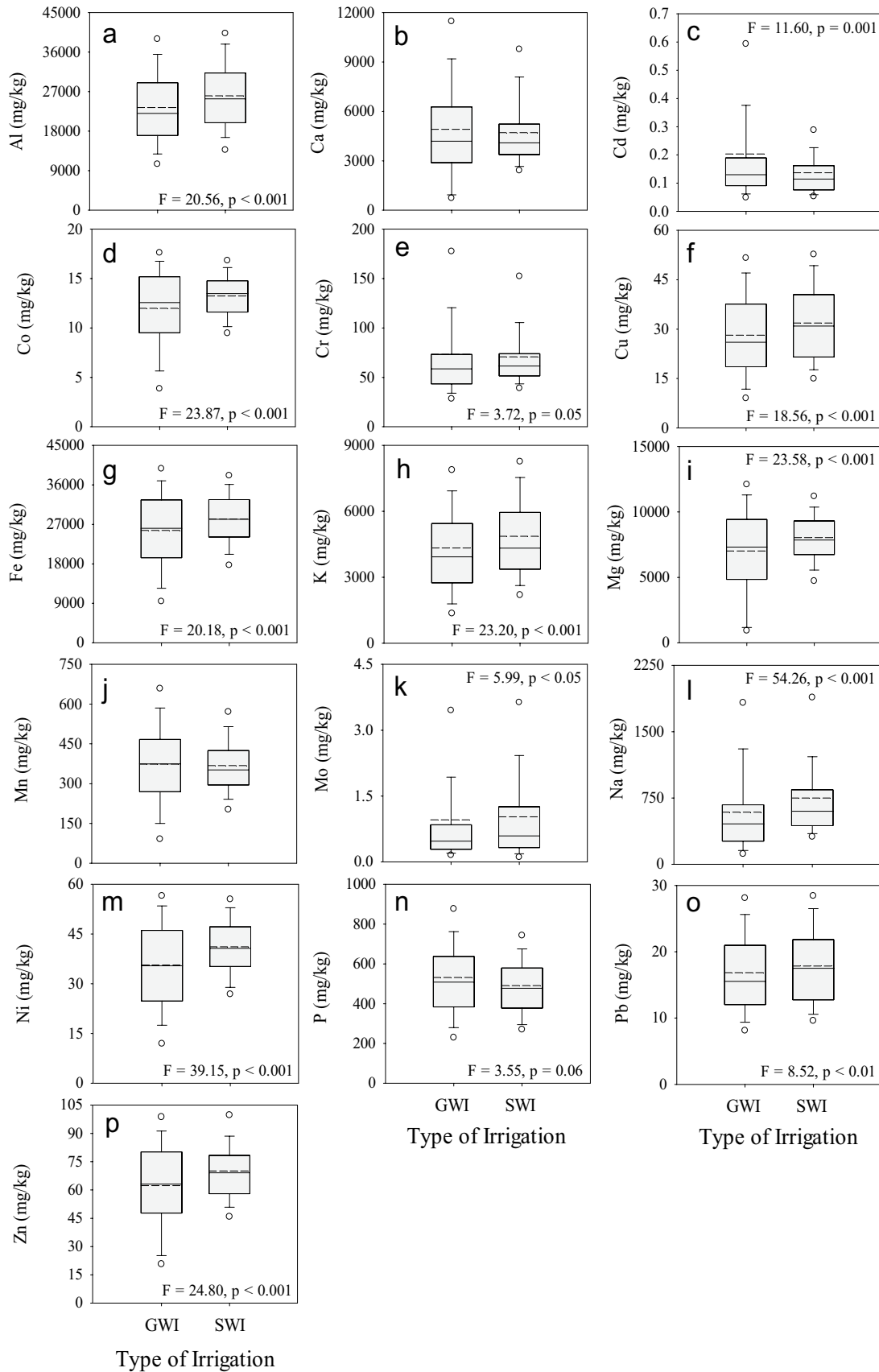
### 2.1 Collection of soil samples

A total of 1444 soil samples (topsoil, 0–15 cm from the surface) from paddy fields ( $n=1209$ ) and neighboring non-paddy areas ( $n=235$ ) were collected from 57 sub-districts (upazilas) of 17 districts within the Holocene floodplains and Pleistocene terraces of Bangladesh as described in Chowdhury et al. [7]. Non-paddy soils were defined as the soils where paddy cultivation and groundwater irrigation had not been practiced within known memory of the farmers. The source of irrigation water for the paddy soils was recorded (groundwater,  $n=904$ ; surface water,  $n=281$ ; both,  $n=24$ ). Only the soils that had a non-mixed irrigation source were used for analyzing the impact of irrigation type on soil geochemistry.

The collected soils were categorized into six inundation land types of Bangladesh [24], using the inundation land-type map sourced from Bangladesh Agricultural Research Council (BARC): highland, HL ( $n=258$  paddy and 57 non-paddy soils); medium highland-1, MHL-1 ( $n=62$  paddy and 10 non-paddy soils); medium highland-2, MHL-2 ( $n=226$  paddy and 55 non-paddy soils); medium lowland, MLL ( $n=230$  paddy and 37 non-paddy soils); lowland, LL ( $n=394$  paddy and 69 non-paddy soils); and very lowland, VLL ( $n=39$  paddy and 7 non-paddy soils) (Fig. S1).

### 2.2 Sample processing and chemical analysis

The samples used in this study had previously been analyzed for total arsenic and a set of other geochemical elements. Sample preparation and processing can be found in Chowdhury et al. [7]. The ICP-MS (Agilent Technologies 7500c, Japan) was used to determine the total concentrations of arsenic, cadmium, cobalt, copper, chromium, lead, manganese, molybdenum, nickel, phosphorus and zinc in the soil digests and the MPAES (Agilent Technologies 4100 Series, USA) was used to determine the total concentrations of aluminum, calcium, iron, magnesium, potassium



**Fig. 1** Box and whisker plots showing the concentrations of different elements in paddy soils irrigated with groundwater and surface water. GWI=groundwater irrigation,  $n=904$  and SWI= surface water irrigation,  $n=281$ . The boxplots indicate the lower and upper quartile (box), the median (solid line), the mean (dash line), the 10th and 90th percentiles (whiskers) and the 5th and 95th percentiles (circles). The  $F$ -value and  $p$  value are from one-way analysis of variance (ANOVA) test

and sodium in the soil digests. In each batch of digestion, 10% of the total number of samples were selected randomly for duplicate analysis ( $n=172$ ). Every batch of samples consisted of 33 randomly selected soil samples, 4 duplicates, 1 blank and 1 soil CRM (certified reference material) (NCS ZC 73007, China National Analysis Center for Iron and Steel), which were randomized prior to chemical analysis.

### 2.3 Statistical analysis

All statistical analyses were performed using the statistical software Minitab v.19 (State College PA) and SigmaPlot v.14 (Systat Software Inc., CA). The data were checked for normality and were transformed prior to statistical analysis where appropriate.

## 3 Results and discussion

### 3.1 Extent and variability of the geochemical elements in paddy soils irrigated with groundwater and surface water

The concentrations of the elements in the paddy and non-paddy soils analyzed are presented in Table S1. The individual soil maps showing the geographical distribution of the element concentrations in the non-paddy and paddy soils are presented in Figs. S2–S33. Compared to the soils irrigated with groundwater, the surface water-irrigated paddy soils had higher concentrations of aluminum, cobalt, copper, iron, potassium, magnesium, molybdenum, sodium, nickel, lead and zinc (Fig. 1). On the other hand, the groundwater-irrigated paddy soils were found to have higher concentrations of cadmium, chromium and manganese compared to the elements in the surface water-irrigated soils (Fig. 1). These elemental concentrations indicated that paddy soils in Bangladesh contained high levels of a number of heavy metals, exceeding the typical concentrations of the elements in soils [45, 46] as well as the concentrations reported for some agricultural soils of Bangladesh in previous studies [47–49]. The concentrations of the elements, except calcium, manganese and phosphorus, in the paddy soils irrigated with groundwater varied significantly ( $0.001 \geq p \leq 0.05$ ) from

the concentrations of the elements in the soils irrigated with surface waters (Fig. 1). Calcium (in the form of gypsum,  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and phosphorus (mainly as triple super phosphate, TSP) fertilizers are applied to the agricultural soils and the elements are amply present in both groundwater and surface water [10]. A wide range of manganese concentrations were found both in the groundwater- and surface water-irrigated soils, a number of soils (21%,  $n=188$  and 13%,  $n=37$  of the groundwater- and surface water-irrigated soils, respectively) having concentrations exceeding the world-soil average concentration of 488 mg/kg [46]. High manganese concentrations (up to 618 mg/kg) in some agricultural soils of Bangladesh have previously been reported [48, 49]. High concentrations of manganese in the groundwater of Bangladesh have also been reported in BGS and DPHE [9] and Hasan and Ali [50] indicating geogenic abundance of manganese in Bangladesh sedimentary environment.

While the average concentrations of cadmium in uncontaminated soils are less than 1 mg/kg [46], the concentrations of cadmium were as high as 5.58 mg/kg in the paddy soils, which indicated a potential concern from the view point of national health and food security in Bangladesh. Meharg et al. [51] reported that cadmium concentrations in rice grain were the highest in Bangladesh among twelve different countries across the world, exposing Bangladeshi populations to excessively high levels of cadmium in their diet. The use of contaminated water for irrigation, discharge of effluents and wastewater in the surrounding land areas, and long-term use of cadmium containing phosphatic fertilizers in the agricultural lands could be the possible reasons for the high concentrations of cadmium accumulated in these soils [4, 17, 52–55]. High concentrations of sodium were mostly found in the soils of coastal districts, where paddy irrigation was usually done with sodium laden brackish water. Elevated concentration of sodium in soil solution affects various morphological, physiological and biochemical functions in plants and limits the uptake of mineral nutrient elements by the plant roots, thus causing reduced yield as well as poor nutritional quality of the crops [56–59].

Chowdhury et al. [7] previously reported that arsenic concentrations in the paddy soils irrigated with groundwater were significantly different compared to the soils irrigated with surface water across Bangladesh, the average arsenic concentrations being higher in the groundwater-irrigated soils (8.5 mg/kg) than in the soils irrigated with surface water (5.7 mg/kg). The study explained that the differences in soil arsenic due to different irrigation waters appeared to be a general trend across the country, and the arsenic concentrations in the paddy soils might be confounded by the underlying geomorphological variabilities. The groundwater used for irrigation might also be

an important source for the inputs of some elements like aluminum, calcium, iron, lead, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, sodium and zinc in the paddy soils. However, differences in geochemical mobilizations in the groundwater sediments and surface soils that are largely regulated by complex interactions of geological and pedo-environmental factors lead to variable inputs of the elements in the groundwater-soil systems [11, 12, 34, 44, 60]. The elevated concentrations of the elements, particularly the heavy metals, in the surface water-irrigated topsoil could also reflect the impacts of anthropogenic activities [4, 17, 54]. It is probable that the sources of surface water become contaminated to some extent as a result of contamination through discharge of untreated or partially treated effluents from nearby industries and small factories, indiscriminate use of toxic metal containing fertilizers and pesticides in agricultural fields, application of untreated sewage sludge in arable lands and vehicular emissions from the roads and highways alongside the agricultural lands [4, 17, 18, 54, 61]. While irrigation with groundwater increases soil arsenic concentrations, the use of surface water, which is generally free of or very low in arsenic, is recommended for paddy irrigation [13, 62, 63]. The present study revealed that irrigating paddy soils with surface water could reduce arsenic loading in the paddy soils, but at the same time increase the concentrations of some other toxic elements in the soils.

### 3.2 Geochemical variations in the soils within the inundation land types

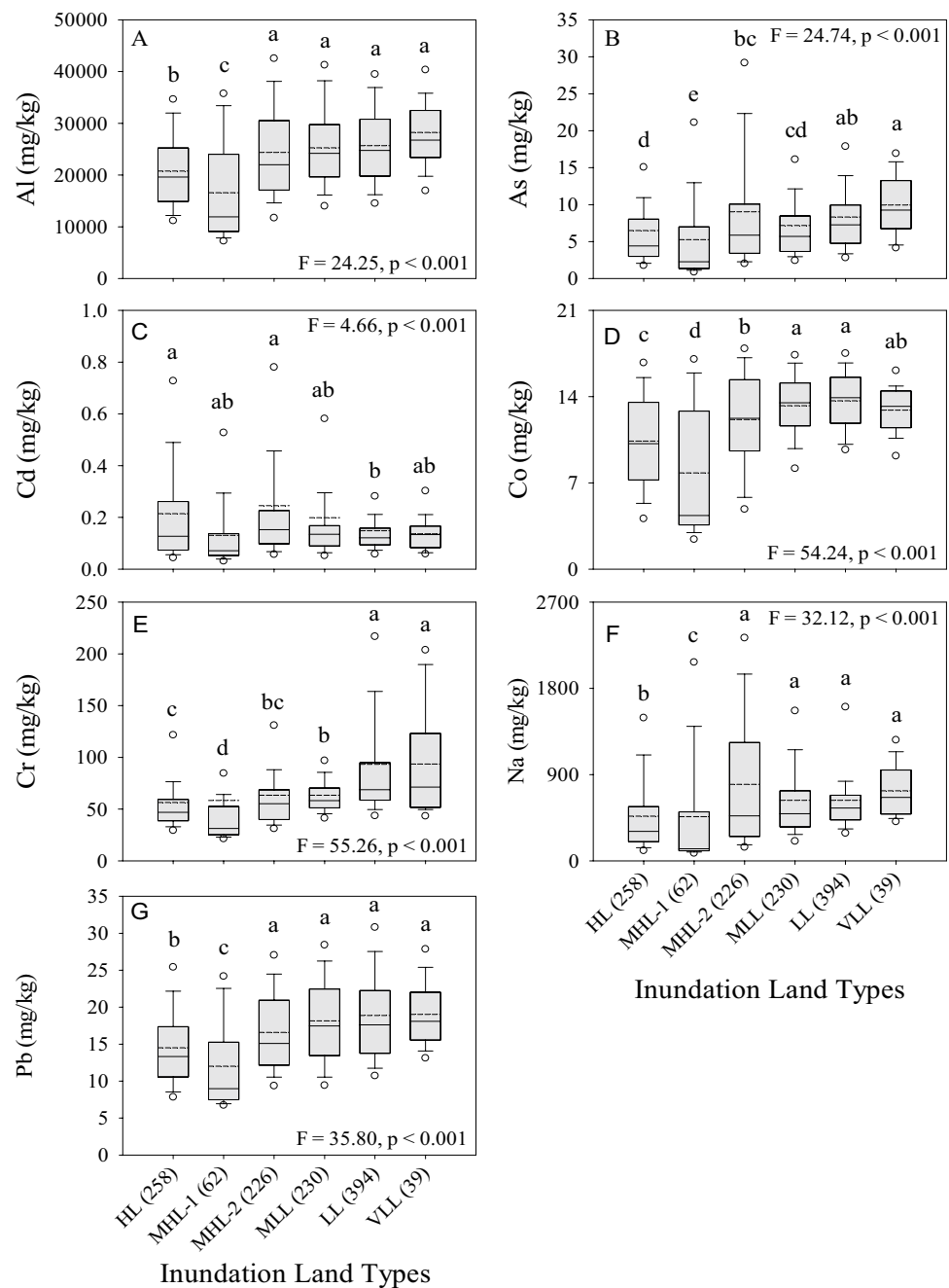
Variabilities of a range of non-essential (aluminum, arsenic, cadmium, cobalt, chromium, sodium and lead) and essential (macronutrients: calcium, magnesium, potassium and phosphorous; and micronutrients: copper, iron, manganese, molybdenum, nickel and zinc) elements in the soils of different inundation land types were assessed in the present study. The non-essential/toxic and essential/macro- and micronutrient elements were found to be varied highly significantly in the paddy and non-paddy soils of the inundation land types (Figs. 2, 3, 4 and Figs. S34–S36, respectively). However, less variations were observed in the non-paddy soil elemental concentrations compared to the variations in the paddy soils within the different inundation land types. Soil pH also varied significantly ( $F_{ANOVA} = 13.58, p < 0.001$  and  $F_{ANOVA} = 3.57, p < 0.01$  for paddy and non-paddy soils, respectively) within the inundation land types.

The average arsenic concentration was found to be the highest in the very lowland paddy soils (10 mg/kg) among the inundation land types. The average arsenic concentrations in the paddy soils at different inundation land types were observed in the order of very

lowland > lowland > medium highland-2 > medium lowland > highland > medium highland-1 (Fig. 2B). The concentrations of the other geochemical elements analyzed were also observed to be higher, in general, in the soils of very lowland and lowland (Figs. 2, 3, 4). Higher concentrations of chromium (93.47 and 93.28 mg/kg, respectively), copper (35.16 and 33.10 mg/kg, respectively), lead (19.04 and 18.89 mg/kg, respectively) and nickel (44.13 and 42.89, respectively) were observed in the paddy soils of very lowland and lowland compared to the high lands (Figs. 2E, 4A, 2G, 4E, respectively). Higher concentrations of cobalt in paddy soils were found in lowland and medium lowland (13.66 and 13.26 mg/kg, respectively) (Fig. 2D). The average concentrations of all the elements, except cadmium, in the paddy soils were found to be the maximum in very lowland and/or in lowland, and the minimum in medium highland-1. The average concentration of cadmium in the paddy soils was found to be the highest in medium highland-2 (0.24 mg/kg), followed by highland (0.21 mg/kg), medium lowland (0.20 mg/kg), lowland (0.15 mg/kg), very lowland (0.14 mg/kg) and medium highland-1 (0.13 mg/kg) (Fig. 2C). The average cadmium concentration in non-paddy soils was also found to be the highest in medium highland-2 (0.19 mg/kg). In the non-paddy soils, the average concentrations of most of the elements were observed to be the highest in very lowland or medium highland-2, and the lowest in highland or medium highland-1. Surprisingly, concentrations of all the elements in the paddy soils, and only calcium, cadmium and phosphorus in the non-paddy soils were found to be the lowest in medium highland-1. The reason is perhaps related to the complex landscape topographical variations within the local areas [8].

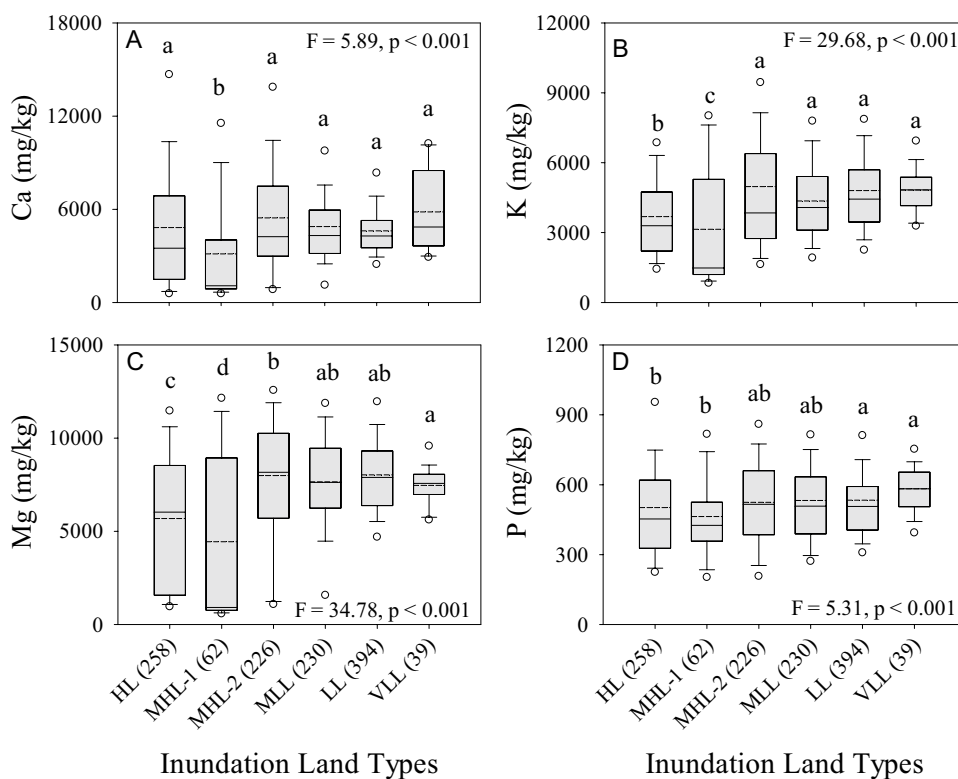
Bangladeshi soils are highly and inherently variable in their concentrations of geochemical elements [7]. Spatial occurrence and accumulation of elements as well as their mobility and availability in soils are largely regulated by the topography of the landscape [12, 64]. The distribution of arsenic in Bangladeshi paddy soils is heterogeneous, the variability being temporal and spatial, both lateral and vertical [27, 28, 35, 36]. It is well documented that arsenic accumulation in the topsoil of paddy fields occurs due to the use of arsenic rich groundwater for irrigation purpose [6, 7]. Arsenic in the surface paddy soils that increases during the dry season irrigation period decreases over the monsoon season through monsoon flooding [35, 37, 39]. Due to the natural relief of the lands, the monsoon floodwater stands on the lowlands for prolonged time. It remobilizes and redistributes soil arsenic, which was deposited at the time of irrigation in the preceding dry season, laterally over a large area. At the end of the monsoon season, this arsenic containing floodwater is transported to the local rivers, and ultimately to the Bay of Bengal leaving

**Fig. 2** Box and whisker plots showing the concentrations of non-essential elements in paddy soils at the different inundation land types: HL, Highland; MHL-1, Medium highland-1; MHL-2, Medium highland-2; MLL, Medium lowland; LL, Lowland; and VLL, Very lowland. The numbers of samples (*n*) at each of the inundation land types are given within the parentheses. The boxplots indicate the lower and upper quartile (box), the median (solid line), the 10th and 90th percentiles (whiskers) and the 5th and 95th percentiles (circles). One-way analysis of variance was used to compare pair-wise the means of the elements at each of the inundation land types. Land types that share the same letter **a–d** are not significantly different. The letters indicate Tukey groupings for the inundation land types with respect to their mean soil elemental concentrations



behind only a residual amount of arsenic on the paddies [39, 65]. The river water carrying arsenic may cause further deposition and redistribution in the downstream landscape [39]. On the other hand, in the areas, for instance, highlands where monsoon flooding is limited, the arsenic added during the irrigation season has been found to be retained into the soil [65]. Thus, the inundation land types affect the distribution and retention of arsenic in the paddies [26, 66]. However, arsenic in paddy soils added through irrigation water can also be lost through vertical leaching to sub-surfaces [67–69]. Loss of arsenic from the

paddies can also occur through biovolatilization, although thought to be on smaller scale [70]. The overall management of the paddy soils make the retention and removal of arsenic in the soils complex [7]. The irrigation season in Bangladesh is normally from December until May, and the majority of the present soil samples were collected during February–March [37]. A part of the soil samples was also collected just before the onset of the monsoon season (during June–July), where the monsoon season usually lingers from mid-June to late October [37]. The concentrations of arsenic found in the present soils, therefore, were



**Fig. 3** Box and whisker plots showing the concentrations of macro-nutrient elements in paddy soils at the different inundation land types: HL, Highland; MHL-1, Medium highland-1; MHL-2, Medium highland-2; MLL, Medium lowland; LL, Lowland; and VLL, Very lowland. The numbers of samples (*n*) at each of the inundation land types are given within the parentheses. The boxplots indicate the lower and upper quartile (box), the median (solid line), the 10th

and 90th percentiles (whiskers) and the 5th and 95th percentiles (circles). One-way analysis of variance was used to compare pairwise the means of the elements at each of the inundation land types. Land types that share the same letter **a–d** are not significantly different. The letters indicate Tukey groupings for the inundation land types with respect to their mean soil elemental concentrations

a combination of the native soil arsenic and any arsenic added through irrigation in that season, plus the residual arsenic remaining after the previous monsoon flooding.

Higher concentrations of arsenic as well as other geochemical elements in the low-level lands during the irrigation season suggest that the elements were laterally transported to the bottom end fields through surface run-off of the irrigation water as well as through movement of soil particles down the gradient during the growing season of the rice crop. It is also probable that soil arsenic in the low-level lands was not reduced greatly by flooding in the prior monsoon season [66]. The arsenic and other elements added in those low-lying areas were perhaps retained in the topsoil followed by transport down the gradient, although a part of the elements could be lost through other mechanisms already mentioned earlier. Elevated accumulation of the elements in the soils of the low-level lands could also be due to their association with fine-grain sediments and organic matter present in the low-lying flooded/ depression soils [26, 62, 64]. The elevated accumulations in the lower lands of some elements

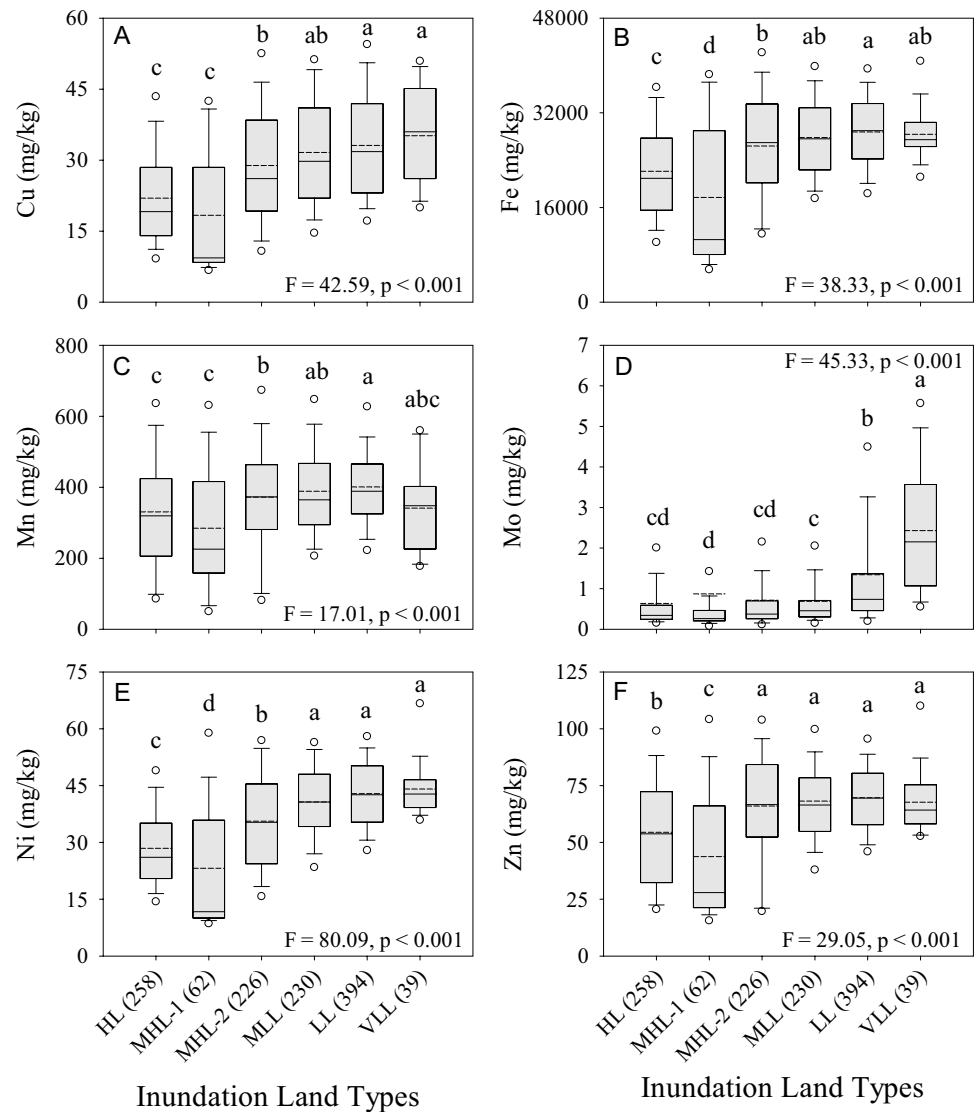
highly toxic to plants such as aluminum, arsenic, cadmium, cobalt, chromium, copper and lead poses a substantial risk to the rice cultivation, which is extensively done in those low-level lands across Bangladesh. Moreover, although the essential nutrient elements were elevated in the low-level lands, high concentrations of arsenic and heavy metals in the soils can limit the accumulation of nutrient elements into rice grains [71, 72]. Both these situations have the potential to lead to rice grains with higher toxic elements and lower nutrient concentrations. However, this is not well investigated and warrants further study in Bangladesh to understand the grain versus soil associations at the different inundation land types for toxic heavy metals as well as primary mineral nutrients of human health importance.

### 4 Conclusion

Higher concentrations of a range of heavy metals, such as aluminum, cobalt, copper, iron, molybdenum, nickel, lead and zinc were found in the surface water-irrigated



**Fig. 4** Box and whisker plots showing the concentrations of micronutrient elements in paddy soils at the different inundation land types: HL, Highland; MHL-1, Medium highland-1; MHL-2, Medium highland-2; MLL, Medium lowland; LL, Lowland; and VLL, Very lowland. The numbers of samples (*n*) at each of the inundation land types are given within the parentheses. The boxplots indicate the lower and upper quartile (box), the median (solid line), the 10th and 90th percentiles (whiskers), and the 5th and 95th percentiles (circles). One-way analysis of variance was used to compare pair-wise the means of the elements at each of the inundation land types. Land types that share the same letter **a–d** are not significantly different. The letters indicate Tukey groupings for the inundation land types with respect to their mean soil elemental concentrations



paddy soils compared to the soils irrigated with groundwater. This indicates inputs of toxic metals in the soils due to paddy irrigation with surface water, which could lead to contamination of the food chain and pose potential risk to human health. The presence of elevated concentrations of cadmium in the irrigated paddy soils also indicates a concern considering its possible accumulation in food crops. Variabilities in the concentrations of different non-essential/toxic and essential nutrient elements were found in the paddy and adjacent non-paddy soils of different inundation land types of Bangladesh, with greater variations observed in the paddy soils. The average arsenic concentrations in the paddy soils at different inundation land types were observed in the order of very lowland > lowland > medium highland-2 > medium lowland > highland > medium highland-1. Elevated accumulations of a range of toxic metal elements, such as aluminum, chromium, cobalt, copper,

lead and nickel in the paddy soils of very lowland and lowland areas, compared to the highlands, present substantial risks considering that rice, the staple food in Bangladesh, is extensively cultivated in these low lands. Further studies and periodic monitoring are needed to assess the extent of soil and crop contamination with toxic elements induced through surface water irrigation practices across Bangladesh. Further fine-scale soil investigations are also vital to explore the extent of contamination of the lowland soils at a landscape scale as well as to relate this to the yield and nutritional quality of the growing crops. The results of this study present an inimitable geochemical database for the surface soils across Bangladesh which can be used in any future studies on the geomorphologically variable agricultural and non-agricultural Bangladeshi soils, providing a basis for environmental pollution assessment and sustainable mitigation approaches.

**Acknowledgements** This work was done as part of a doctoral fellowship plan funded by the Commonwealth Scholarship Commission in the UK. We gratefully acknowledge Bangladesh–Australia Centre for Environmental Research and Department of Soil, Water and Environment of the University of Dhaka for the support during the processing and preparation of the soil samples in Bangladesh. We also gratefully acknowledge the Computer and GIS Unit of Bangladesh Agricultural Research Council (BARC) for providing GIS files for mapping of soils and land types. The soil samples were imported into the UK under import license IMP/SOIL/6/2013 issued by Science and Advice for Scottish Agriculture.

**Author contributions** MTAC collected samples, prepared materials, analyzed and interpreted the data and wrote the first draft of the manuscript. AAM contributed to the study conception and commented on previous versions of the manuscript. AHP and GJN contributed to the study conception and design, supervised the study and commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** This study was funded by the Commonwealth Scholarship Commission in the UK.

**Availability of data and material** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

**Consent for publication** All the authors have given their consent for publication of this manuscript.

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