Spatial Dependency of Arsenic in Soils, Irrigation Water and Plants from Arsenic Contaminated Tube Well Used for Irrigation in Boro Rice Cultivation

M S Kabir
Principal Scientific Officer, Agricultural Statistics Division,
Bangladesh Rice Research Institute, Gazipur, Bangladesh
kabirms.stat@brri.gov.bd

Abstract: The experiments were carried out during the Boro season 2003 and 2004 in four Shallow Tube Well (STW) command areas: B. Baria and Faridpur Sadar upazila, the smallest administrative unit in Bangladesh. The size of the command area varied from 1.54 ha (Faridpur) to 2.43 ha (B.Baria). Each command area was grided by 20m distance and the sampling points were geo-referenced by a global positioning system (GPS). Composite soil samples (0-15 cm), Plants and water samples were collected from the grids. Micro elevation model was created only for Faridpur command area. Geostasistical analysis was performed to analyse the data and create the elevation surfaces. In both the command areas, the concentration of arsenic in water flowing through the irrigation channel reduced with the distance from the tube well. A considerable amount of arsenic in water was absorbed in soils while flowing through the channel. As loading in the soil of a rice field from As contaminated irrigation water would be relatively higher in depressed areas than in elevated areas. Micro elevation may be an impacting factor for As loading in soil. The concentrations of Arsenic (As) in both the locations varied widely. The positive correlations among the soil, grain and straw As concentration are highly significant in both the locations. Which posed the cause of contamination by As in soil as well as grain and straw. Arsenic can enter into the edible plant parts and is influenced by soil As content. High concentration of As in rice straw can influence the translocation of As to grain. The spatial dependency of soil arsenic gives an indication that longer irrigation channels or ponded ground water prior to irrigation and discouraging standing water for long periods in rice fields could be positive measures in reducing arsenic loading in irrigated rice soil. In that case alternate wetting and drying (AWD) method can be a remedial measure to reduce As contamination in soil as well as food chain.
Keywords: Spatial variability, STW, Command area, Arsenic (As), Micro elevation, Geostatistics, Semivariogram, Krigging

1. Introduction

Soil contamination is posing increasing threat to human health and environmental quality. Among the soil and environmental pollutants, heavy metals (HM) have received considerable attention over the last few decades [1]. Arsenic concentrations in soils, particularly in agricultural lands, have in some areas reached in threatened levels for food safety via plant uptake. In order to develop effective management recommendations, spatial patterns of pollutants must be known. In practice, however, it is difficult to characterize accurately, As polluted areas because of their complex spatial pattern, high coefficient of variation and occurrence of hot spots of locally contaminated soils [1]. Predictions of polluted areas are often based on geostatistical methods, which calculate unbiased estimates of heavy metal concentrations at un-sampled locations [2]; [3]; [4]; [5]. These methods provide either an estimated mean value of heavy metal concentration or the probability of exceeding a given threshold level [6].

With regard to drinking-water, the As-affected areas in Bangladesh are mainly located in the south and southwest. With an estimated 20 percent of the drinking-water STWs having As concentrations above the Bangladesh drinking-water standard of 0.050 mg/l, it can be expected that a substantial percentage of irrigation STWs also have high As levels. The exact percentage is unknown because the spatial distribution of irrigation STWs is not similar to that of drinking-water STWs. In groundwater, only AsIII and AsV have been found and levels are within the same order of magnitude [7].

Shallow Tube Wells (STW), each with a small command area (i.e., the area irrigated using the water of a single STW) are the main source of irrigation water for Boro (dry season) rice cultivation in Bangladesh. A vast majority of the STWs pump arsenic contaminated ground water adding arsenic to top soils in Bangladesh, the critical soil layer for rice production. Large areas of Bangladesh have to rely on arsenic-contaminated groundwater for irrigation of staple crops such as rice [8]; [9]. Irrigation with arsenic contaminated groundwater is leading to elevated levels of arsenic in paddy soils [10] which may lead to increased concentration of arsenic in rice [11]; [12], vegetables [13] and other agricultural products of the arsenic affected areas [14]. The high arsenic drinking water coupled with arsenic contaminated foodstuff is causing a mass poisoning in Bangladesh and West Bengal. Ground water is used extensively in irrigation of rice, the staple food of Bangladesh, with 83% of the total irrigated area under rice cultivation [15].

Inverse distance methods and Krigging are commonly used GIS tools to obtain spatial maps of soil parameters from soil samples, based on a coarse grid over the field of study [16]; [17]; [18]. Kriging has been applied to quantify variability of various spatial variables in soils.

The model relationship using sample semivariograms can be used by kriging to estimate values between sampled points [19]. This paper assesses the distribution of arsenic concentration in the soil surrounding of a single arsenic contaminated STW in two different locations in Bangladesh; identify the means to reduce As contamination in rice soils as well as food chain.

2. Materials and Methods

Study area

The study was conducted in two command area under two locations Faridpur and B.Baria Sadar Upazila (Fig. 1). The area extends within northing of 23°29' to 23°44' N latitude and easting of 89°41' to 89°56' E longitude and northing of 24°03' to 23°58' N latitude and easting of 90°45' to 91°44' E longitude, respectively (Fig. 1a,b).

Command area

Faridpur and B.Baria command areas are under Faridpur and B.Baria Sadar Upazila, respectively, where relatively high soil and water As exists. The studied areas are located within 23°31'23" to 23°31'29"N latitude and 89°46'10" to 89°46'15"E longitude and 23°59'12" and 23°59'19"N latitude and 90°59'38" and 90°59'48" E longitude, respectively (Fig. 1a,b). The command area maps were screen digitized using Arcview GIS from the mouza map and built in Arcinfo environment. The soil of the two sites was sampled at 101 and 96 points, respectively at 0-15 cm depth and geo-referenced using GPS. The distribution of the samples is shown in Fig. 1c; cover the field quite evenly. The average sampling interval was 12.35 m over an area of 1.54 ha in Faridpur and 15.9 m over an area of 2.43 ha in B.Baria; the smaller sampling intervals were chosen to resolve any short-scale variation that might be present. At the time of sampling, the crop was irrigated rice (winter rice). The soil samples were air-dried and analyzed by Tri Acid method and the results of the soil elements (As, Fe, Mn, P, OC, pH and soil texture) were recorded accordingly. Data were analyzed using Arcview Spatial Analyst 3.2 GIS software.

3. Geo-Statistical Analysis

Semivariograms were calculated to determine the spatial dependency of soil, water, grain and straw As, Fe, Mn and P for Faridpur by GS+ 5.3.2. Maximum lag distance and lag interval for the semivariance were determined iteratively to best fit the model having highest R^2, the lowest residual sum of squares (RSS) and spatial dependence close to unity. Kriging interpolation was performed to create As surfaces to spatially describe the distribution of As concentration in surface soils, irrigation water, grain and straw. Soil As was measured in the irrigation channels at 20-meter intervals from the irrigation source (STW). For assessing the spatial dependency of soil As, semi-variance analysis was performed. Semi-variogram $\gamma(h)$ was defined as

$$\gamma(h) = \frac{1}{2[N(h)]} \sum_{N(h)} (z_i - z_j)^2$$

where, N(h) is the number of pairs of data locations at a lag distance of "h" apart, and z_i and z_j are point locations.

Micro elevation model of the command area was created at Faridpur with elevation measured at 315 spots within the command area. These include 101 sampling points used for measuring soil As. Theodolite (Fig. 2a) was used to measure the elevation. A wooden device with 6´´x 6´´ platform was used to mount the stuff (Fig. 2b) in order to avoid the depression of soil surface created due to foot pressing during transplanting and other cultural operations. Within the command area, the micro elevation model or relief was defined separately within each plot due to the fact that the variation in elevation is more between plots than within plot and that plowing and leveling of soils prior to transplanting are done by the farmers within the bunded plots. Inverse Distance Weight (IDW) method was used to create the elevation surface.

$$Z_j(est) = S[z_i/(h_{ij} + s)^p]/S[1/(h_{ij} + s)^p]$$

Where,

Z_j(est)	=	estimated value for location j;
z_i	=	measured sample value at point i;
h_{ij}	=	distance between $Z_i$est and z_j;
s	=	smoothing factor; and
p	=	weighting power

The parameter of IDW used was determined iteratively to best fit the observed elevations. The relief so created for individual plots were then joined together to obtain the relief of the whole command area.

4. Results and Discussion

The descriptive statistics of As for the two sites of soil, grain and straw is presented in Table 1. The mean concentration in soil and grain in Faridpur and B.Baria was below the threshold value (20 ppm) but straw As exceed the critical value. The maximum value of soil, grain and straw in B.Baria and straw in Faridpur considerably exceed the threshold levels which posed the cause of contamination by As that is, contaminatied by As is suspected. But, As contamination in soil and grain in Faridpur, the maximum value is lower than the corresponding critical value (1.0 ppm, BD standard).

Comparing the standard deviations with means (not 1/3 of their mean) the distributions are not symmetric [2]. The skewness coefficients are strongly positively skewed which indicates the data need transformation.

The coefficients of variation CV of As in soil, grain and straw were very high and indicate that the concentrations of As in both the locations vary widely. The positive correlations of As concentration in among soil, grain and straw As concentration are highly significant (Table. 2) in both the locations. This implies that As can enter into the edible plant parts and is influenced by soil As content. Significant positive relationship between straw and grain of As concentration implies that high concentration of As in rice straw can influence the translocation of As to grain.

In both the command areas, the concentration of arsenic in water flowing through the irrigation channel reduced with the distance from the tube well (Fig. 3). It indicates that a considerable amount of arsenic in water was absorbed in soils while flowing through the channel. The absorption of As is higher near the source (STW) than at the tail end of the irrigation channel. This gives an indication that As loading in soils from irrigation water at any point in a well leveled command area is spatially related to its distance from the tube well.

The semi-variance (Fig. 4) indicated spatial dependency of soil As at both the command areas but the nature as well as the extent of dependency were not the same in all locations. The semi-variance for soil, grain and straw at Faridpur was best explained by exponential model. The same is true for grain at B.Baria. In contrast, the semi-variance model was spherical for soil and straw as judged by high R^2 value and the lowest residual sum of squares (Table 3).

The range of spatial dependency (Table 3) within the command area for soil, grain and straw was about 190, 461 and 326 m, respectively at B. Baria and these values are 101, 20, 25 m at Faridpur. The large range of spatial dependency at B. Baria was due to the fact that As concentration within the command area varied relatively more systematically from point to point than at Faridpur as indicated by the spatial distribution of As in soil, grain and straw (Fig. 5). The proportion of spatial structure to sampling variance was close to unity with small nugget variance for soil and straw at B. Baria and grain and straw at Faridpur (Table 3) indicating small analytical error and less variability in their As within the lag intervals and the semi-variogram model explained most of the sampling variation (99.8%, 100%, 99.9% and 99.8%, respectively). While, for grain at B.Baria and soil at Faridpur only 63% and 50%, respectively of sampling variance within the lag interval could be attributed to spatial structure, which indicated that some factors other than distance also contributed to the variation of As level within the command area. Between two command areas, only at B. Baria, As concentration in soil, grain and straw showed decreasing trend with the increase of distance from the tube well (Fig. 5). Such trend, however, was not consistent throughout at Faridpur command area, rather, As concentration occurred in patches spread over the command area.

The range of semi-variance was also found to vary with the texture of surface soil – it was higher for soils with higher silt and lower with higher clay content (Table 4).

It was observed during soil sampling that the standing water level in certain areas of some of the rice fields was higher meaning that the rice fields were not uniformly leveled during land preparation. In other words, there were micro differences in plot elevation creating some local and patchy depressions within a rice field where irrigation water could stay longer time and the amount of water consumed was higher than those of elevated areas. It was then quite reasonable to hypothesize that As loading in the soil of a rice field from As contaminated irrigation water would be relatively higher at the depressed areas than those of the elevated areas.

In order to test the above hypothesis, micro elevation model or micro relief was created for Faridpur command area. The comparison of soil As surface (Fig. 6a) and elevation model (Fig. 6b) exhibited close agreement between elevation of the rice field and spatial variability of soil As. In general, soil As was found to be higher in depressed areas than in elevated ones. The correlation coefficient between elevation and soil As within each rice field (Table 5) ranged from -0.58 to -0.82 all of which were negative and except plot no. 11, all the coefficients were significant at 5% probability level implying that soil As is expected to be low in high elevated areas. Soil As summarized within the zones of elevation (Fig. 7) revealed that As loading in soils was the highest (>15 ppm) in the lowest elevation zone (0.42 – 3.68 cm) that gradually decreased with the increase in elevation with the only exception in the elevation zone of 16.74 - 20.01 cm.

5. Conclusions

The conclusions that follow from this study are

- Micro elevation may be an impacting factor for As loading in soil.
- Longer irrigation channels or ponded ground water prior to irrigation and discouraging standing water for longer periods in rice fields could be positive measures in reducing arsenic loading in irrigated rice soils.
- Alternate Wetting and Drying (AWD) method can be a remedial measure to reduce As contamination in soil as well as food chain.

6. References

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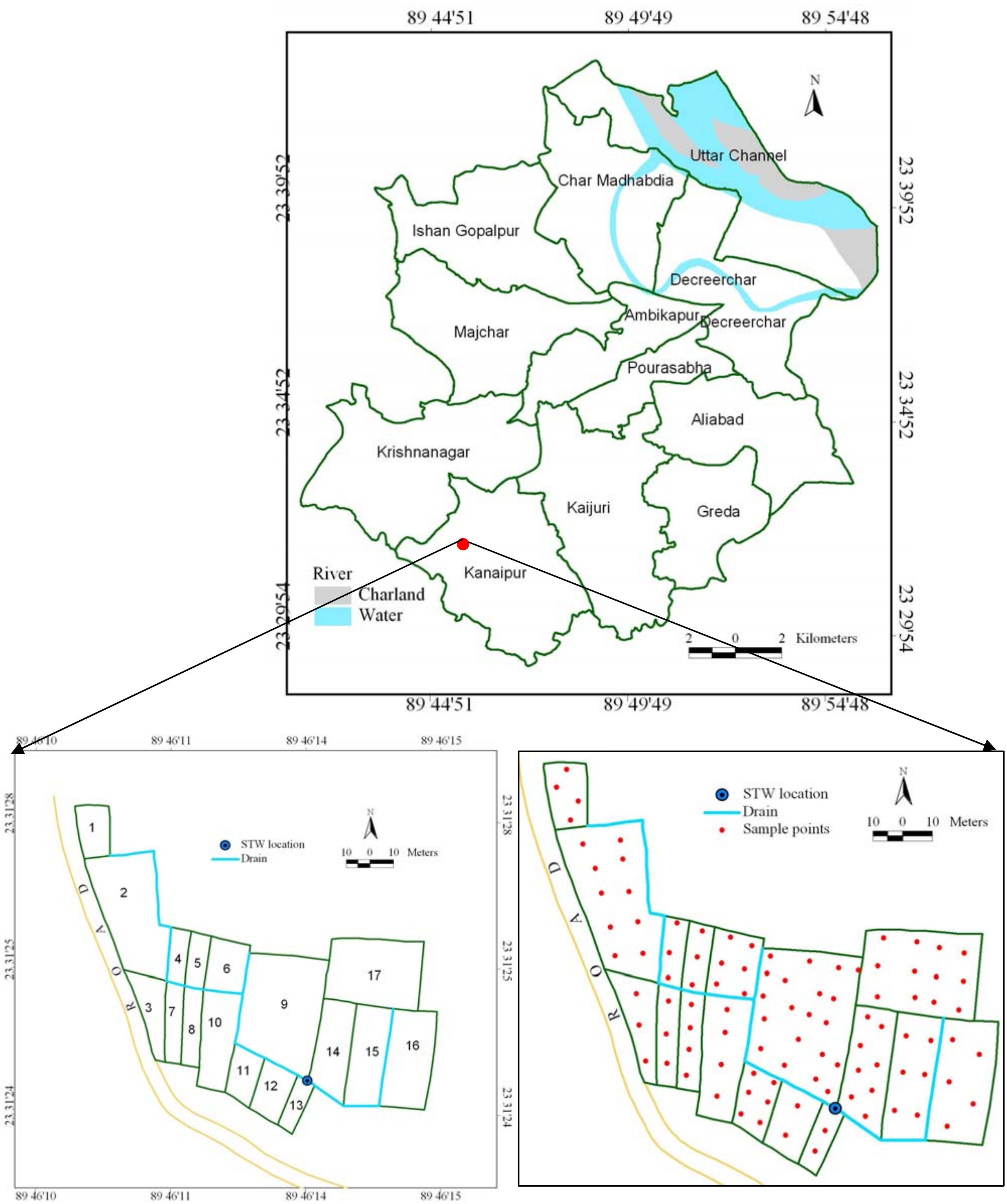

Fig. 1a. Study area and the distribution of the sample points sampling in Faridpur command area in Faridpur sadar upazilla, Faridpur.

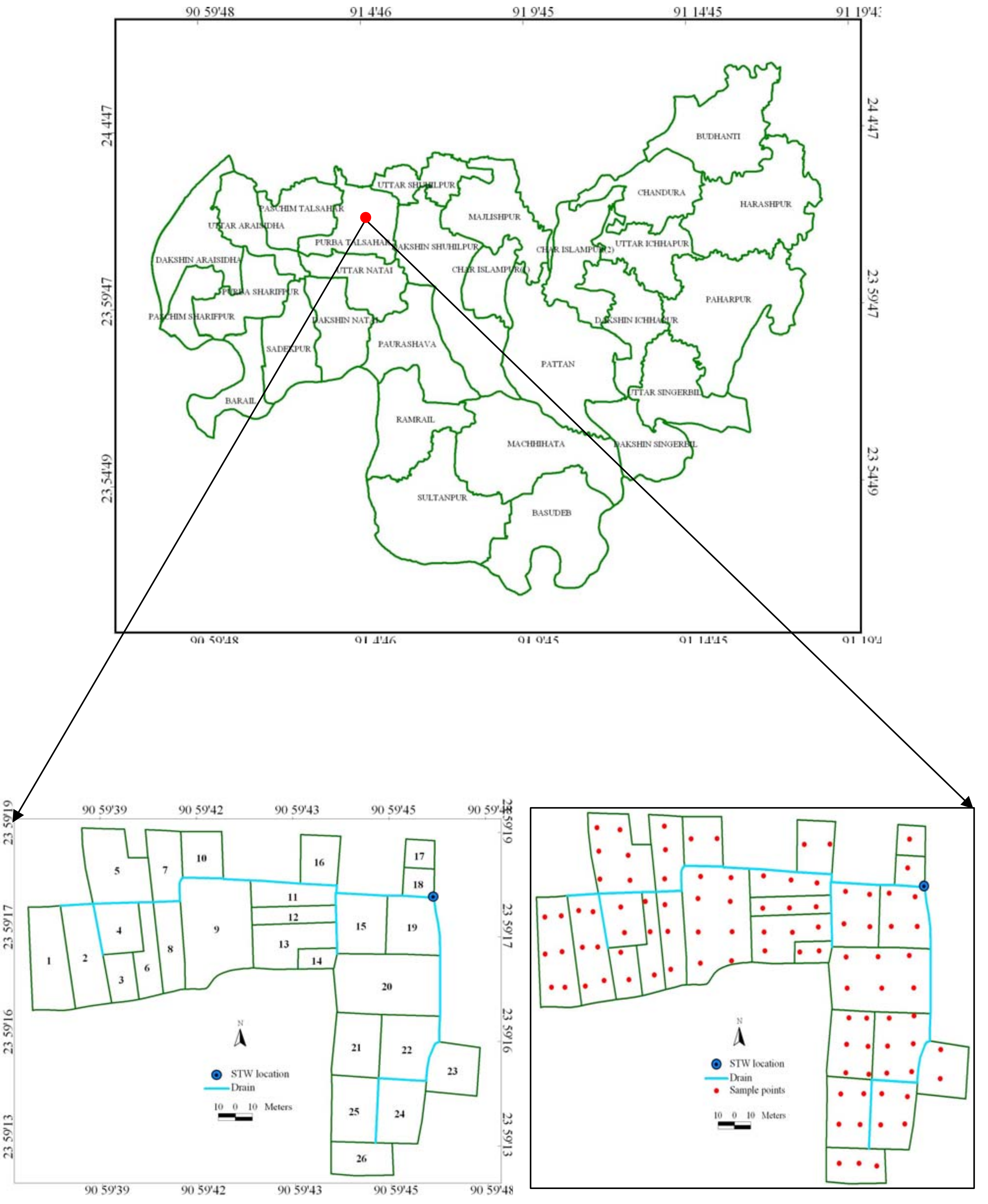

Fig. 1b. Study area and the distribution of the sample points sampling in B.Baria command area in B.Baria sadar upazilla, B Baria.

Fig. 2a, b. Measuring elevation using Theodolite (left) and Stuff (right)

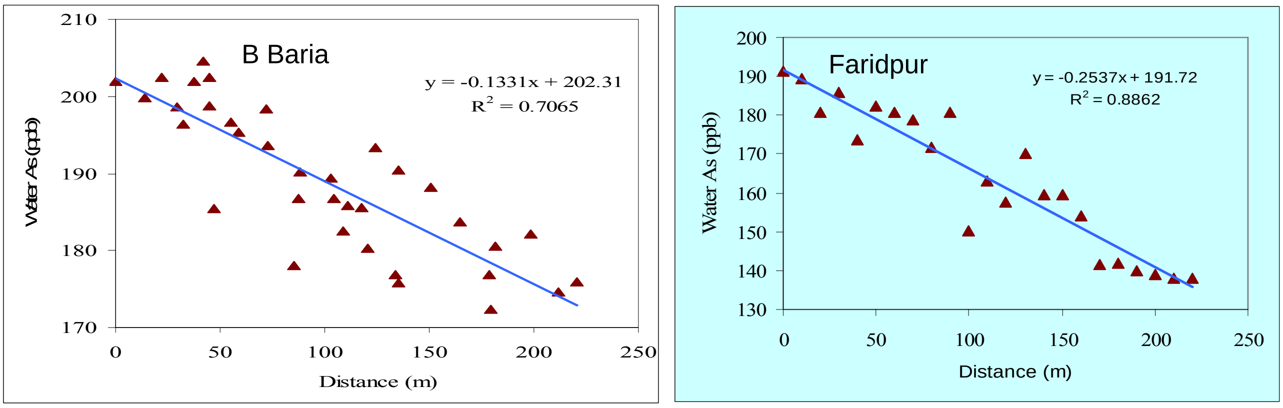

Fig. 3. Relationship between water AS and distance from the source (STW)

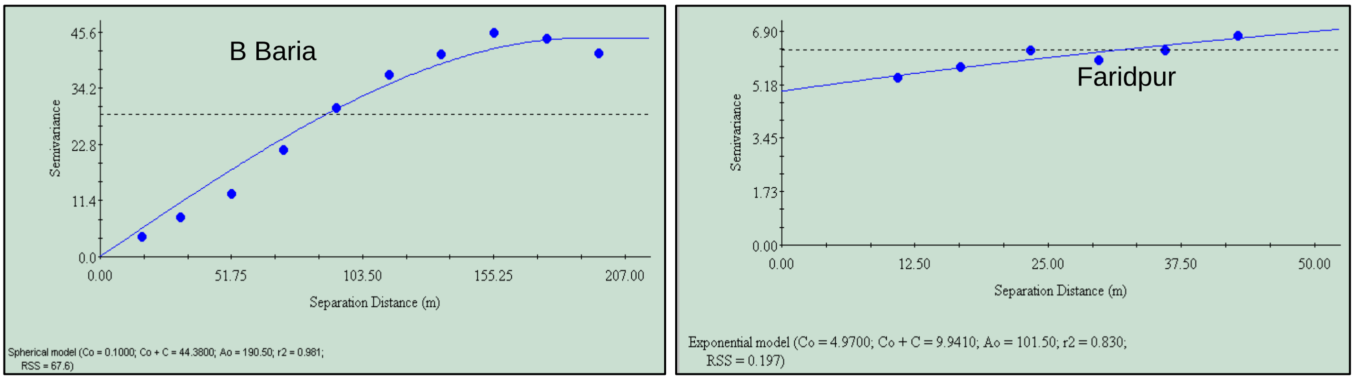

Fig. 4. The semi-variogram models of soil As in command areas

B.Baria Faridpur

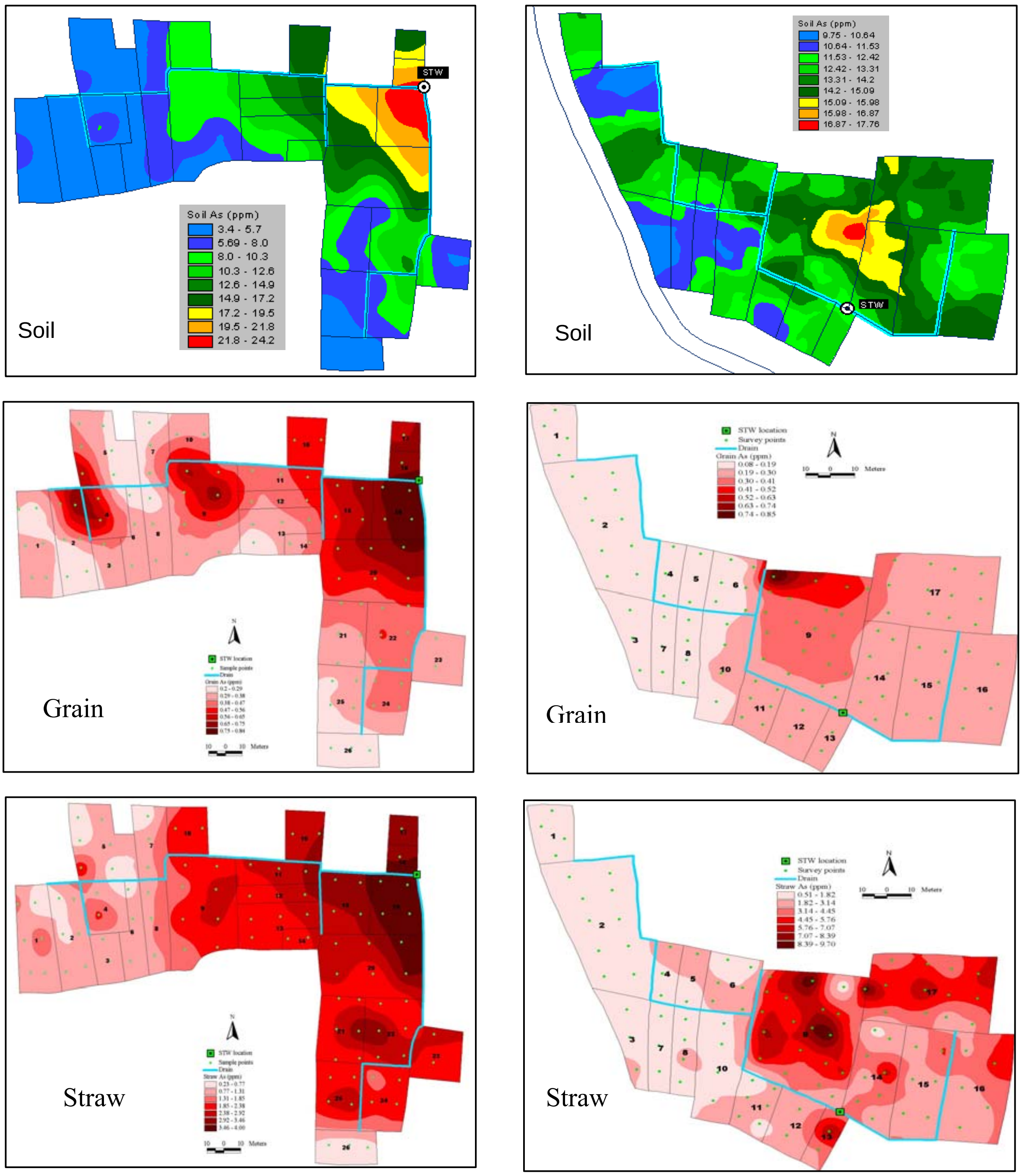

Fig. 5. Spatial variation of soil, grain and straw As at B.Baria and Faridpur command area

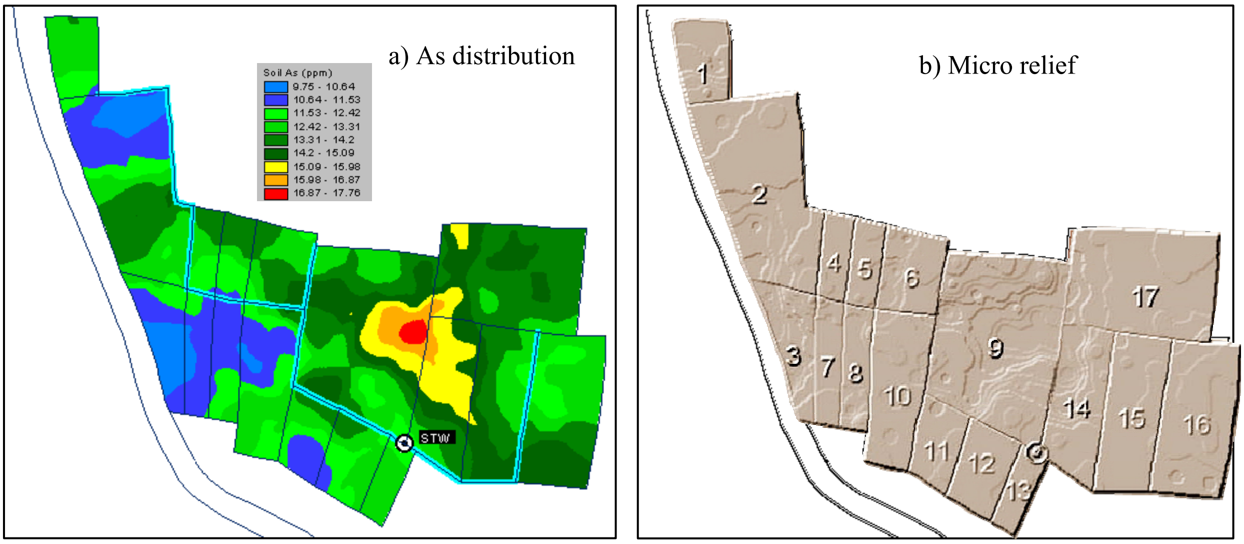

Fig. 6a, b. Comparison of soil As surface and elevation model

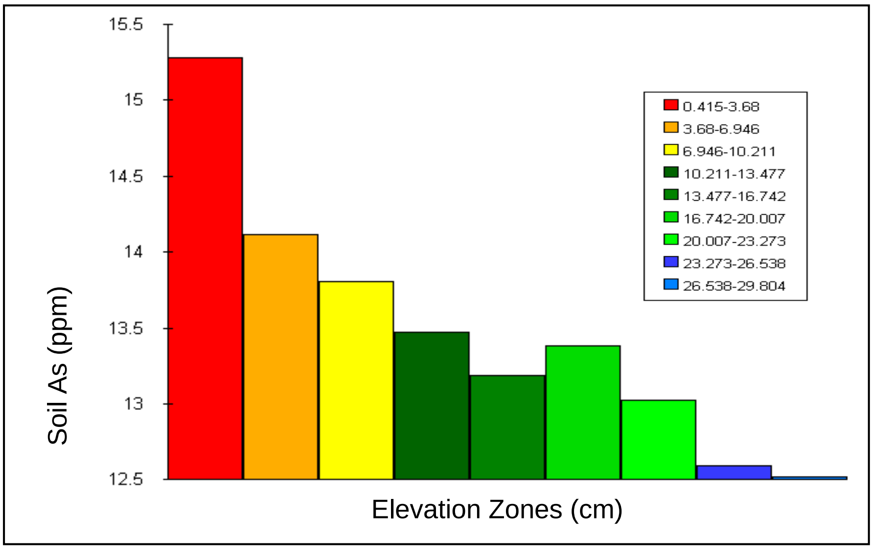

Fig. 7. Soil As (ppm) summarized within the zones of elevation (cm)

Table 1. Descriptive statistics Arsenic concentrations (ppm)

Variable	B.Baria			Faridpur		
	Soil	Grain	Straw	Soil	Grain	Straw
Mean	9.42	0.43	2.00	13.15	0.24	3.03
Median	7.85	0.36	2.11	12.90	0.22	2.30
Sd	5.38	0.22	0.96	2.51	0.12	2.22
Min	3.21	0.16	0.33	6.99	0.08	0.46
Max:	24.43	1.20	1.02	18.99	1.00	10.05
CV	57.05	50.05	47.78	19.10	47.23	73.20
Skewness	0.89	1.38	0.02	0.09	3.11	1.04

Table 2. Correlation coefficient of measured As concentrations in soil, grain and straw

Variable	B.Baria			Faridpur		
	Soil	Grain	Straw	Soil	Grain	Straw
Soil	1.00			1.0		
Grain	0.63**	1.00		0.32**	1.0	
Straw	0.84**	0.61**	1.00	0.29**	0.62**	1.0

Table 3. Variogram models of As in different command areas

Variable	B.Baria			Faridpur		
	Soil	Grain	Straw	Soil	Grain	Straw
Model	Spherical	Exponential	Spherical	Exponential	Exponential	Exponential
Lag distance	207	225	225	50	190	80
Lag interval	20.7	22.5	22.5	6.69	19	8
Nugget	0.10	0.034	0.001	4.97	0.00001	0.001
Sill	44.38	0.093	2.01	9.94	0.014	0.505
Range (m)	190.50	461.50	326.30	101.50	19.90	25.10
Proportion of structural variance to total sampling variance	0.998	0.63	1.00	0.50	0.999	0.998
R^2	0.98	0.90	0.96	0.83	0.65	0.96
RSS	67.6	4.57E-05	0.114	0.019	3.18E-05	6.17E-03

Table 4. Soil As level and textural parameters of surface soil of different command areas.

Location	Sample size	Soil As (ppm)	Soil textural parameters		
			Sand %	Clay %	Silt %
B. Baria	96	9.42	20.33	26.43	53.24
Faridpur	100	13.15	24.50	37.42	38.08
Tala	60	20.22	7.98	35.40	56.62
Sonargaon	144	9.12	7.69	85.31	7.00

Table 5. Correlation coefficient between soil As and elevation of the plots

Plot number	No. of observation	r
2	10	-0.79**
4,5	6	-0.81*
6	6	-0.73*
9	20	-0.70*
11	6	-0.58^{ns}
14	8	-0.79**
15	6	-0.82*
17	12	-0.60*

1. Plots having less than 6 sampling points were excluded from the analysis.
2. Plots 4 and 5 had similar elevation as indicated by micro elevation model.