

Quantification of the severity, reserve and extent of acidity in the twenty profiles of acid sulfate soils and their threats to environment

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Abstract

Selected characteristics of acid sulfate soils that are arising problems to environments were investigated during 1999 to 2001. The studied soils occurred in eight series and classified as Salidic Sulfaquept and Typic Sulfic Halaquept (new name to be considered for soil classification). Due to heavy rain, flash flood and wide spread run off from adjacent hill areas, the surface soils were eroded by about 10 to 30 cm during the last decade. Yellow patches resembling Jarosite were identified at the depths of 10 to 150 cm in the 20 profiles, which making not only acidity problems of the soils but also creating a lot of troubles to the surroundings. Most of the studied soils are rich in clay. Exchangeable sodium percentage of the soils ranged from 14 to 55. Extreme pH values (2.6-5.2) were observed in the studied profiles. The content of total sulfuric acidity of the soils ranged from 3 to 19 c mol kg⁻¹. The pH and EC values of water samples collected from the nearby ditches, ponds and rivers ranged from 3.1 to 7.2 and 1.2 to 7.0 dS m⁻¹ and the high concentrations of SO₄²⁻ (1096 to 1314 mg L⁻¹) and Al³⁺ (1 to 17 mg L⁻¹) in the samples were determined round the year.

Key words: SO₄²⁻, Al³⁺, environment, *Salidic Sulfaquept*, *Typic Sulfic Halaquept*

Introduction

Acid sulfate soils can cause severe environmental degradation. It has been recently estimated that these soils affect some 100 million hectares (M ha) of land world-wide (Sheeran, 2003). Van Mensvoort and Dent (1998) claimed for about 24 M ha of land is covered by acid sulfate soils of which about 0.7 M ha are located in different pockets of the old mangrove forest areas in the coastal zones of Bangladesh (Khan, 2000). The nature and characteristics of these pockets seemed to be varied from place to place and within pockets owing to the difference in mangrove vegetations and accumulation of sediments. At present, these soils are not only unproductive but also creating severe problem like massive fish killing and polluting surrounding environment though these soils have high agricultural potential (Khan *et al.*, 1994). Massive fish killing and the losses due to it from such situations in the coastal plains of Bangladesh were about \$ 3.4 million during 1988-1989 (Callinan *et al.*, 1993).

As long as these sediments remain waterlogged, the presence of pyrite is not harmful to the environment. When they are subjected to drainage a significant amount of H₂SO₄ has been produced. This H₂SO₄ brings the soil pH below 4, sometimes as low as to 2. With connection to this acidification, a number of chemical, biological and physical problems arise. Cook *et al.* (2006) reported that the progressive oxidation of organic matters, sulfides and increasing acidity in the profile of acid sulfate soil not only

decrease Ca/Al ratios in the soil solution but also strongly affect the fate/mobility of metals and metalloids in the groundwater, posing threat to groundwater quality and health of both terrestrial and aquatic ecosystems. Nordmyr *et al.* (2006) stated that acid sulfate soils liberate more metals into watercourses than the whole Finish industry. They suggested that the environmental impact of metal leakage extends far beyond the geographically adjacent environment, which poses a significant issue for land management.

Acid sulfate soils cause several problems, Al toxicity in drained soils, Fe and H₂S toxicity in flooded soils, salinity and nutrient deficiencies, corrosion of steel and concrete; uneven subsidence, low bearing strength and fissuring leading to excessive permeability of unripe soils, blockage of drains and filters by ochre and the difficulties of establishing vegetation cover on earthworks and restored land (Ritsema *et al.*, 2000). Potential acid sulfate soils may have high pH like 6 to 7, which does not mean that the soils are safe. Because such a situation may create H₂S, Fe, some organic acids and CO₂ problems. In New South Wales of Australia, severe environmental effects occur from the drainage of potential acid sulfate soils by releasing toxic amounts of soluble metals (e.g. Fe, Al and Mn) and mineral deficiencies (P and Cu) in plants (Rosicky *et al.*, 2006).

The weathering of sulfidic mine spoil and overburden presents the same problems, so the acid sulfate soils are not the concern of soil science alone; agronomy, fisheries and

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environmental management, land and property development, civil, mining and water engineering, and public health all have an acute interest in these problem soils. For proper management, the occurrence and potential extent of acid sulfate soils require extensive studies (Dent and Pons, 1995). Therefore, the objectives of the present study were to examine the severity, reserve and extent of acidity in different pockets of acid sulfate soils and their possible threats to the associated ecosystems.

Materials and Methods

Sites

The studied sites (Figure 1) located in the coastal zones have a great variation in geology and landforms. Most of the area is occupied by a relatively smooth, nearly level to gently undulating landscape of piedmont alluvial fans, river and tidal floodplains with ridges and shallow basins, mainly lying 3 to 4 m above the mean sea level. They are underlain by the recent alluvial sediments, which are mainly medium and moderately fine textured at or near the surface. The studied sites were selected mainly on the basis of differences in land type, land use, hydrology, ecology and environmental conditions of the soils (Table 1). The studied sites enjoyed sub-tropical monsoon climate, which has three main seasons namely the monsoon, the dry and pre-monsoon. The monsoon (or rainy: June – October) season, which is warm and humid, during this period the area receives more than 85 % of the total annual rainfall. The dry season (or winter: November – February), which has very little rainfall and has the lowest temperature and humidity of the year. During this time drying of the land, depletion of soil moisture and upward translocation of salts through capillary rise of subsoil moisture or groundwater take place. The pre-monsoon (or hot: March to May) season has the highest temperature and evapo-transpiration of the year. This is the period when the most of the desiccation of the soils accompanied by oxidation/acidification and salinization of their profiles occurs.

Soils

Twenty profiles of acid sulfate soils within 150 km² areas in the coastal plains of Cox' Bazar (Latitude 21°38' to 21°55' N, Longitude 91°55' to 92°10' E), Bangladesh were investigated during the dry seasons of 1999-2001. These soils are classified into eight soil series (Figure 1). Pits of approximately 1.5 m deep were dug depending on the ground water level. The soil profiles were studied following methods of Klute (1986). The studied soils (Table 1) have been classified on the basis of their diagnostic horizons and properties (Soil Taxonomy, 1999; World Reference Base, 1993).

Sample collection and analysis

The soils were sampled and analyzed for every 10 cm from the surface to a depth of 100 cm. The bulk samples obtained from each horizon were stored at the field moist condition (by putting the soil samples into a polyethylene bag in an air tight box). Just prior to laboratory analysis, sub-samples were air-dried and gently crushed to pass through 1 and 2 mm mesh sieves as required. Textural classes of the soils were determined (Black, 1965). Water samples were collected in dry, clean plastic bottles from the nearby ditches and ponds from nine different sites during October, 1999; April, 2000 and August, 2000. These samples were kept in cooling boxes as soon as collected from the fields and then were preserved in a refrigerator in the laboratory.

The pH of the soil samples was determined by three different methods: (i) field conditions (1:1 soil-water ratio), (ii) laboratory condition (dry soil) and (iii) 0.02 M CaCl₂ (dry soil) by using a corning glass electrode pH meter. The ratio of soil to solvent for pH measurement was 1:2.5 in the laboratory as suggested by Jackson, 1973. The electrical conductivity (EC) of the soil was determined first with a ratio of soil - water = 1: 5 by EC meter (USSLS, 1954) and then that value was converted in to the value of saturation extract (ECe) using the formula of ECe = (500 x EC at 1:5 water)/the maximum water holding capacity of the soil. Organic matter content (Nelson and Sommers, 1982), cation exchange capacity, exchangeable and water soluble ions of the soil sample were determined following the methods of Chapman (1965). The water soluble nutrients were extracted by distilled water at the ratio of 1:10. Nitrate in water samples was determined by Micro-Kjeldahl's distillation method of Jackson (1973). Phosphate in water was determined colorimetrically after developing blue color (Sakai, 1978). Water soluble sulfur in the extract was determined colorimetrically by using spectrophotometer after developing turbidity with BaCl₂ using Twin-80 (Sakai, 1978).

Actual acidity, potential acidity and sulfur acidity

The total sulfur acidity (TSA) of the soils was obtained from the differences between total potential acidity (TPA) and total actual acidity (TAA) as proposed by Hendro-Prasetyo *et al.* (1990). These methods are relatively easy and quick, without the use of sophisticated laboratory equipment or expensive chemicals. The TSA represents all the reduced sulfur fractions in the soil. The TSA is therefore, a measure for the acidity that may be generated by the oxidation of the sulfur fractions. The TAA and TPA were determined following the methods of Konsten *et al.* (1988).

Figure Distribution of pH in the 20 profiles of acid sulfate soils in the coastal plains of Cox' Bazar, Bangladesh

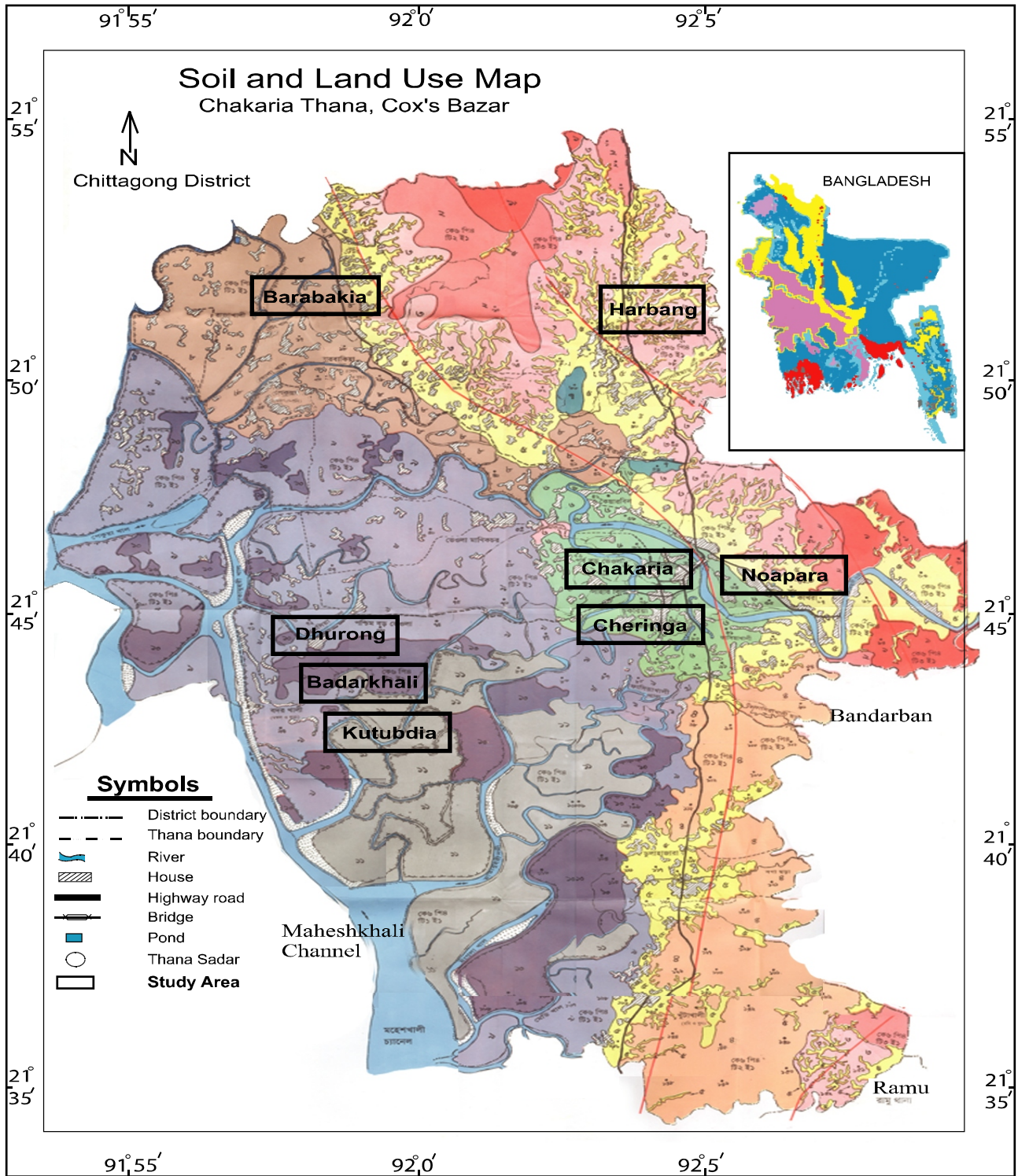


Fig. 2: Occurrence of acid sulfate soils indicating all the studied soils in the coastal plains of Cox's Bazar, Bangladesh.

The TAA is defined as the amount of NaOH titratable acidity that is actually present in a soil sample. The acidity is titrated up to pH 5.5 in a 1 mol L⁻¹ of NaCl suspension (soil-water ratio = 1: 2.5; moist soil). In the determination of TAA no forced oxidation with hydrogen peroxide was considered. Therefore, the acidity as determined by the TAA method reflects the actual total of free hydrogen ions, aluminum, organic acids and possibly ferrous iron. At soil pH below 3 to 3.5 ferric irons too contribute to the TAA. The acidity measured indicates the maximum acidity to be neutralized or to be leached, in order to permit the soil pH to rise to 5.5 under actual conditions. The TPA is the amount of acidity, which may develop in the soil upon complete oxidation of all reduced sulfur species. The TPA is defined as the amount of NaOH titratable acidity up to pH 5.5 of a fresh soil sample in a 1 mol L⁻¹ NaCl suspension (soil-water ratio = 1: 2.5, moist soil) after complete forced oxidation with hydrogen peroxide. The suspension in 1 mol L⁻¹ of NaCl is applied in order to create a standard, strongly saline solution that eliminates a possible pH effect by (differences in) the soil salinity. For soils that are already (partly) acidified, TPA includes most of the sulfate acidity actually

present in the soil. It includes however, the acidity originally from organic acids. The latter are destroyed by the forced oxidation process (AARD and LAWOO, 1992). Correlations between selected parameters and level of significance were determined following statistical packages in Office 2003 program.

Results and Discussion

The studied twenty profiles of acid sulfate soils occur in eight soil series and were classified into two categories as *Salidic Sulfaquept* and *Typic Sulfic Halaquept* (new name for the consideration in soil classification) as per USDA and Sali-thionic Fluvisols (gleyic, orthidystic and orthieutric), Sali-thionic Fluvisols (gleyic, hyperdystic) and Thioni-salic Fluvisols (gleyic, orthidystic and orthieutric) as per the WRB classification. Both the USDA and WRB classification systems were not enough to classify these soils in a right place. Because, these soils have high acidity (pH 3-5; exch. acidity 4-31 c mol kg⁻¹ within 100 cm) and high salinity (ECe 0.4-6.5 dS m⁻¹; ESP 14-55%) problems. It is well known that the physical features are the most important factor in order to identify the soils for proper correction,

Table 1. Selected characteristics of the studied 20 profiles of acid sulfate soils (0-100 cm) in the coastal plains of Cox's Bazar in Bangladesh

Parent material	Soil series	Sampling spot	Soil Classification		Elevation height (m)	Distance from sea (km)
			US Taxonomy	WRB ^a		
Tidal alluvium	Harbang	01. Amin High School	Typic Sulfic Halaquept	Thioni-salic F. (orthidystic)	4.0	25
	Kutubdia	02. Koralkhali	Typic Sulfic Halaquept	Thioni-salic F. (orthidystic)	3.8	23
		03. Koralkhali Salt Bed	Salidic Sulfaquept	Thioni-salic F. (orthieutric)	3.5	22
		04. Chiradia	Typic Sulfic Halaquept	Sali-thioni F. (orthieutric)	3.6	12
		Dhurong	05. Napitkhalipara	Salidic Sulfaquept	Thioni-salic F. (orthidystic)	3.7
	Noapara	06. Omkhali	Salidic Sulfaquept	Thioni-salic F. (orthieutric)	3.7	21
	Badarkhali	07. Purbapukuria	Salidic Sulfaquept	Thioni-salic F. (orthidystic)	3.6	15
	Chakaria	08. Mohorizora	Typic Sulfic Halaquept	Thioni-salic F. (orthidystic)	3.6	12
		09. Satdaliapara	Typic Sulfic Halaquept	Thioni-salic F. (orthidystic)	3.6	17
		10. Elisha	Salidic Sulfaquept	Thioni-salic F. (orthidystic)	3.7	24
		11. Sarisabari-I	Salidic Sulfaquept	Thioni-salic F. (hyperdystic)	3.0	11
	Barabakia	12. Ringbong	Typic Sulfic Halaquept	Thioni-salic F. (orthidystic)	3.4	15
		13. Lumbamura	Salidic Sulfaquept	Thioni-salic F. (orthidystic)	3.6	14
	Cheringa	14. Sarisaghata	Typic Sulfic Halaquept	Sali-thioni F. (orthidystic)	3.5	14
		15. Cheringa	Typic Sulfic Halaquept	Thioni-salic F. (orthidystic)	3.5	13
		16. Dulhajara	Typic Sulfic Halaquept	Thioni-salic F. (orthidystic)	3.5	13
		17. Malumghat	Typic Sulfic Halaquept	Thioni-salic F. (orthidystic)	3.4	13
		18. Dargagate	Salidic Sulfaquept	Thioni-salic F. (orthidystic)	3.4	11
		19. Sarisabari	Salidic Sulfaquept	Thioni-salic F. (orthidystic)	3.2	12
		20. Sarisabari-II	Salidic Sulfaquept	Thioni-salic F. (orthidystic)	3.2	12

Cont'd...

Table 1. (Continued)

Soil series	Sampling spot	Land type	Land use of sampling sites	Jarosite layer ^b (cm)	ECe ^c (dS m ⁻¹)	ESP ^d (%)	EA ^e (c mol/kg)	Textural class	n-value
Harbang	01	Medium low	Rice-Veg.-fallow	60+	4–9	17–21	09-11	Si L	0.53–0.62
Kutubdia	02	Medium low	Rice -fallow	50+	10–26	19–29	09-15	Si C – Si C L	0.49–0.57
	03	Medium low	Salt bed	30+	18–65	38–43	14-17	Si C – Si C L	0.50–0.61
	04	Low	Salt bed	150+	15–34	29–41	04-08	Si C – Si C L	0.48–0.57
Dhurong	05	Medium low	Fallow	20+	19–53	31–55	09-18	Si C – Si C L	0.51–0.59
Noapara	06	Medium low	Shrimp culture	40+	17–58	25–40	10-18	Si C – Si C L	0.51–0.60
Badarkhali	07	Medium low	Fallow	20+	13–34	25–36	11-14	Si C L	0.45–0.56
Chakaria	08	Medium low	Rice - fallow	60+	10–17	29–37	06-10	Si C L	0.48–0.60
	09	Medium low	Rice - fallow	50+	7–15	16–22	09-25	Si C L	0.50–0.61
	10	Medium low	Fallow	10+	9–18	23–30	10-21	Si C L	0.49–0.61
	11	Medium low	Fallow	40+	8–14	15–22	19-29	Si C L	0.51–0.62
	12	Low	Fallow	60+	6–19	17–21	15-20	Si C L	0.49–0.59
Barabakia	13	Low	Rice - fallow	40+	7–20	18–21	15-31	Si C L	0.51–0.60
Cheringa	14	Medium low	Rice - fallow	100+	11–19	14–20	18-26	Si C L– Si C	0.43–0.52
	15	Low	Rice - fallow	80+	4–19	16–23	09-19	Si C L– Si C	0.41–0.52
	16	Low	Rice - fallow	70+	2–38	17–35	04-16	Si C L– Si C	0.44–0.55
	17	Low	Rice - fallow	60+	5–18	15–24	05-15	Si C L– Si C	0.40–0.51
	18	Low	Fallow	30+	7–28	15–18	17-25	Si C L– Si C	0.42–0.52
	19	Low	Fallow	20+	11–19	14–20	21-30	Si C L	0.41–0.53
	20	Low	Fallow	30+	8–18	14–19	21-30	Si C L	0.42–0.52

^a = World Reference Base for Soil Resources, FAO, 1998, ^b = Upper boundary of Jarosite layer under field condition, ^c = Electrical conductivity of saturation extract; ^d = Exchangeable Sodium Percentage; ^e = Exchangeable Acidity (CEC – exchangeable bases); n-value = $(A - 0.2R)/(L + 3H)$, where A = % of water in the soil in field condition calculated on a dry soil basis, R = % of silt + sand, L = % of clay and H = % of organic matter.

planning and utilization of the problem soils. Accordingly, the land type of the 10 profiles was observed as low land and the rest 10 profiles were in medium low land. The texture of the soils ranged from silty clay to silty clay loam, except for Amin High School of Harbang series, which possesses silt loam texture (Table 1). Most of the studied soils are rich in clay. Due to high clay content of these soils, the reclamation of these acid sulfate soils through leaching is not an effective method. Because, leaching through Na-enriched seawater may reduce the permeability of the soils by Na-adsorption that may result in the sodicity problem of the soils. Land use conditions of these soils were mainly Fallow (9 profiles) and Rice-Fallow (8 profiles). Only two sites are under salt bed and one site is being used for shrimp culture.

During field investigations, Jarosite layers were identified at depths of 10 to 150 cm in the 20 profiles. The upper boundary of the hazardous layers, i.e. yellow patches of Jarosites were identified in three soils at depths of 30 to 40 cm during 1989, whereas in 1999 these boundaries were detected at depths of 10 to 20 cm (Table 2). These upper

boundary of Jarosite layers were identified during the year 2000 within the depths of 60 cm in 16 profiles and the severity of these problems were determined for 7 profiles, where the Jarosite layers were identified within or around root zone depth (10-30 cm from the soil surface: Table 1). Due to severe erosion, deforestation and cultivation, these Jarosite layers have been brought very near to surface soil and making not only acidity problems of the soils but also creating a lot of problems to the associated ecosystems. During the last 10 to 15 years, the surface soils were eroded by more than 10 to 30 cm due to heavy rains, flashfloods and widespread runoff from the adjacent hilly areas (Khan, 2000; Table 2). Frightening conditions in pH levels, soluble sulfate, Al and Na –saturation, and Ca/Al ratios were determined in the soils (Table 2), which are very dangerous for the associated environments.

All the acid sulfate soils studied at 20 sites have pH values ranging from 3.1 to 5.6, which might be due to their Jarosite layers within the 100 cm depth, except for the Chiradia soil, where Jarosite layer was observed at depth of

>150 cm and which has been used as salt bed (Table 1). Among the 20 profiles, the soil pH (0.02 M CaCl₂) of 10 profiles (Koralkhali, Satdaliapara, Elisha, Purbapukuria, Sarisabari-I, Lumbamura, Sarisaghata, Cheringa, Sarisabari

Table 2. Comparison of 11 years data obtained from three acid sulfate soils (0-15 cm depth) at the coastal plains of Cox' Bazar in Bangladesh

Properties	Cheringa Series		Chakaria Series		Badarkhali Series		Unit
	1989 ^a	1999	1989 ^a	1999	1989 ^a	1999	
Textural class	Silty clay	Silty clay loam	Silty clay loam	Silty clay	Silty clay	Silty clay	
Bulk density	1.01	1.03	1.08	1.04	1.03	1.10	Mg m ⁻³
Soil pH (Field)	4.5	3.9	5.8	4.5	5.2	4.2	
Soil pH (CaCl ₂)	3.4	3.2	4.6	4.1	4.4	3.4	
Jarosite layer	30+	20+	40+	10+	40+	20+	cm
ECe	16	19	16	12	14	16	dS m ⁻¹
Organic matter	36.4	40.3	34.0	25.0	26.7	31.3	g kg ⁻¹
C/N ratio	15.8	16.5	16.0	10.0	15.0	15.0	
Available N	4.29	3.65	4.0	2.43	3.29	3.27	m mol L ⁻¹
Available P	0.17	0.10	0.20	0.08	0.17	0.11	m mol L ⁻¹
CEC	16.7	18.2	16.5	28.5	19.0	19.6	c mol kg ⁻¹
Base saturation	43	22.2	48.9	44.0	33.3	24.9	%
Al-saturation	58.9	42.4	12.9	15.8	63.9	43.2	%
Fe-saturation	20.5	8.3	21.5	11.5	16.5	7.8	%
Na-saturation	27.1	13.4	29.2	29.0	20.3	14.8	%
K-saturation	4.7	1.4	4.5	3.2	3.5	1.5	%
Ca-saturation	4.3	1.8	4.7	2.0	3.1	2.0	%
Mg-saturation	7.3	5.6	10.4	10.0	6.5	6.6	%
Ca/Mg ratio	0.59	0.32	0.45	0.19	0.48	0.30	
Ca/Al ratio	0.07	0.04	0.36	0.13	0.05	0.04	
Water soluble ions:							
Calcium	0.35	0.27	0.39	0.41	0.42	0.33	c mol kg ⁻¹
Magnesium	2.62	3.34	2.02	3.10	2.22	3.66	c mol kg ⁻¹
Aluminum	1.14	2.12	0.39	1.12	1.32	1.84	c mol kg ⁻¹
Iron	0.25	0.33	0.29	0.36	0.33	0.30	c mol kg ⁻¹
Chloride	3.32	2.86	3.45	2.97	3.26	2.60	c mol kg ⁻¹
Sulfate	3.42	4.96	4.60	3.82	4.92	4.12	c mol kg ⁻¹

^aSource: Khan *et al.*, 1993 and Khan *et al.*, 1996

Table 3. Distribution of total sulfuric acidity (TSA: c mol kg⁻¹) in the 20 profiles of acid sulfate soils in the coastal plains of Cox' Bazar in Bangladesh

Depth (cm)	1. Amin High School	2. Koralkhali	3. Koralkhali Salt Bed	4. Chiradia	5. Napitkhalipara	6. Omkhali	7. Purbapukuria	8. Mohorizora	9. Satdaliapara	10. Elisha
0-10	8.06	6.88	14.74	12.21	19.60	11.04	14.36	19.86	8.99	3.57
10-20	8.84	3.72	14.72	12.39	6.67	13.77	19.00	15.14	1.79	2.31
20-40	8.82	14.14	9.30	10.25	23.60	12.78	15.54	17.51	5.05	3.02
40-60	11.62	9.67	17.57	8.47	10.81	12.59	20.61	21.33	6.83	1.17
60-80	9.85	9.85	18.87	11.03	8.84	13.02	15.57	9.40	7.89	2.57
80-100	9.58	11.01	11.60	7.07	8.24	12.60	17.04	6.27	12.65	3.19
Weighted average	9.46	9.21	14.47	10.24	12.96	12.63	17.02	14.92	7.20	2.64
SD	1.23	3.57	3.58	2.11	6.94	0.89	2.37	5.96	3.67	0.85
r (depth/TSA)	0.56*	0.52*	0.08 NS	-0.80**	-0.47*	0.24 NS	0.13 NS	-0.74**	0.63**	-0.14 NS
Depth (cm)	11. Sarisabari-I	12. Ringbong	13. Lumbamura	14. Sarisaghata	15. Cheringa	16. Dulhajara	17. Malumhat	18. Dargagata	19. Sarisabari	20. Sarisabari-II
0-10	14.23	11.32	12.09	9.69	8.73	10.17	11.04	13	14.76	13.8
10-20	13.55	14.5	10.38	9.51	10.03	10.55	12.96	16.51	12.35	14.55
20-40	12.62	16.27	16.01	9.3	10.02	10.68	12.03	16.31	8.03	11.09
40-60	14.02	19	14.62	11.63	14.63	11.03	17.47	22.07	16.76	17.87
60-80	16.08	18.47	16.08	17.03	15.01	13.91	17.87	22.11	14.08	16.31
80-100	24.65	20.72	20.65	17.23	16.09	18.38	21.26	22.8	23.58	24.77
Weighted average	15.86	16.71	14.97	12.41	12.42	12.45	15.44	18.8	14.93	16.4
SD	4.05	3.42	3.58	3.74	3.17	3.2	4.03	4.07	5.16	4.7
r (depth/TSA)	0.77**	0.94**	0.89**	0.92**	0.95**	0.88**	0.95**	0.93**	0.64**	0.78**

* and ** = significant at 5 and 1% level, respectively, NS = Non significant.

and Sarisabari-II: Figure 2) were determined below pH 4 and 4 profiles (Amin High School, Koralkhali salt bed, Napitkhalipara and Omkhali) were found to have pH >4 through out the 100 cm profiles. Only Chiradia soils have pH ranged from 5.0 to 6.3 through out their profiles (Table 1). The rest 5 profiles were found to have the soil pH values

ranged from 2.6 to 5.2. At these low pH values, all soil processes, ion dynamics, mineralogy, etc. were seriously affected and these harmful effects lead to the degradation of the soils through losses of basic cations by the exchange of enriched acidic cations (Allbrock, 1973; Metson *et al.*, 1977). Almost all the studied profiles showed the high ECe

Table 4. Groupings of the soil profiles based on the studies of total sulfuric acidity (TSA) and lime requirement (LR)

Group	Location of soil profile (Classification)	TSA (c mol kg ⁻¹)	LR (t ha ⁻¹)
A	10. Elisha (Salidic Sulfaquept = SS)	3	<50
B	1. Amin High School (Typic Sulfic Halaquept=TSH), 2. Koralkhali (SS), 9. Satdaliapara (TSH)	5-9	50-100
C	3. Koralkhali salt bed (SS), 4. Chiradia (TSH), 6. Omkhali (SS), 19. Sarisabari (SS), 11. Sarisabari-I (SS), 20. Sarisabari-II (SS), 14. Sarisaghata (TSH), 13. Lumbamura (SS), 15. Cheringa (TSH), 16. Dulhajara (TSH) and 17. Malumghat (TSH)	10-13	100-150
D	8. Mohorizora (TSH), 5. Napitkhalipara (SS), 7. Purbapukuria (SS), 12. Ringbong (TSH) and 18. Dargagate (SS).	14-18	150-200

Table 5. Selected properties of water samples collected from nearby ponds and ditches of the studied 20 profiles in the coastal plains of Cox' Bazar, Bangladesh

Sl. No.	Sampling Spot	pH	EC (dS m ⁻¹)	Na ⁺	K ⁺	NO ₃ ²⁻	PO ₄ ³⁻	SO ₄ ²⁻	Al ³⁺
		(mg L ⁻¹)							
<u>Sampling Date: 16.10.1999</u>									
01.	Purbapukuria Expt. Site-1a	3.9	3.1	789.1	49.6	0.22	1.09	1096	14.0
02.	Purbapukuria Expt. Site-1b	4.1	2.5	491.3	40.3	0.21	1.04	1018	10.0
03.	Badarkhali Cyclone Centre	6.1	2.8	934.8	99.4	0.34	1.34	624	3.5
04.	Lake water of Purbapukuria	4.0	2.6	486.4	95.0	0.34	2.41	1040	12.0
05.	Mathamuhuri River	6.3	1.3	112.2	117.6	0.52	13.92	580	1.3
06.	Chowdhuribari Fish Pond	4.3	2.0	149.7	33.5	0.40	2.54	960	11.0
07.	Sarisabari Expt. Site-2	3.9	2.9	155.4	47.6	0.34	1.15	1343	14.5
08.	Lambamura pond	3.6	3.4	106.8	29.0	0.32	0.96	1521	16.0
09.	Cheringa Site	3.2	3.3	173.5	23.0	0.24	0.86	1685	16.5
	Mean	4.4	2.7	377.7	59.4	0.33	2.81	1096	11.0
	SD	1.1	0.7	314.5	34.9	0.10	4.21	372	5.3
<u>Sampling Date: 22.04.2000</u>									
10.	Purbapukuria Expt. Site-1a	3.7	3.8	850.0	31.0	0.24	0.86	1225	15.0
11.	Purbapukuria Expt. Site-1b	4.1	3.2	818.8	34.8	0.22	0.97	1155	11.0
12.	Badarkhali Cyclone Centre	5.8	7.0	1980.0	74.0	0.36	1.12	1511	9.0
13.	Lake water of Purbapukuria	3.9	3.6	823.8	35.9	0.29	0.96	1251	15.0
14.	Mathamuhuri River	7.0	1.6	198.0	132.0	0.48	12.32	601	1.8
15.	Chowdhuribari Fish Pond	4.1	2.8	141.5	30.5	0.38	1.65	1086	9.5
16.	Sarisabari Expt. Site- 2	3.8	3.6	288.4	29.8	0.24	0.95	1547	13.0
17.	Lambamura pond	3.4	3.8	246.9	21.8	0.27	1.14	1631	15.5
18.	Cheringa Site	3.1	3.8	342.4	18.6	0.22	0.86	1816	17.0
	Mean	4.3	3.7	632.2	45.4	0.30	2.3	1314	11.9
	SD	1.3	1.4	582.6	36.2	0.09	3.8	361	4.7
<u>Sampling Date: 17.08.2000</u>									
19.	Purbapukuria Expt. Site -1a	4.2	3.3	720.0	46.5	0.25	1.56	1124	12.0
20.	Purbapukuria Expt. Site-1b	5.3	3.0	740.0	54.8	0.24	2.13	1036	9.0
21.	Badarkhali Cyclone Centre	6.6	3.8	937.5	58.5	0.41	2.13	1011	3.5
22.	Lake water of Purbapukuria	3.9	3.3	823.8	35.9	0.26	1.84	1168	13.0
23.	Mathamuhuri River	7.2	1.2	90.8	112.0	0.52	12.10	607	1.3
24.	Chowdhuribari Fish Pond	4.4	2.0	123.5	36.2	0.35	2.71	942	8.5
25.	Sarisabari Expt. Site - 2	3.9	2.8	126.4	52.4	0.32	0.85	1316	12.5
26.	Lambamura pond	3.6	2.6	119.3	34.2	0.28	0.76	1484	13.5
27.	Cheringa Site	3.3	3.2	198.6	28.9	0.25	0.62	1551	16.0
	Mean	4.7	2.8	431.1	51.0	0.32	2.74	1138	9.9
	SD	1.4	0.8	361.3	25.1	0.09	3.58	289	4.9

values ($>4 \text{ dS m}^{-1}$) within the 100 cm depths (Table 1). The highest E_{Ce} value was obtained from the profile in Koralkhali salt bed ($18\text{-}65 \text{ dS m}^{-1}$) followed by Omkhali (17-58), Napitkhalipara (19-53), Dulhajara (2-38), Chiradia (15-34), Purbapukuria (13-34), Dargagate (7-28) and Koralkhali (10-26). The rest of the profiles, where the E_{Ce} values were recorded within the range of 4 to 19 dS m^{-1} . Except Koralkhali salt bed and Chiradia profiles, all the profiles showed the increased trend of the E_{Ce} values with deeper depths. These two soils showed the higher E_{Ce} values in the surface soils (0-10 cm) due to the process of salt production on their surface soils. The above conditions of the soils demonstrated that the studied soils were highly affected by salinity. Marius (1982) reported that salinity levels in acid sulfate soils are variable. The highest level occurred in young acid sulfate soils in regions with a prolonged dry season such as Senegal, where E_{Ce} values were more than 80 dS m^{-1} occurs in the upper 30 cm of soil and surface salt crust was formed during the dry season. The ESP of the soils ranged from 14 to 55 (Table 1), which is very dangerous for crop growth and for some physico-chemical properties of the soils as well as hazardous for aquatic life, water quality and drinking water. The ESP increased towards the deeper depths of the soil profiles. These characteristics indicate that all the study areas were strongly influenced by saline seawaters. The highest content of 21 to 30 c mol kg^{-1} exchangeable acidity (EA) was recorded in Sarisabari and Sarisabari-II followed by Sarisabari-I (19-29), Sarisaghata (18-26), Dargagate (17-25), Satdaliapara (9-25) and Elisha (10-21). Other soils were found to have their EA values within the range of 5 to 20 (Table 1), except for Chiradia, which had EA of 4 to 8 c mol kg^{-1} . It is also noticed that these EA values increased at or near the Jarosite layers within the profiles. Khan (1994) reported that EA in acid sulfate soils increased strikingly with the prolonged period of dryness and the values ranged from 2.4 to $28.4 \text{ c mol kg}^{-1}$.

All the studied soils showed their characteristics of having n-value of the soil ranged from 0.4 to 0.6 (within 0-100 cm depth), which reflected that the matured/ripen soil horizon development in all these soils (Table 1). The amounts of exchangeable Ca and Mg were high in the studied 20 profiles of acid sulfate soils, which might be attributed to the impact of acidity in the soils. These results are in agreement with findings of van Breemen (1993) on the acid sulfate soils of Thailand. He stated that the exchangeable Ca and Mg contents of acid sulfate soils were higher than those of the Ca and Mg in the ocean water, which might be due to the release of cations liberated by cation exchange and mineral weathering during pyrite oxidation. The amount of exchangeable Mg in the soils was higher than Ca, which is an indication of old marine deposits

where the Ca has largely been leached and Mg is maintained at a relatively high level, probably as results of progressive clay disintegration and release of Mg (Ahmed and Wilson, 1992). Moreover, the higher amount of Mg content presumably was due to the connection with seawater of high Mg content (Khan *et al.*, 1994).

Quantities of total sulfuric acidity (TSA)

The maximum quantity ($18.8 \text{ c mol kg}^{-1}$ soil, average of 100 cm) of TSA was determined within 100 cm of the profile at Dargagate followed by Purbapukuria (17.0), Ringbong (16.7), Sarisabari-II (16.4), Sarisabari-I (15.9), and Malumghat (15.4) profiles (Table 3). The average lowest quantity of TSA was obtained from the profiles at Elisha ($2.6 \text{ c mol kg}^{-1}$) > Satdaliapara (7.2) > Koralkhali (9.1) > Amin High School (9.6). The rest of the profiles were found to be contained 10 to 15 c mol kg^{-1} of TSA. However, the maximum TSA content up to 40 cm of the profile was found at Mohorizora ($17.5 \text{ c mol kg}^{-1}$) followed by the profiles at Napitkhalipara (16.6), Purbapukuria (16.3), Dargagate (15.3), Ringbong (14.0, Table 3). The Distribution of TSA with their corresponding depths showed strong positive relationships for 13 profiles ($p \leq 0.05$), significant negative relationships with 3 profiles and the rest 4 profiles showed no significant relationships with the depths (Table 3). The pattern of distribution of TSA evidenced that the techniques for the neutralization of acidity in these soils would be different. It is noticed that one mole of acidity requires 50 g (or $11 \text{ t lime ha}^{-1}/\text{c mol}$ in the surface 10 cm soil) of lime (CaCO_3) to neutralize the soil. Thus, the profiles studied can be grouped into 4 categories on the basis of lime requirement to neutralize the surface 40 cm of the soils (Table 4).

The lime requirements as shown in this study agreed well with the findings of van Breemen (1993) who reported that 1% oxidizable sulfur will require 30 t of lime to neutralize per ha of 10 cm surface of acid sulfate soil. Usually acid sulfate soil contains 1 to 5% oxidizable sulfur and the studied soils contained 2 to 7% oxidizable sulfur (Khan and Syeed, 2000), which indicate a huge amount of lime would be needed. But in practice, the lower doses of lime (about 10 t ha^{-1}) often have distinct beneficial effect, while larger doses are rarely economical (Khan, 1994). Moreover, this may create problems for micronutrients and therefore, these soils should be reclaimed by physical changes or can be used for other purposes like reclamation of saline soils, sulfur-deficient soils, etc. instead of in situ neutralization. However, basic research should be considered for the neutralization of these soils under various state and soil conditions.

Water quality

Impacts of different seasons on acid sulfate soils and associated water quality were monitored in the 9 sites during October 1999, April and August 2000. The pH values of water ranged from 3.2 to 6.3 during October 1999, 3.1 to 7.0 during April 2000 and 3.3 to 7.2 during August 2000 (Table 5). The maximum pH values (6.3-7.2) among the 9 sites were recorded throughout the seasons in the water of Mathamuhuri River, where the lowest pH (6.3) value was determined during October 1999 and the higher pH values of 7.0 and 7.2 were recorded in April 2000 and August 2000, respectively. These variations in pH might be due to the dilution effect of acidity with rainwater. On the other hand, minimum pH values (3.1-3.6) were always recorded for the pond water at Cheringa and Lumbamura, where the maximum decrements of the pH values were determined during April 2000. This indicates that the acidity produced during dry season (October to April) was drained into the water, which made it more acidic. The water having such low pH values (< 4) is not at all suitable for the growth of crops as well as for other aquatic lives, even unsuitable for drinking purpose. Almost similar properties of waters in the acid sulfate soil areas had also been reported by Callinan *et al.* (1993). The EC values of water ranged from 1.3 to 3.4 dS m⁻¹ (October 1999), 1.6 to 7.0 (April 2000) and 1.2 to 3.8 during August 2000. The concentrations of sodium have shown similar trends as those of the EC values of the waters throughout the year. The concentration of potassium in waters showed strong positive correlation ($r = 0.69$) with pH during April 2000 followed by ($r = 0.76$) August 2000 and ($r = 0.45$) October 1999. This suggests that the pH had a positive effect on the availability of soil potassium. The significant ($p \leq 0.05$) negative correlation between sulfate contents of the water samples and their corresponding pH values during October 1999 was ($r = -0.92$) and in August and April 2000 were -0.81 and -0.78 , respectively. This indicates that the SO₄²⁻ contents increase when the pH of the water samples decrease. The striking increment of SO₄²⁻ content in the studied waters was determined during April, i.e. beginning of the rainy season. This might be due to wash out of the huge amount of SO₄²⁻ from the oxidation of pyrite in acid sulfate soils. The concentration of SO₄²⁻ in river water was low as compared with the other sites (Table 5), which might be due to the dilution effect of rain and stream waters.

The Al³⁺ contents of the studied water samples were strikingly alarming. Highly significant ($p \leq 0.01$) negative correlations ($r = -0.97$ to -0.99) between the Al³⁺ and their corresponding pH values were obtained round the year. The average Al³⁺ content was high during April, which might be due to the wash out of Al³⁺ from the adjacent acid sulfate soils. In August, the concentration of Al³⁺ in water was slightly low because of dilution effect. The concentrations of

Al³⁺ in waters of the studied sites were ranged from 1.3 to 17.0 mg L⁻¹, which is very hazardous/toxic compared to the standards, and that of potable water mostly range between 0.05 and 1.5 mg Al³⁺ L⁻¹ (Sitting, 1994).

Concentrations of 1-2 mg Al³⁺ L⁻¹ are toxic to most crops, while fish are most susceptible; fish killing occur at >0.5 mg Al³⁺ L⁻¹. It is noted that a considerable amount of Al³⁺ was also determined at around pH 6 of waters, which might be due to the result of organically bound Al in these waters.

Conclusions

The studied 20 profiles of acid sulfate soils were classified into two categories as Salidic Sulfaquept and Typic Sulfic Halaquept. The Ca content of the soils is low in relation to Mg. The Al content was at toxic level for plant growth and aquatic lives. On the basis of lime requirement to neutralize the total sulfuric acidity (TSA) in the surface 40 cm of the soils, the studied sites can be grouped in to 4 categories as - A: <50 t CaCO₃ ha⁻¹ for soils having 3 c mol of TSA; B: 50 to 100 t for 5 to 9 c mol; C: 100 to 150 t for 10 to 13 c mol; and D: 150 to 200 t for 14 to 18 c mol of TSA. Due to high organic matter, sulfur and micronutrient status, these soils or sulfidic materials may be used as bio-fertilizers specially for sulfur deficient soils and can be applied as amendment to calcareous, alkaline and tea soils; and can also be used for nursery crops, which will require extensive research. The removal of sulfidic materials will reclaim not only the soils but will also bring benefits to the different classes of peoples.

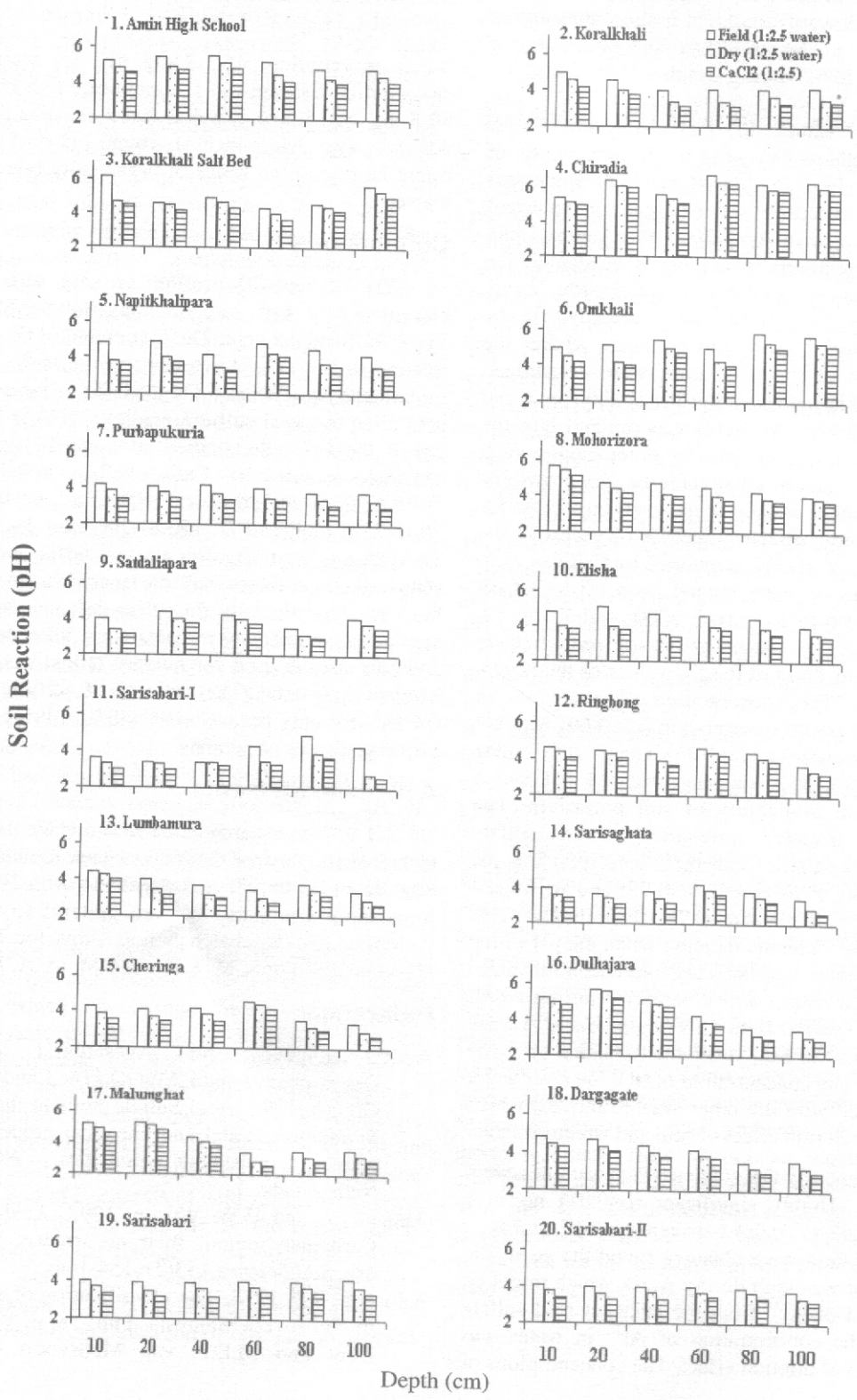
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Figure 2. Distribution of pH in the 20 profiles of acid sulfate soils in the coastal plains of Cox's Bazar, Bangladesh.



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