Transport of aqueous arsenic in selected arsenic affected soils of West Bengal : A miscible displacement study

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A laboratory transport study of aqueous arsenic under constant pressure head in four surface soils, collected from the paddy fields at four different arsenic-affected sites of the Deganga block of North 24-Parganas district of West Bengal, was conducted with the help of double-chambered vertical column made of Borosil glass. The experimental data led to the Darcy's saturated hydraulic conductivity of the soils and accumulation or relative hold-up of arsenic in these soils as revealed by the corresponding breakthrough curves. The sigmoid shape of these breakthrough curves for the given passage of aqueous arsenic solutions through the present soils, thereby suggesting hydrodynamic dispersion, was noted, with a concomitant shift of the curves to the left of the corresponding inflextion points (at $P_v = 1.0$). Based on this, substantial arsenic retention by the given soils was inferred. In this regard, the arsenic retention through its interactions with the soil organic matter and the clay fractions was also emphasized. Moreover, an attempt has been made in the present study to relate the arsenic retention by the given soils to the corresponding relevant physico-chemical properties. The findings from the laboratory experiment were found to be satisfactorily correlated with the arsenic build-up in the different parts of summer (boro) paddy cultivated in the given affected soils. The latter may be taken to elucidate the effect of such irrigation on crops grown in the arsenic contaminated soils using the contaminated groundwater as the irrigation source.

Arsenic (As) is placed in Group V(b) and Period 4 of the Periodic table. It is a toxic semimetal and is highly mobile under neutral to slightly alkaline conditions in natural eco-system. Arsenic is ubiquitous in the environment and its input to the environment, either through natural processes of weathering of arsenic-bearing rocks and/or use of arsenic-contaminated groundwater for irrigation, or through a host of anthropogenic activities, such as mining operations, smelting of base metal ores, combustion of coal and application of arsenicals as agricultural pesticides is widely reported[1]. Arsenic is a nonessential element for plants, and its inorganic forms are generally highly phytotoxic. An overexploitation of groundwater and the change in landuse pattern is believed to have triggered the mobilization of arsenic into the groundwater in the Bengal Delta Basin[1,2]. The geochemical characteristics of the aquifer play a crucial role in understanding the mobilization of arsenic. Arsenic input to soils may have toxic effect on plants with its accumulation, mainly into the vegetative part of the latter, thereby leading to entry of arsenic into the animal and human food-web. The problem of arsenic contamination in groundwater in the vast tract of alluvial aquifers in the Bengal Delta Plains (BDP) is a subject of global concern and is known to have affected populations of about 7–8 million in West Bengal and more than 10 million in 61 out of 64 districts of Bangladesh. In West Bengal as many as

81 blocks in 9 districts covering an area of more than 39000 km^2 are reported to be severely affected[2,3].

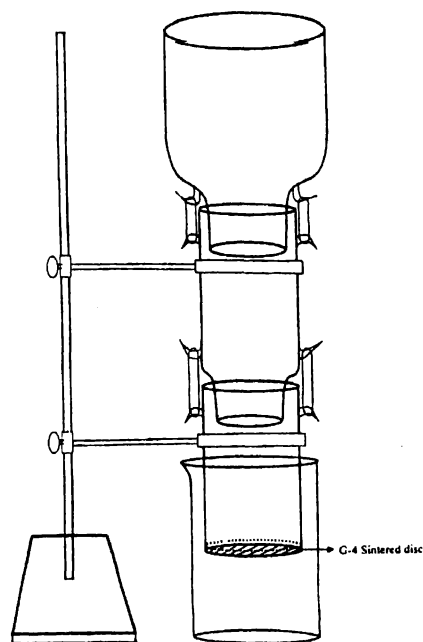The main focus of attention, until recently, has been exclusively on arsenic contamination in groundwater-derived
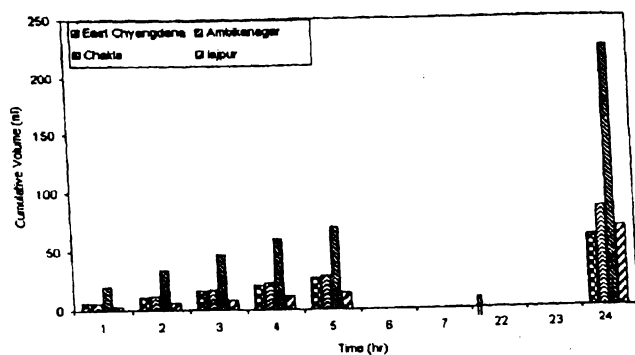

Fig. 1. Vertical soil column.

Fig. 2. Arsenic transmission characteristic bar diagram (for 200 mg As L^{-1}) of four soils.

drinking water. However, since groundwater is also used extensively for crop irrigation in the arsenic affected belt of West Bengal, the possibility of a build-up of arsenic in agricultural soils and agronomic produce was anticipated[1]. Arsenic uptake by crop plants grown in soils contaminated with high concentrations of arsenic, and irrigated with arsenic-contaminated groundwater has also been reported[4,5]. It is also evident that soil labile pool of arsenic and its intake by plants from soil varies from region to region, depending on the extent and nature of interaction of soil components with arsenic. The latter is a function of the properties of the soils concerned. In this context it is worthnoting that the surface water bodies in the entire affected belt have remained free of the toxin. This seems to suggest that the soil, which is receiving the arsenic contaminated groundwater as irrigation source, acts as a major sink of arsenic inflow to agroecosystems[1,6-10], thereby reducing the availability of the toxicant in the groundwater-soil-plant/animal/human continuum[1].
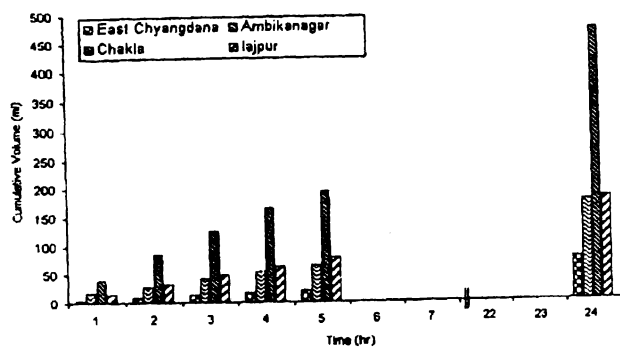

Fig. 3. Arsenic transmission characteristic bar diagram (for 400 mg As L^{-1}) of four soils.

Keeping these facts in view, the present study was conducted to explore the arsenic retention/release behaviour of selected surface soil samples, located in the affected study site, during passage of aqueous arsenic through these soil samples taken in a vertical soil column. The latter has important bearing to the leaching losses beyond the crop root

zone, nutrient availability and potential contamination of groundwater resources. Several workers[11-14] have treated solute transport on a macroscopic basis, i.e. with the water flow velocity, hydrodynamic dispersion, etc., being treated as the associated parameters that describe the soil system. In the present study, an attempt has been made to explore aqueous solute transport through vertical soil column and to relate such transport/retention to the relevant properties of the given soils. The information so generated hopefully would help to elucidate the extent of partitioning of arsenic (i.e. the pollutant) from the flowing contaminated water onto the soil in contact during irrigation.
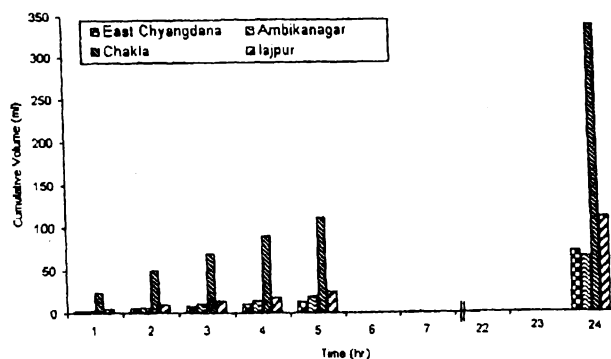

Fig. 4. Arsenic transmission characteristic bar diagram (for 800 mg As L^{-1}) of four soils.

Results and discussion

The surface soil samples, collected from the four arsenic affected areas, namely East Chyangdana, Ambikanagar, Chakla and Iajpur, were neutral to slightly alkaline in nature (pH 7.42 to 7.85) with varying organic carbon and clay contents (Table 1), and hence C.E.C. The textural class of the soils ranged between sandy loam and silty clay loam. The electrical conductivity of the soils varied from 0.30 to 0.60 dS/m. Organic carbon content ranged from 9.2 to 18.9 g kg^{-1}. The soils had high base saturation and moderate CEC values, ranging between 15.6 and 18.9 cmol (p$^+$) kg^{-1}. The exchangeable Ca content was quite high in all the soils. The specific surface area also varied among the present soil samples. The available P was high in the soils of Chayangdana East and Ambikanagar compared to the soils of Chakla and Iajpur. The oxalate extractable (amorphous) Fe content was greater in the Iajpur soil followed by that in the Ambikanagar, East Chyangdana and Chakla soils. The Olsen extractable (0.5 *M* NaHCO$_3$, pH 8.5) arsenic content was also relatively high in the Iajpur soil, followed by that in the Chakla, Ambikanagar and East Chayangdana soils.

Findings from the leaching of aqueous arsenic down the vertical soil column : Results presented in Table 2 showed that the effluent concentration varied with the progress of

Table 1. Important physico-chemical properties of soils

Soil taxonomy	East Chyangdana	Ambikanagar	Chakla	Iajpur
	Typic Haplaquept	Typic Haplaquept	Typic Haplaquept	Typic Haplaquept
Sand (%)	15.4	18.5	55.7	17.3
Silt (%)	54.8	50.4	32.2	66.6
Clay (%)	29.8	31.1	12.1	16.1
Texture	Silty clay loam	Silty clay loam	Sandy loam	Silty loam
pH (1 : 2.5)	7.47	7.42	7.85	7.77
EC (1 : 5) (dS m^{-1})	0.33	0.30	0.38	0.60
Org. C (g kg^{-1})	14.2	11.6	11.2	18.9
Surface area (m^2 g^{-1})	105	107	69	82
CEC [cmol (p$^+$) kg^{-1}]	18.9	15.6	17.2	16.7
Exchangeable cations [cmol (p$^+$) kg^{-1}]				
Na	0.17	0.13	0.16	0.14
K	0.33	0.46	0.32	0.30
Ca + Mg	17.5	14.7	16.3	16.0
Amorphous Fe (%)	0.41	0.43	0.32	0.61
Olsen extractable (mg kg^{-1})				
As	1.60	2.90	6.50	19.4
P	42.0	40.0	38.0	37.0

Table 2. Observed trends of findings for transport of aqueous arsenic solutions through soils under paddy

Soil sample collected from	Time interval (h)	Permeating arsenic concentration (mg As L^{-1})	Relative concentration $(C'/C_0) \times 10^3$	Permeating arsenic concentration (mg As L^{-1})	Relative concentration $(C'/C_0) \times 10^3$	Permeating arsenic concentration (mg As L^{-1})	Relative concentration $(C'/C_0) \times 10^3$
East Chayangdana	1.0		1.35		2.55		8.70
	2.0		1.22		3.15		12.3
	3.0		1.19		5.20		12.9
	4.0	200	1.63	400	4.62	800	8.39
	5.0		2.00		5.05		14.6
	24.0		2.20		7.33		19.6
Ambikanagar	1.0		1.71		2.98		7.88
	2.0		1.65		5.76		20.3
	3.0		1.96		5.04		12.6
	4.0	200	2.38	400	5.98	800	20.9
	5.0		5.30		8.81		19.4
	24.0		7.48		11.5		23.8
Chakla	1.0		4.76		3.35		11.7
	2.0		4.97		5.11		17.0
	3.0		7.39		5.96		23.1
	4.0	200	7.74	400	7.25	800	25.1
	5.0		9.03		7.72		28.6
	24.0		10.4		14.8		33.3
Iajpur	1.0		1.62		4.13		10.5
	2.0		1.57		5.24		17.6
	3.0		1.98		4.98		23.9
	4.0	200	1.62	400	6.31	800	24.5
	5.0		4.84		6.63		24.8
	24.0		7.95		12.1		28.4

time. A general trend of gradual rise in the concentration of arsenic in the leachate with time of flow (as reflected in the corresponding values of the ratio, C'/C_0) was noted in all the four soils, suggesting a lower degree of retention of arsenic by the soils at longer intervals. The greater average time of dilution in the soil of East Chyangdana (being 625, 215 and 88.0 for aqueous permeating arsenic solutions at the feed-level concentrations of 200, 400 and 800 mg As L^{-1}) than in the remaining soil samples for all the different aqueous arsenic solutions used as the permeating electrolyte, suggested a higher degree of arsenic accumulation in the former, possibly due to a moderately high organic carbon and clay contents in this soil (Table 1). The lowest time of dilution reported for the Chakla soil, with all the aqueous

Table 3 Solute accumulation parameter (r) and saturated hydraulic conductivity (k) of soils using aqueous arsenic at different time periods

Soil	Permeating arsenic concentration (mg As L^{-1})	Time interval (h)	Volume of leachate (ml)	Cumulative volume (ml)	Pore volume (P_v)	Relative concentration (C/C_0) × 10^3	Solute accumulation parameter (r) $r = 1 - C/C_0$	Flux (q) × 10^4 (cm s^{-1})	Saturated hydraulic conductivity (k) × 10^4 (cm s^{-1})
East Chyangdani	200	1.0	5.5	5.5	0.038	1.35	0.999	2.88	2.08
		2.0	5.0	10.5	0.072	1.22	0.999	2.75	1.97
		3.0	5.8	16.3	0.115	1.19	0.999	2.84	1.45
		4.0	4.8	21.1	0.152	1.63	0.998	2.76	1.29
		5.0	5.5	26.6	0.189	2.00	0.998	2.78	1.01
		24.0	33.8	60.4	0.409	2.20	0.998	1.32	0.952
Ambikanagar	200	1.0	5.5	5.5	0.041	1.71	0.998	2.48	1.79
		2.0	5.6	11.1	0.085	1.65	0.998	2.51	1.81
		3.0	6.0	17.1	0.126	1.963	0.998	2.58	1.86
		4.0	5.5	22.6	0.172	2.38	0.998	2.55	1.84
		5.0	5.6	28.2	0.209	5.30	0.995	2.55	1.84
		24.0	55.5	83.7	0.556	7.48	0.993	1.58	1.13
Chakla	200	1.0	20.0	20.0	0.097	4.76	0.995	6.91	5.11
		2.0	14.0	34.0	0.164	4.97	0.995	5.87	4.35
		3.0	13.0	47.0	0.248	7.39	0.993	5.41	4.00
		4.0	13.0	47.0	0.303	7.74	0.992	5.18	3.83
		5.0	9.5	69.5	0.353	9.03	0.991	4.80	3.55
		24.0	15.5	225	0.577	10.4	0.990	3.23	2.39
Lajpur	200	1.0	3.0	3.0	0.012	1.62	0.998	1.57	2.88
		2.0	2.6	5.6	0.024	1.57	0.998	1.47	2.84
		3.0	2.8	8.4	0.035	1.98	0.998	1.47	2.61
		4.0	2.5	10.9	0.044	1.62	0.998	1.43	1.08
		5.0	3.0	13.9	0.057	4.84	0.995	1.45	1.09
		24.0	54.0	67.9	0.281	7.95	0.992	1.48	1.02

Table 4 Solute accumulation parameter (r) and saturated hydraulic conductivity (k) of soils using aqueous arsenic at different time periods

Soil	Permeating arsenic concentration (mg As L^{-1})	Time interval (h)	Volume of leachate (ml)	Cumulative volume (ml)	Pore volume (P_v)	Relative concentration (C/C_0) × 10^3	Solute accumulation parameter (r) $r = 1 - C/C_0$	Flux (q) × 10^4 (cm s^{-1})	Saturated hydraulic conductivity (k) × 10^4 (cm s^{-1})
East Chyangdani	400	1.0	4.5	4.5	0.021	2.55	0.998	2.03	1.40
		2.0	4.0	8.5	0.038	3.15	0.997	1.92	1.33
		3.0	4.0	12.5	0.055	5.20	0.995	1.88	1.30
		4.0	4.5	17.0	0.074	4.62	0.995	1.92	1.31
		5.0	4.0	21.0	0.091	5.05	0.995	1.90	1.31
		24.0	54.0	75.0	0.323	7.33	0.993	1.41	0.97
Ambikanagar	400	1.0	16.0	16.0	0.074	2.98	0.997	6.29	4.53
		2.0	13.0	29.0	0.125	5.76	0.994	5.76	4.10
		3.0	15.0	44.0	0.189	5.04	0.995	5.76	4.15
		4.0	10.0	54.0	0.225	5.98	0.994	5.30	3.82
		5.0	11.5	65.5	0.279	8.81	0.991	5.15	3.71
		24.0	108.5	174	0.823	11.5	0.989	2.85	2.05
Chakla	400	1.0	40.0	40.0	0.174	3.35	0.997	15.7	10.9
		2.0	45.0	85.0	0.369	5.11	0.995	16.7	11.5
		3.0	40.0	125	0.583	5.96	0.994	16.4	11.4
		4.0	40.0	165	0.770	7.25	0.993	16.2	11.2
		5.0	30.0	195	0.889	7.72	0.992	15.3	10.6
		24.0	275	470	2.02	14.8	0.985	7.69	5.31
Lajpur	400	1.0	14.5	14.5	0.059	4.13	0.996	5.70	4.22
		2.0	16.5	31.0	0.131	5.24	0.995	6.09	4.51
		3.0	17.0	48.0	0.201	4.98	0.995	6.29	4.66
		4.0	16.0	64.0	0.259	6.31	0.994	6.29	4.66
		5.0	15.5	79.5	0.321	6.63	0.997	6.25	4.63
		24.0	100	180	0.742	12.1	0.998	2.94	2.18

Table 5. Solute accumulation parameter (r) and saturated hydraulic conductivity (k) of soils using aqueous arsenic at different time periods

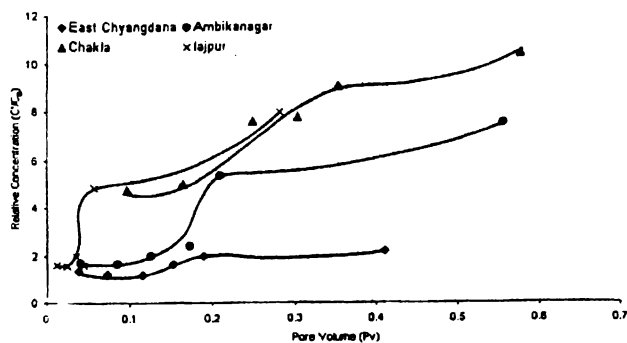| Permeating arsenic concentration (mg As L⁻¹)	Time interval (h)	Volume of leachate (ml)	Cumulative volume (ml)	Pore volume (P_v)	Relative concentration $(C/C_0) \times 10^3$	Solute accumulation parameter (r) $r = 1 - C/C_0$	Flux (q) $\times 10^4$ (cm s⁻¹)	Saturated hydraulic conductivity (k) $\times 10^4$ (cm s⁻¹)
East Chyangdana 800	1.0	2.5	2.5	0.009	8.70	0.991	0.86	0.62
	2.0	2.5	5.0	0.019	12.3	0.998	0.86	0.62
	3.0	2.5	7.5	0.028	12.9	0.994	0.86	0.62
	4.0	2.5	10.0	0.038	8.39	0.992	0.86	0.62
	5.0	3.0	13.0	0.049	14.6	0.985	0.89	0.64
	24.0	57.5	70.5	0.243	19.6	0.980	1.02	0.73
Ambikanagar 800	1.0	3.0	3.0	0.014	7.88	0.992	1.18	0.85
	2.0	3.0	6.0	0.026	20.3	0.979	1.18	0.85
	3.0	4.0	10.0	0.043	12.6	0.987	1.31	0.94
	4.0	5.0	15.0	0.063	20.9	0.979	1.47	1.06
	5.0	4.5	19.5	0.083	19.4	0.981	1.53	1.10
	24.0	45	64.5	0.305	23.8	0.976	1.06	0.76
Chakla 800	1.0	23	23	0.108	11.7	0.988	9.04	6.33
	2.0	27	50	0.232	17.0	0.983	9.82	6.87
	3.0	20	70	0.356	23.1	0.978	9.17	6.42
	4.0	20	90	0.439	25.1	0.975	8.84	6.19
	5.0	21	111	0.544	28.6	0.972	8.72	6.10
	24.0	225	336	0.623	33.3	0.967	5.50	3.85
Jajpur 800	1.0	5.5	5.5	0.020	10.5	0.989	2.16	1.56
	2.0	4.0	9.5	0.042	17.6	0.982	1.87	1.35
	3.0	5.5	15.0	0.066	23.9	0.976	1.96	1.41
	4.0	4.0	19.0	0.084	24.5	0.974	1.87	1.35
	5.0	5.5	24.5	0.109	24.8	0.974	1.93	1.39
	24.0	84.5	109	0.480	28.4	0.971	1.78	1.28

Fig. 5. Breakthrough curves for four soils using arsenic solution (200 mg As L⁻¹) as permeating electrolyte.
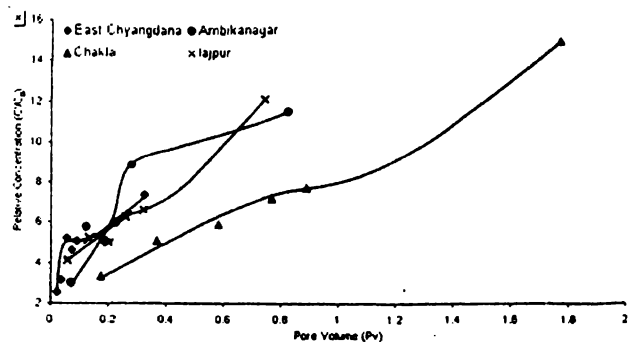

Fig. 6. Breakthrough curves for four soils using arsenic solution (400 mg As L⁻¹) as permeating electrolyte.

arsenic permeating solutions (being respectively 134, 142 and 43.3 for 200, 400 and 800 mg As L⁻¹ feed solution concentrations) could have arisen from the lowest organic carbon and clay contents in this soil (Table 1). The solute accumulation parameter (r) and the saturated hydraulic conductivity (k) of the soils, using aqueous arsenic solutions at different time periods, are shown in Tables 3–5. In agreement with the above stated trends of arsenic retention by the given soils, the saturated hydraulic conductivity of the Chakla soil was generally higher for all concentrations (namely 200, 400 and 800 mg As L⁻¹) of the permeating aqueous arsenic solutions than the corresponding values in

the remaining three soils studied, while it was the lowest in the East Chyangdana soil (Tables 3 to 5). The average solution conductivity values (Table 6) ranged from 1.46×10^{-4} to 3.87×10^{-4} cm s⁻¹ for 200 mg As L⁻¹ aqueous arsenic solution, 1.27×10^{-4} to 10.1×10^{-4} cm s⁻¹ for 400 mg As L⁻¹ arsenic solution and 0.64×10^{-4} to 5.96×10^{-4} cm s⁻¹ for 800 mg As L⁻¹ aqueous solution in the experimental soils. An apparently higher retention of solute by the East Chyangdana soil compared to the other soils suggests that this soil was rather prone to arsenic accumulation.
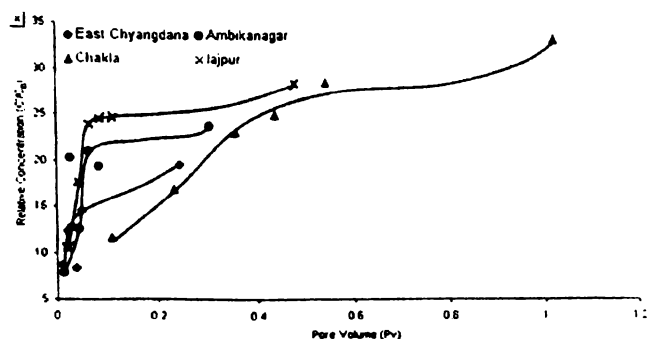
Fig. 7. Breakthrough curves for four soils using arsenic solution (800 mg As L^{-1}) as permeating electrolyte.

Table 6. Conductivity and arsenic retention by four soils using arsenic solution as permeating electrolyte

Soil	Average solution conductivity × 10^4 (cm s^{-1})	Accumulation parameter (r) (% accumulation)	Time of dilution of average solute permeating arsenic solution
Permeating arsenic solution : 200 mg As L^{-1}			
East Chyangdana	1.46	99.9	625
Ambikanagar	1.71	99.7	294
Chakla	3.87	99.3	134
Iajpur	1.92	99.7	307
Permeating arsenic solution : 400 mg As L^{-1}			
East Chyangdana	1.27	99.6	215
Ambikanagar	3.73	99.3	150
Chakla	10.1	99.3	142
Iajpur	4.14	99.4	152
Permeating arsenic solution : 800 mg As L^{-1}			
East Chyangdana	0.64	98.5	88.0
Ambikanagar	0.93	98.2	57.2
Chakla	5.96	97.7	43.3
Iajpur	1.39	97.9	46.2

*Data computed from those presented in Tables 2, 3, 4 and 5.

Bar diagrams of the data on aqueous solute transport through the given soils were also made (Figs. 2–4) from which the general trend of permeability of different soils, namely Chakla > Ambikanagar > Iajpur > East Chyangdana at different concentrations of aqueous arsenic permeating solutions, was apparent.

The apparently sigmoid shape of the breakthrough curves (Figs. 5–7) for aqueous arsenic solutions in the given soils indicates the hydrodynamic dispersion, that is, mixing of the permeating solution, with the soil solution originally present, leading to displacement of the latter. A shift of the breakthrough curve to the left of the inflexion point (at $P_v = 1.0$) was also observed in each case. Such shifting is also proposed to be higher, the higher the clay and organic matter contents of the soils[15], since the former provide a relative measure of the volume of original soil solution that is not displaced by the permeating solution. Such expectation

was generally corroborated by the present findings that the shift was, in general, maximum for the East Chyangdana soil for all the arsenic concentrations used, and the lowest for the Chakla soil, suggesting a higher degree of arsenic retention in the former and a lower retention in the latter (Figs. 5–7). This may possibly be linked with the relatively higher clay content of the East Chyangdana soil and a lower clay content of the Chakla soil (Table 1) as mentioned earlier.

Table 7. Total arsenic content in different plant parts of summer (boro) paddy samples collected from the study areas

Plant samples collected from	Sample description	Plant parts	Arsenic content (mg As kg^{-1})
East Chyangdana	Boro paddy (standing)	Root	73.5
		Shoot	17.7
		Leaf	13.7
		Economic produce	12.8
Ambikanagar	Boro paddy (standing)	Root	72.6
		Shoot	26.9
		Leaf	28.0
		Economic produce	22.9
Chakla	Boro paddy (standing)	Root	89.7
		Shoot	39.3
		Leaf	36.7
		Economic produce	23.8
Iajpur	Boro paddy (standing)	Root	80.1
		Shoot	42.5
		Leaf	32.8
		Economic produce	21.2

The findings from the present vertical transport studies are expected to provide additional information on the nature of arsenic retention/release processes in the given surface soil samples, alongwith that on the deposition or accumulation of the dissolved arsenic down the soil profile from the contaminated groundwater-irrigation source. Such retention/deposition of arsenic in the given soils has been related to the texture and organic matter contents in the present soils.

Total arsenic content in the triacid digests of different parts (i.e. root, shoot, leaf and economic produce/grain) of summer (boro) paddy grown in the given soils is summarized in Table 7. The total arsenic loading in the different parts of boro paddy collected from Chakla was found to be generally higher than those for the remaining three sites. On the other hand, such arsenic content was much lower in case of boro paddy grown in the soils of the East Chyangdana. This may possibly be related to the lower binding capacity of the Chakla soil, causing thereby a greater degree of arsenic extraction by the plant roots in this soil.

Experimental

Four surface soil samples were used in this investiga-

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tion, namely those from East Chyangdana, Ambikanagar, Chakla and Iajpur. All the four sites, which were arsenic affected, were situated in the Deganga Block of North 24-Parganas district, West Bengal. The soil samples were air-dried and crushed to pass through a 2 mm sieve to form the initial soil samples. A number of relevant physical and chemical properties of these soils were measured by the standard methods[16]. Soil pH was measured in a 1 : 2.5 (w/v) soil-water mixture[16] using a combined glass electrode-pH meter (Model : Systronics 335). Electrical conductivity (E.C.) of the soil suspensions (soil : water : : 1 : 5) was determined by using a direct reading conductivity meter (Model : Systronics 303). Orgnaic carbon content of soil samples was measured by the method of Walkley and Black[17] (Nelson and Sommers)[18]. The C.E.C. of the soils was determined by extracting the soils with buffered $BaCl_2$ solution at a pH 8.1, adjusted with triethanolamine, by way of following the method of Bascomb[19], as outlined by Dewis and Freitas[20]. Sand, clay and silt percentages were determined by the International pipette method and the texture of the soils was also ascertained from the particle-size distribution of sand, silt and clay. Olsen P content of the present soils was determined by extracting 2.5 g of each soil with 50 ml of 0.5 M $NaHCO_3$ (pH 8.5) for 30 min and determining the phosphorus by the L-ascorbic method[21]. The oxalate-extractable (amorphous) Fe content of the given soils was obtained by extracting the soils with 0.3 M ammonium oxalate in oxalic acid solution, pH 3.25[22], followed by measurement of Fe by atomic absorption spectrophotometer (see later). The surface area of each soil sample was measured by the ethylene glycol retention method[23]. To determine the exchangeable cations, soil sample were treated with neutral normal ammonium acetate solution (pH 7.0) in 1 : 10 ratio[17]. After 1 h shaking, followed by filtration, the leachate was used for the determination of Ca^{2+}, Mg^{2+}, Na^+ and K^+. Calcium and Mg^{2+} ions were determined by means of chelometric titration using disodium salt of ethylene diamine tetra-aceticacid (EDTA). Potassium and Na^+ ions in the leachate were measured by using a flame photometer (Model : Systronics 121). The soil samples were also subjected to extraction of labile arsenic pool in soil by using Olsen's extractant, namely 0.5 M $NaHCO_3$, pH 8.5[24]. The arsenic content of soil extracts was measured by using the atomic absorption spectrophotometer (AAS), coupled with a hydride generator unit (Model : GBC932B, HG-3000). Solution conductivity through the given soils was computed by way of fitting the transport data to the appropriate form of the Darcy's law[15].

Flow through vertical soil column : The soils under

study were taken into a double-chambered vertical column (Fig. 1) made of Borosil glass. The upper column slipped into the lower one through a B-34/35 standard joint, leaving a length of 20 cm for each of the upper and lower columns. The internal diameter of each column was 3.0 cm, and the bottom of the lower column was closed by a G-4 sintered glass disc on the top which was placed a filter paper of the appropriate circular size. This formed the base of the soil column which was then subjected to a constant pressure head of aqueous arsenic solutions of different concentrations (C_0), namely 200, 400, 800 mg As L^{-1} by means of a Marriot arrangement, attached to the upper column through a standard joint system (Fig. 1). The leachates were collected at different intervals of 1.0 h, and the experiment was continued overnight for each soil for each feed solution. The time periods used were pre-set depending on the permeability characteristics of the given soils. The volumes of the leachates, collected at different time intervals, were noted, while the corresponding arsenic concentrations (C') were measured by using the above stated atomic absorption spectrophotometer (AAS), coupled with the hydride generator unit.

The study with the present vertical column was conducted to ascertain the Darcy's saturated hydraulic conductivity (k), arsenic accumulation in the experimental soils and the relative hold-up of arsenic by the given permeating media (i.e. the present soils). The k value was obtained by applying the Darcy's law (eq. (1)) to the given soil-flow system. Thus,

$$q = k \frac{\Delta H}{L} \tag{1}$$

where q is the volume flux density through the soil column, ΔH the hydraulic head difference and L is the length of the soil column. The data generated from the given experiment were also used in the formalism developed by Johnson et al.[25] in assessing the solute accumulation parameter, r (eq. (2)), by the soil column (permeated by the given arsenic solution), namely

$$r = 1 - \frac{C'}{C_0} \tag{2}$$

where C' and C_0 are the solute (arsenic) concentrations in the effluent and the feed solution, respectively.

The breakthrough curves (BTC) for the given electrolyte : The above stated results were plotted, showing (C'/C_0) against the number of pore volume, P_v, of the effluent (leachate), obtained from (eq. (3)), namely

$$P_v = \frac{V}{V_0} \tag{3}$$

where V is the volume of the leachate collected in a given time t and V_0, the volume of the voids, containing the displacing fluid in the soil column. The latter was obtained from eq. (4), namely

$$V_0 = n_0 V_1 \tag{4}$$

where n_0 is the water-filled porosity at the given time and V_1 is the total volume of the soil column. The value of n_0 at the appropriate time intervals used in the given experiment was obtained by soaking the soil (from bottom upward) with water over the given time periods[9,13].

The plant samples [in this case, summer (*boro*) paddy] were collected from the selected farmer's fields of the present four sites and brought to the laboratory. These plant samples were next washed properly [initially with tap water to remove the adhering soil particles (particularly for the root zone soil samples) and thereafter rinsed with double distilled water] and processed to obtain different plant parts like root, shoot, leaf and economic produce (such as rice grain). The latter were appropriately labelled, dried in an air-oven at 105°C for 24 h. The dried plant samples were ground and a portion (such as 1.0 g) of each dried plant sample was digested on a sand bath with triacid mixture ($HNO_3 : H_2SO_4 : HClO_4 : : 10 : 1 : 4$, by volume) to obtain the clear digest. The digests were cooled and diluted with double distilled water and then filtered through Whatman No. 42 filter paper[24]. Total arsenic content of the filtrates was determined by using the atomic absorption spectrophotometer, coupled with the given hydride generator unit.

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