Hydromorphic soils of Tripura: their pedogenesis and characteristics

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Hydromorphic soils that have developed on gently to very gently sloping flood plain areas of Tripura, North East India under humid tropical climate, were studied for characterization with reference to the degree of hydromorphism. The soils are characterized by the redoximorphic features, viz. mottling, gley with chroma 2 or less, and have a typical gley colour from the surface to subsoil, mostly influenced by the high groundwater level. These soils support the granary of the state. The degree of hydromorphism in these soils has been determined by the extent and distribution of mottles and gley in the profiles, which reflects the effect of the fluctuating groundwater table and depth of the permanent water table. The soils are deep to very deep with varying texture and drainage classes and have some common characters during pedogenesis under impeded drainage condition. Soils are acidic, medium to high in organic carbon, low in cation exchange capacity (CEC) and medium to high in base status. The low value of 1N KCl extractable Al^{+3} corroborates relatively high proportion of hydroxy-interlayered vermiculitic clay mineral present in the soil. Soil texture is found to be the key factor in developing hydromorphism as well as soil organic carbon stock in the hydromorphic soils of Tripura. Translocation of clay and free iron oxide (Fe_d) is generally prominent in the soils with medium to coarse texture. Based on the physical and chemical properties and the hydromorphic index, the soils can be arranged as Nayanpur > Dukli II > Dharaichherra > Dukli I > Goachand to indicate the degrees of hydromorphism.

Keywords: Gley, hydromorphic soils, mottles, soil organic carbon.

PROLONGED water saturation and seasonal alteration between waterlogging and drainage has profound effects on soil chemical and morphological properties. Changes in the degree of water saturation affect the supply of O_2 to the soil, which in turn affects the oxidation state of important elements. The oxidation state of iron, manganese and sulphur strongly influences their solubility and colour, explaining the brown, grey, blue, black and yellow mottles often seen in periodically wet, so-called hydromorphic soils. Redox processes often involve production or consumption of H^+ ions and so have an important effect on soil pH as well. The essential requirements of the hydromorphic soils are: (i) saturation with water – a vital requirement for the process of reduction, an excess of water in the soil during a given time to have a sufficient supply; (ii) absence of oxygen; (iii) presence of dissolved organic matter – by moving slowly through the soil, water will be charged with organic residues and acquires a strong reducing character; soils which are poor in organic matter do not, in general, present hydromorphic features, unless they remain saturated with water during a considerable length of time; (iv) high temperature – in a way the temperature should be sufficiently high in order not to limit biological activity. Due to the fact that the oxidation–reduction reactions are slow, the activity of microorganisms, which act as catalysts, is necessary. Therefore, temperatures should remain above 5°C during the hydromorphic phase, as this is the limit generally accepted for microbial activity, and (v) a not too low pH – as the reduction of Fe and Mn is fundamentally a biochemical process; also pH will be a limiting factor[1].

Tripura, a small state in North East India, covers an area of 1.05 m ha. It displays a variety of landforms starting from hills to flood plains and with varying types of soil[2–7]. The flood plain soils of Tripura occupy about 19% of the area and are considered as the granary of the state. The soils have developed in the presence of excess moisture which tends to suppress aerobic factors in soil building and hence are termed as the hydromorphic soils. Typical hydromorphic clay-rich soils of paddy fields occurring in Tripura valley (Aquepts : Inceptisols with aquic moisture regime[8]) are more acidic in nature than those from other parts of the country, mainly due to their development from the hill-wash materials from the surrounding uplands which are highly acidic in nature (pH 4.1–4.2). The clay CEC and base saturation are also low compared to other paddy soils[7]. The acidification of topsoil may also be caused by the continual displacement of bases by ferrous ions during the anaerobic or reduction phase associated with annual flooding[9], wherein the cations are exchanged by Fe^{+2} ions upon submergence and lost. When soil becomes dry, the reduced iron is oxidized and precipitates leaving H^+ ions to acidify and disintegrate clay. These soils are saturated for a long time to give distinctive gley horizons resulting from oxidative–reductive processes and have mottled B horizons with rusty iron and manganese mottles or streaks due to slow diffusion process[10,11]. In the latter, the drainage impedance is caused by impervious layers in the lower horizons of the soils. The process that leads to the development of properties caused by poor drainage conditions is called hydromorphism[12]. As opposed to the other terrestrial soils, hydromorphic soils also store carbon in the subsoil. In view of the importance of these hydromorphic soils in connection with their conservation and management for optimum crop yield, information of these soil resources

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plays a vital role in understanding the biophysical processes in terms of cause–effect relationship in the pedo-environment[5]. Limited information is available on the flood plain areas of the Brahmaputra valley of Assam[8,11,13–15]. The development of aquepts on the Brahmaputra alluvium in Assam valley was reported by Bhattacharyya *et al.*[11], who explained that the change in the course of the river Brahmaputra and its tributaries influenced the soil formation. The geomorphic processes of erosion and accretion in the Brahmaputra valley are more active than pedogenic processes of soil formation[15]. However, no systematic studies have been conducted so far on the hydromorphic soils of Tripura in NE India, keeping in view their constraints and potential to make the soil sustainably fertile and productive at an enhanced level. Therefore, the present study is an attempt to examine the hydromorphic soils of Tripura in the light of their physical and chemical properties and to establish a relationship of the soil properties with the degree of hydromorphism vis-à-vis the soil organic carbon (SOC) stock. The study will generate datasets for the typical hydromorphic soils, which can be stored and utilized through (GIS) information technology software in a user-friendly mode and can be retrieved for management recommendations to address issues like land degradation and food security in the existing scenario of global climate change.

Five soil series of Tripura[16], namely Goachand, Dukli I, Dukli II, Nayanpur and Dharaichherra representing the gently to very gently sloping flood plains of south, west and north Tripura districts of the state have been selected for the present study. These soils have developed mostly from alluvium derived from the sedimentary rocks like sandstone, shale and clay belonging to the Surma, Tipam and Duptila Groups. Climate is humid sub-tropical characterized by high rainfall ranging from 2000 to 2300 mm per annum. The humidity ranges from 100% to 42% with 'udic' soil moisture regime and 'hyperthermic' temperature regime. The maximum and minimum temperatures are 29°C and 13°C during summer and 24°C and 9°C during winter.

The pedons are exposed to study the morphological characteristics of the soils following the methods laid down in the Soil Survey Manual[17]. Horizon-wise soil samples were collected, air-dried and processed (2 mm sieve) for various analyses following standard methods[18,19]. Hydromorphic index was calculated following the method outlined by Chaplot *et al.*[20]

$$\mathrm{HI} = P/\mathrm{Ch} \times V,$$

where P is the proportion of the total depth of soil profile constituted by horizons with some degree of hydromorphic feature development (%). Hydromorphic features may be a grey matrix and/or the presence of brown roots for organo-mineral horizons and light and/or rusty mottles for organo-mineral horizons. Total thickness of the soil profile includes thickness of the loamy horizons, Ch, the moist Munsell colour chroma of the surface organo-mineral horizon; and V – the moist Munsell value of the surface organo-mineral horizon. The relative gain and loss of the element under consideration has been achieved by comparing the element : clay ratio in a pedon (P ratio) with the element : clay ratio of the (mixture of) parent material (C ratio), as described by Sommer and Stahr[21].

The location, environmental conditions and classification of the studied soils are presented in Table 1. Soils belong to south, west and north Tripura with varying areal coverage. Goachand, Dukli I and Dukli II soil series occur mostly on the gently sloping flood plains, whereas the Nayanpur and Dharaichherra soils occur mostly in the somewhat lower landforms on very gently sloping flood plains. Soils are generally imperfectly drained, except in the Nayanpur and Dharaichherra series, which are mostly poorly drained. Paddy is the major crop grown in this area. Deep-water rice is grown most extensively. In fact, lowland soils are agriculturally productive and are rich in soil nutrients[22]. These soils may potentially be used for the cultivation of vegetables, horticultural crops such as water melon and melon in the summer season. The fertility of these soils is enhanced by siltation during flooding. The land use and crop selection depends on the timing and duration of flooding.

Some salient morphological characteristics of the acid hydromorphic soils from the gently to very gently sloping flood plains of Tripura are presented in Table 2. These are deep with varying depth of groundwater. Soils exhibit grey matrix colour with value 3 to 6 and chroma 1 to 2, possibly due to prolonged submergence and subsequent development of reducing conditions during flooding season. The presence of brown to red mottles, prominent in the soils of the Goachand and Dukli I series, indicates considerable oxidation and reduction due to fluctuation of groundwater table. However, the soils of Nayanpur and Dharaichherra series are clayey in texture, with high groundwater level and show gleying without any mottle, indicating prolonged reducing condition. The Dukli II soils with loamy texture, possess comparatively low groundwater level with redox depletion indicating fluctuation of groundwater level. The severity of gleying is judged by the lower chroma of the soils, because of poor drainage conditions due to topographical position and high groundwater table. A low chroma of the matrix is generally associated with the gleying phenomenon of the soils. Stoops and Eswaran[23] noted that with increasing hydromorphism, Fe-hydroxide segregations appear in the ground mass developing low chroma in the peds. The presence of gleyed/pseudogleyed layers and mottling near the surface shows that these soils have developed hydromorphic properties.

The soils have developed from alluvium deposited by different fluvial processes. The Goachand, Dukli I and Dukli II soils are characterized by fine loamy texture,

Table 1. Location, environmental conditions and classification of soils in Tripura

Soil	Location	Area* (ha)	Landform	Drainage/flooding scenario	Land use	Soil family
Goachand	South Tripura 23°00′55″N 91°34′42″E	45,018 (4.29%)	Gently sloping flood plain	Imperfectly drained/ occasional flooding	Paddy–fallow	Fine-loamy, kaolinitic, hyperthermic Aquic Dystrudepts
Dukli II	West Tripura 24°01′03″N 91°38′03″E	43,890 (4.18%)	Gently sloping flood plain	Imperfectly drained/ occasional flooding	Paddy–fallow	Fine-loamy, kaolinitic, hyperthermic Typic Endoaquepts
Nayanpur	West Tripura 23°47′48″N 91°38′03″E	43,106 (4.11%)	Very gently sloping flood plain	Poorly drained/ frequent flooding	Paddy–paddy	Very fine, mixed, hyperthermic Typic Endoaquepts
Dharaichherra	North Tripura 23°47′48″N 91°38′03″E	7250 (0.69%)	Very gently sloping flood plain	Poorly drained/ occasional flooding	Paddy–fallow	Fine, mixed, hyperthermic, Typic Endoaquepts
Dukli I	West Tripura 23°48′03″N 91°17′13″E	5281 (0.50%)	Gently sloping interhill valley	Imperfectly drained/ occasional flooding	Paddy–fallow	Fine-loamy, kaolinitic, hyperthermic Fluventic Epiaquepts

*Values in parentheses indicate percentage of the state area.

whereas the Nayanpur and Dharaichherra soils are fine to very fine. Dukli I and Dukli II soils show no regular textural variation, indicating lithological discontinuity. Goachand, Dukli I and Dukli II soils are friable under moist condition; non-sticky, non-plastic to sticky and plastic under wet condition. The soils of Nayanpur and Dharaichherra are friable to very firm under moist conditions, but are sticky, plastic to very sticky to very plastic under wet condition. All the soils show gradual and smooth horizon boundaries, reflecting the process of soil development as young under fluvial processes.

All the soils are fine loamy to very fine textured (Table 3). Sand is the dominant fraction (23.6–86.4%) in Dukli I soils (pedon 5) and it decreases with the increase in soil depth. Silt is dominant in Goachand and Dukli II soils. Clay is dominant in Nayanpur and Dharaichherra soils (pedons 3 and 4) and it ranges from 55.4% to 69.0% and increases gradually with depth, particularly in pedon 4. The variation of different fractions in these soils is mainly due to the deposition of alluvium brought down by water under different fluvial cycles under different landform situations. The decrease of clay down the depth in the poorly drained soils of Ohio was reported by Smeck *et al.*[24]. The sand to silt ratio of more than 0.2 indicates lithological discontinuity in Dukli I and Dukli II soils[25].

The soils are strongly acidic and pH (H_2O) value ranges from 4.4 to 5.2 (Table 3). Highly acidic nature of the soils may be due to the reducing environment under waterlogged condition. Within the pedon, pH value is low at the surface and it gradually increases with increase in depth. The low pH of the surface soils is due to the process of ferrolysis which reduces clay containing iron during the oxidation and reduction cycle. Ponnamperuma[9] noted that acidification of topsoil is caused by continual displacement of bases by ferrous iron during the anaerobic or reduction phase associated with annual flooding. The fluctuation of the groundwater level may also be a cause for higher pH value of the surface soil (pedon 5). The lower value of pH KCl in all the soils and the negative Δ pH (pH KCl – pH H_2O) values are presumed to be due to the difference in reserve acidity.

The organic carbon content of soil is mostly high and varies from 8.9 to 24.3 g kg^{-1} at the surface and 0.5 to 21.4 g kg^{-1} in the subsurface (Table 3). It is generally high at the surface and decreases gradually with the increase in soil depth. The high organic carbon content of the hydromorphic soils was also reported by Ponnamperuma[10]. However, the irregular distribution of organic carbon in the soils of pedons 2 and 5 indicates the influence of fluvial activity. The higher organic carbon content in the surface may be due to accumulation of organic matter from the surrounding upland area and is important for sequestering atmospheric carbon[26,27].

CEC of the soil varies between 3.0 and 21.2 cmol (p+) kg^{-1} at the surface and 1.6 and 20.2 cmol (p+) kg^{-1} in the subsurface (Table 4). The higher amount of clay in the soils of pedons 3 and 4 may be responsible for the higher CEC value of the soils. The clay CEC of soils [12–55 cmol(p^+)kg^{-1}] indicates heterogeneity of mineralogical composition of clays, mostly dominated by soils with more than 50% kaolin hydroxy interlayered vermiculite mineral (KI/HIV)[5]. The destruction of clay may not be the only process that has affected the clay fraction. Either the surface properties of clay were modified in the upper horizons or clay minerals were decomposed or preferentially eluted[15].

Table 2. Morphological properties of the soils in Tripura

Horizon	Depth (m)	Matrix colour (moist)	Mottle colour (moist)	Texture	Structure	Consistency (moist) (wet)	Boundary	Existing land use	HI*
Pedon 1. Goachand, South Tripua. Gently sloping flood plain									
Ap	0–0.11	10YR 5/2	2.5 YR 4/6	l	m1 sbk	fr ss ps	gs	Paddy–fallow	3.3
Bw1	0.11–0.50	2.5Y 5/2	2.5YR 4/6	l	m1 sbk	fr ss ps	gs		
Bw2	0.50–0.95	2.5Y 5/2	2.5YR 4/6	sic	m2 sbk	fr ps	gs		
Bw3	0.95–1.25	2.5Y 5/2	2.5YR 4/6	cl	m2 sbk	fr ss ps	gs		
Bw4	1.25–1.50	2.5 Y 5/2	2.5 YR 4/6	cl	m2 sbk	fr ps			
Pedon 2. Dukli II, West Tripura. Gently sloping flood plain									
Ap	0–0.14	10YR 4/2	7.5Y R4/6	sicl	m1 sbk	fr s p	cs	Paddy–fallow	11.0
2Bg1	0.14–0.26	10YR 4/1	7.5YR 4/6	l	m2 sbk	fr ss ps	cs		
2Bg2	0.26–0.37	10YR 3/1	7.5YR 4/6	l	m2 sbk	fr sp	cs		
2Bg3	0.37–0.51	10YR 3/1	7.5YR 4/6	l	m2 sbk	fr ss ps	cs		
2Bg4	0.51–0.71	7.5YR 3/1	7.5 YR 4/6	cl	m2 sbk	fr ss ps	cs		
3BCg1	0.71–0.90	10YR 4/1	7.5 YR 4/6	sl	gr	l s_0 p_0	cw		
4BCg2	0.90–1.17	10YR 6/1		ls	gr	l s_0 p_0			
W	1.17 +	Groundwater							
Pedon 3. Nayanpur, West Tripura. Very gently sloping flood plain									
Apg1	0–0.10	10YR 5/2	–	c	m2 sbk	fi vs vp	cs	Paddy–paddy	15.6
Apg2	0.10–0.20	10YR4.5/1	–	c	m2 sbk	vfi vs vp	gs		
Bg2	0.20–0.45	10YR 5/1	–	c	m2 sbk	vfi vs vp			
W	0.45 +	Groundwater							
Pedon 4. Dharaichherra, North Tripura, Very gently sloping flood plain									
Apg1	0–0.08	10YR 5/1	–	c	m1 sbk	fr sp	cs	Paddy–fallow	8.1
Apg2	0.08–0.25	10YR 5/1	–	c	m2 sbk	fi sp	cs		
Bg1	0.25–0.65	2.5Y 6/2	–	c	m2 sbk	fi vs vp	cs		
Bg2	0.65–1.00	10YR 6/2	–	c	m2 sbk	vfi vs vp	cs		
Bg3	1.00–1.25	10YR 5/2	–	c	m2 sbk	vfi vs vp	gs		
Bg4	1.25–1.50	10YR 5/2	–	c	m2 sbk	vfi vs vp			
Pedon 5. Dukli I, Gently sloping flood plain									
Ap1	0–0.05	10YR 4/2	5YR 3/4	sl	f1gr to sg	fr s_0 p_0	cs	Paddy	5.5
2Ap2	0.05–0.19	10YR 6/4	5YR 4/6	ls	Sg	fr s_0 p_0	cs		
3Bg1	0.19–0.32	10YR 5/2	2.5YR 3/4	sl	m1 sbk	fr s_0 p_0	cs		
4Bg2g	0.32–0.57	10YR 5/2	2.5YR 3/4	l	m2 sbk	fr ss ps	cs		
5Bg3	0.57–0.76	10YR 6/2	7.5YR 4/6	c	m2 sbk	fr sp	cs		
5Bg4	0.76–1.05	10YR 6/2	7.5YR 4/6	cl	m2 sbk	fr s ps	cs		
5Bg5	1.05–1.30	10YR 6/2	7.5YR 4/6	c	m2 sbk	fr sp	cs		
W	1.30 +	Groundwater							

Note – Texture: l, Loam; sl, Sandy loam; ls, Loamy sand; sicl, Silty clay loam; sic, Silty clay; cl, Clay loam; c, Clay. Structure: m1 sbk, Weak medium subangular blocky; m2 sbk, Moderate medium subangular blocky; f1 gr, Weak fine granular; sg, Single grain. Consistency (moist): fr, Friable; fi, Firm; vfi, Very firm. Consistency (wet): S_0P_0, Non-sticky and non plastic; ss ps, Slightly sticky and slightly plastic; sp, Sticky and plastic; vs vp, Very sticky very plastic. Boundary: cs, Clear smooth; gs, Gradual smooth and cw, Clear weavy.
*HI, Hydromorphic index.

Among the exchangeable bases, Ca^{2+} ion is dominant followed by Mg^{2+} in most of the pedons with some exceptions (Table 3). The Ca^{2+}/Mg^{2+} ratios indicate considerable recycling of bases, rather than the process of gleying during soil formation. However, the dominance of exchangeable Mg^{2+} over Ca^{2+} and K^+ in the exchange phase in some of the horizons (pedons 1, 3 and 4) indicates that the soils are more gleyed. This observation is in conformity with the result obtained by Saunders[28], who reported that under gleying process in soil formation, exchangeable Mg^{2+} becomes the dominant cation in the exchange complex showing Ca^{2+}/Mg^{2+} ratio near unity[29]. The higher amount of exchangeable bases at the surface in some of the soils may be due to fluctuation of groundwater level, where the bases remain at the surface with the lowering of groundwater table. Soils are medium to high in base status and the base saturation of these soils varies from 39% to 91% in the surface and 29% to 97% in the subsurface and subsoil.

The neutral 1N KCl-extractable acidity of these soils is low and it varies from 0.3 to 4.3 cmol (p+) kg^{-1} on the surface and 0.1 to 3.9 cmol (p+) kg^{-1} in the subsurface (Table 4). Exchangeable Al shows major contribution towards exchangeable acidity, except in pedon 4 in which a

Table 3. Physical and chemical characteristics of soils in Tripura

Horizon	Depth (m)	Sand (%)	Silt (%)	Clay (%)	pH H_2O	pH KCl	Organic C (g kg^{-1})	*P* ratio	*C* ratio
Pedon 1. Goachand, South Tripura. Gently sloping flood plain; fine-loamy, kaolinitic, hyperthermic Aquic Dystrudepts									
Ap	0–0.11	31.5	43.5	25.0	4.4	3.7	8.9	0.38	0.04
Bw1	0.11–0.50	40.6	34.4	25.0	4.9	3.8	6.6		
Bw2	0.50–0.95	13.2	42.8	44.0	4.7	3.6	6.6		
Bw3	0.95–1.25	22.4	42.6	35.0	4.6	3.6	6.8		
Bw4	1.25–1.50	24.6	42.4	33.0	4.7	3.6	5.8		
Pedon 2. Dukli II, West Tripura. Gently sloping flood plain; fine-loamy, kaolinitic, hyperthermic Typic Endoaquepts									
Ap	0–0.14	8.8	56.6	34.6	4.9	4.2	17.1	0.17	0.02
2Bg1	0.14–0.26	25.6	48.8	25.6	4.8	4.2	9.1		
2Bg2	0.26–0.37	22.0	47.4	25.6	4.8	4.1	11.3		
2Bg3	0.37–0.51	29.2	44.2	26.6	5.0	4.2	6.9		
2Bg4	0.51–0.71	21.2	45.2	33.6	4.8	4.1	10.4		
3BCg1	0.71–0.90	72.6	11.8	15.6	5.0	4.3	2.5		
4BCg2	0.90–1.17	83.6	5.8	10.6	5.2	4.6	0.5		
W	1.17 +	--- Groundwater ---							
Pedon 3. Nayanpur, West Tripura, Very gently sloping flood plain; very fine, mixed, hyperthermic Typic Endoaquepts									
Ap1g	0–0.10	1.8	32.7	65.5	4.8	3.7	24.3	0.22	0.02
Ap2g	0.10–0.20	1.7	29.3	69.0	4.9	3.7	21.4		
B2g	0.20–0.45	3.3	31.7	65.0	5.1	3.7	10.6		
W	0.45 +	--- Groundwater ---							
Pedon 4. Dharaichherra, North Tripura, Very gently sloping flood plain; fine, mixed, hyperthermic Typic Endoaquepts									
Apg1	0–0.08	2.4	42.2	55.4	4.4	3.6	18.0	0.46	0.05
Apg2	0.08–0.25	2.1	42.5	55.4	4.4	3.6	17.0		
Bg1	0.25–0.65	2.4	33.9	63.7	5.2	3.8	7.0		
Bg2	0.65–1.00	2.8	33.5	63.7	5.2	3.8	6.0		
Bg3	1.00–1.25	2.4	30.9	66.7	5.2	3.9	5.0		
Bg4	1.25–1.50	2.0	34.3	63.7	5.2	3.9	5.0		
Pedon 5. Dukli I, North Tripura, Gently sloping flood plain; fine-loamy, kaolinitic, hyperthermic Fluventic Epiaquepts									
Ap1	0–0.05	75.0	11.1	13.9	5.2	4.4	12.0	0.21	0.02
2Ap2	0.05–0.19	86.4	3.7	9.9	5.2	4.3	3.0		
3Bg1	0.19–0.32	66.0	18.1	15.9	4.8	4.3	2.0		
4Bg2	0.32–0.57	60.0	21.1	18.9	5.0	4.2	3.0		
5Bg3	0.57–0.76	23.6	28.5	47.9	5.0	4.0	3.0		
5Bg4	0.76–1.05	28.6	35.5	35.9	4.9	4.0	2.0		
5Bg5	1.05–1.30	28.6	34.5	46.9	5.0	3.9	2.0		
W	1.30 +	--- Groundwater ---							

reverse trend is observed. Majority of the soils contain less than 1% KCl extractable Al (Figure 1). This observation further corroborates relatively high proportion of hydroxy-interlayered vermiculites (HIV) in the soil, resulting in lower concentration of Al^{3+} in the soil solution[5].

Free iron oxide (Fe_d) content varied from 3.3 to 18.5 g kg^{-1} on the surface and 0.3 to 38.5 g kg^{-1} in the subsurface and subsoil (Table 4), suggesting a gradual illuviation of Fe_d due to the chelation by humus[30]. In pedon 2, free iron oxide content was high at the surface and decreased markedly with depth. This trend is typical of gleyed soils[31]. The low amount of free iron oxide in the lower horizons may be due to the prevalence of permanently reduced conditions and the loss of reduced iron from this zone along with the drainage water[12]. According to Brinkman[32], more hydromorphic the soil, more free iron oxide will be released from the exchange complex and as such more will be the free iron oxide (Fe_d) content in the subsoil. The significant positive correlation between clay and free iron oxide ($r = 0.66$, $P < 0.01$) also indicates the translocation of iron along with illuviation of clay[15] (Figure 2). The translocation of iron in the process of soil development is also confirmed due to higher *P* ratio in comparison to *C* ratio (Table 3). It appears that higher clay adsorbs more iron leached from the surface horizons. Similar results were obtained by Bhattacharyya *et al.*[11] in some aquepts of Assam valley.

Hydromorphy of soil is generally described in different categories depending on macro and micro morphological, hydrological, physical and chemical characteristics[33]. According to the criteria laid down by Soil Survey Staff[34], all soils possess continuous or periodic saturation and reduction showing aquic condition. The hydromorphic

Table 4. Exchange characteristics of soils in Tripura

Horizon	Depth (m)	CEC soil	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CEC clay	H^{+}	Al^{3+}	Ca^{+2}/Mg^{+2}	BS (%)	Free iron oxide (g kg^{-1})
		cmol (p+) kg^{-1}										
Pedon 1. Goachand series												
Ap	0–0.11	9.1	2.9	0.2	0.5	0.1	36	0.6	0.8	14.5	40	6.0
Bw1	0.11–0.50	11.6	2.1	2.5	0.5	0.1	46	0.5	0.8	0.8	45	16.2
Bw2	0.50–0.95	16.9	2.5	4.3	0.5	0.2	38	1.6	2.1	0.6	44	11.4
Bw3	0.95–1.25	12.5	2.3	3.8	0.1	0.2	36	1.6	1.4	0.6	51	14.0
Bw4	1.25–1.50	11.3	1.8	4.4	0.1	0.2	34	1.3	1.1	0.4	58	12.5
Pedon 2. Dukli II series												
Ap	0–0.14	6.7	1.7	0.5	0.2	0.2	19	0.7	1.4	3.4	39	17.4
2Bg1	0.14–0.26	4.9	0.9	0.3	0.1	0.1	19	0.7	1.2	3.0	29	7.2
2Bg2	0.26–0.37	5.0	1.0	0.3	0.2	0.1	19	0.7	1.7	3.3	32	3.2
2Bg3	0.37–0.51	5.3	1.0	0.3	0.2	0.1	20	0.8	1.4	3.3	30	1.3
2Bg4	0.51–0.71	6.8	1.4	0.5	0.2	0.1	20	0.7	1.4	2.8	33	1.5
3BCg1	0.71–0.90	3.8	0.7	0.3	0.2	0.1	24	0.2	0.5	2.3	34	0.5
4BCg2	0.90–1.17	2.0	0.4	0.2	0.1	0.1	19	–	0.1	2.0	40	0.3
W		Groundwater										
Pedon 3. Nayanpur series												
Ap1g	0–0.10	21.2	5.2	5.8	0.6	0.2	32	0.6	3.7	8.7	56	14.0
Ap2g	0.10–0.20	20.2	3.8	8.5	0.6	0.1	29	0.6	3.3	6.3	64	17.0
B2g	0.20–0.45	19.7	4.3	7.6	0.6	0.1	30	0.5	3.2	7.2	64	14.0
W	0.45++	Groundwater										
Pedon 4. Dharaichherra series												
Apg1	0–0.08	12.2	4.8	5.6	0.5	0.2	53	0.3	Tr	0.8	91	18.5
Apg2	0.08–0.25	11.2	4.9	4.9	0.7	0.1	48	0.2	Tr	1.0	97	19.2
Bg1	0.25–0.65	12.5	6.4	4.0	0.7	0.1	55	0.2	Tr	1.6	97	31.4
Bg2	0.65–1.00	12.5	7.3	3.9	0.7	0.1	54	0.3	Tr	1.8	96	31.4
Bg3	1.00–1.25	15.4	4.7	2.1	0.7	0.2	48	1.0	Tr	2.2	50	38.5
Bg4	1.25–1.50	14.5	4.0	2.5	0.7	0.2	35	0.6	tr	1.6	50	38.5
Pedon 5. Dukli I series												
Ap1	0–0.05	3.0	0.8	0.4	0.1	0.1	21	0.1	0.5	2.0	47	3.3
2Ap2	0.05–0.19	1.6	0.5	0.1	0.1	0.1	16	–	0.3	5.0	50	2.0
3Bg1	0.19–0.32	3.8	0.8	0.3	0.1	0.1	24	0.2	0.7	2.7	54	6.3
4Bg2	0.32–0.57	3.8	0.9	0.3	0.1	0.1	20	0.4	0.7	3.0	34	6.0
5Bg3	0.57–0.76	5.8	1.0	0.4	0.2	0.1	12	0.7	2.2	2.5	37	12.2
5Bg4	0.76–1.05	7.0	2.5	0.5	0.2	0.3	19	0.5	0.6	5.0	29	2.0
5Bg5	1.05–1.30	6.4	1.5	0.8	0.2	0.1	13	0.7	2.0	1.9	50	1.5
W	1.30+	Groundwater										

BS, Base saturation.

index of the soils is calculated based on the proportion of the total soil profile depth constituted by horizons with some degree of hydromorphic feature development and the moist Munsell chroma and value of the surface organo-mineral horizon[20,35]. Accordingly, the hydromorphic index (HI) is highest in the soils of Nayanpur (pedon 3) followed by Dukli II, Dharaichherra (pedon 4), Dukli I (pedon 5) and Goachand soils (pedon 1). The distribution of average free iron oxide of the soil series studied is not in conformity with the hydromorphic index. Again, Fe_d/clay ratio has been estimated as a measure of the enrichment of clay with non-silicate Fe. Pedon 3 shows strong hydromorphic character as indicated by strong gleying with high groundwater level indicating prolonged submergence. The constant Fe_d : clay ratio in this soil indicates that only transformation process is operating with time, through soil development process. However, the higher *P* ratio in comparison to *C* ratio, confirms the gain of iron through soil development process. Soils of pedon 4 reflect moderately hydromorphic characters with strong gleying along with increasing Fe_d : clay ratio with increase in soil depth, indicating enrichment of clay with iron oxide (Figure 3), as supported by the higher *P* ratio than *C* ratio; this points to gain of iron through the process of soil development[21]. However, the period of submergence in this soil is less in comparison to Nayanpur soils showing less hydromorphism. Pedon 2 also reflects strong hydromorphic character as indicated by gleying from subsurface to subsoil under the influence of groundwater. Though the soils are coarser in texture, the

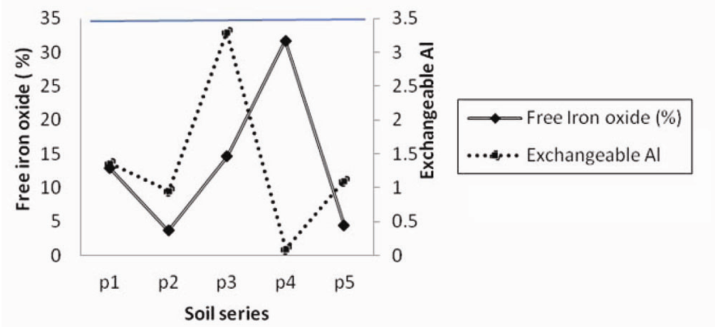

Figure 1. Free iron oxide and exchangeable Al content in the hydromorphic soils of Tripura.

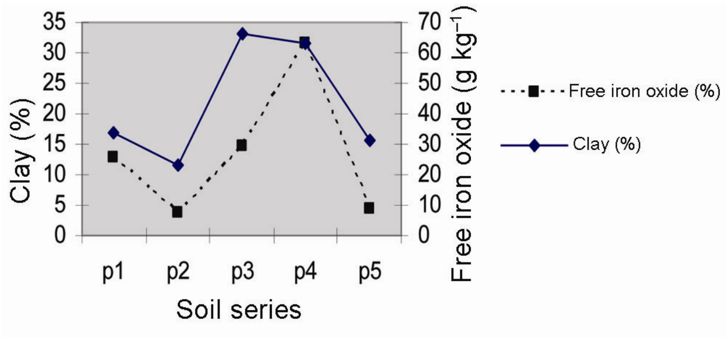

Figure 2. Clay and free iron oxide distribution in the hydromorphic soils of Tripura.

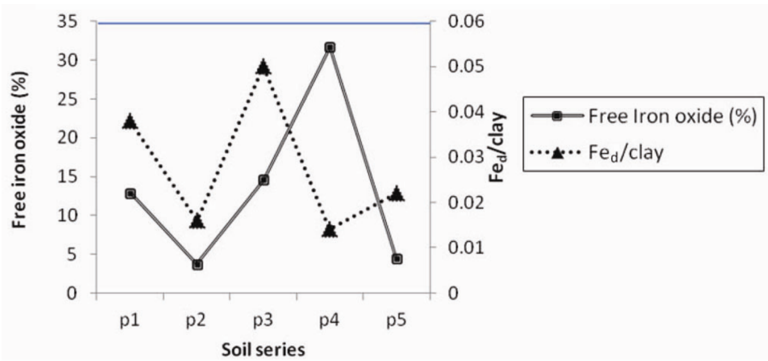

Figure 3. Free iron oxide content in relation to Fe_d/clay ratio in the hydromorphic soils of Tripura.

high hydromorphic nature of the soil, after Nayanpur series, shows that the soil remains under water for a long time. Significant oxidation and reduction has taken place due to the fluctuation of groundwater in pedon 5. The Fe_d : clay ratio in these soils decreases with the increase in soil depth because of the prevalence of permanently reducing conditions and the loss of reduced iron from this zone along with the drainage water. The little gleying character of these soils, with comparatively higher *P* ratio than *C* ratio, groups them as hydromorphic soils. However, Goachand soils (pedon 1) represent incipient hydromorphic soils with redoximorphic features as evidenced by the mottles throughout the profile. The fluctuating Fe_d : clay ratio indicates the influence of groundwater through soil development. However, the gain in iron through soil development is noticed due to higher *P* ratio in comparison to *C* ratio.

On the basis of the increasing degree of hydromorphism, the soils under study are arranged as follows: Nayanpur > Dukli II > Dharaichherra > Dukli I > Goachand.

Bhattacharyya *et al.*[8] identified the hydromorphic soils as one of the important soils of India and mentioned that the acidity of the hydromorphic soils of Tripura is much higher than any other hydromorphic soils of the NE region. Organic and inorganic carbon compounds are stored as C pools in different reservoirs in various quantities.

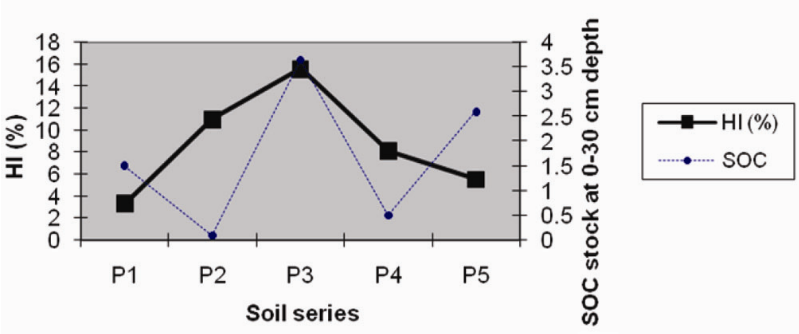

Figure 4. Hydromorphic index and soil organic carbon stock (0–30 cm depth) in the hydromorphic soils of Tripura.

Table 5. Soil organic carbon (SOC) stock in the soils of Tripura

	SOC stock (Tg)				
	Soil depth (cm)				
Soil series	0–30	0–50	0–100	0–150	HI
Goachand	1.508	2.399	4.634	6.761	8.0
Dukli II	0.098	0.144	0.244	0.323	12.5
Nayanpur	3.604	5.011	10.345	15.518	10.0
Dharaichherra	0.509	0.661	1.004	1.276	20.0
Dukli I	2.593	3.704	5.464	5.629	8.2

Because atmospheric CO_2 levels are increasing and SOC is both a source and sink for CO_2, the spatial distribution of organic carbon pools in the soil is of great interest.

Hydromorphic soils, where characteristics are based on the groundwater and its dynamics, store the greatest amount of carbon[26,36]. Flood-plain soils due to the lower topographic position are waterlogged, leading to the development of hydromorphic soils. Typical hydromorphic, clay-rich paddy soils occurring in Tripura valley pose the problem of soil acidity, which is a major limiting factor for crop production[8]. Under anaerobic condition, organic matter decomposition is limited and carbon is accumulated. As opposed to the terrestrial soils, hydromorphic soils also store more carbon in the subsoil. Accumulation of organic matter, especially in tropical rice soil is significant when compared to soils under arable cropping under similar conditions and has often been cited as the basis for sustainable maintenance of fertility of wetland rice soils[37]. In Tripura, SOC content varies from 0.34% to 1.88% (ref. 4). The SOC stock of the hydromorphic soils of Tripura (Table 5) at different depths indicates that it increases with the increase in depth of the soil. The Nayanpur soils represent strongly gleyed soils due to highly hydromorphic nature and exhibit highest hydromorphic index value (15.6) with comparatively high SOC (3.604 Tg C ha^{-1}) stock at 0–30 cm depth (Figure 4). The Goachand soils by contrast exhibit least hydromorphic index (3.3) with comparatively low SOC stock (1.508 Tg C ha^{-1}) at 0–30 cm depth. Dukli II soils with the second highest hydromorphic character (11.0) show much lower SOC (0.098) stock (0–30 cm) which may be due to the soil texture and the duration of submergence. The Dukli I soils with low hydromorphic index (5.5) show the second highest SOC stock (0–30 cm) of 2.593. This may be due to the soil texture and shorter duration of submergence. The degree of saturation required for creating aquic conditions varies depending on the soil environment and is not specified[38]. It is generally established that soils with high clay content have higher SOC compared to those with low clay content under similar land use, climatic conditions and management practices as observed in the study area. Dukli I, Dukli II and Goachand soils, however, show opposite relationship between SOC stock and hydromorphic index. Dukli I and Dukli II soils are characterised by lithological discontinuity, indicating the influence of fluvial deposit under different fluvial cycles. The SOC content of Dukli I is reasonably high in comparison with that of Dukli II, which is justified by higher clay content in these soils. Chaplot *et al.*[39] observed that at the same site, an increase of soil hydromorphy causes an increase in the hydromorphic index and HI is governed by SOC. In Dukli II soils, the higher hydromorphic index (11.0) indicates prolonged submergence in water. Similar is the case with Goachand soils having low hydromorphic index, but showing higher SOC stock due to more clay. Hence, the study leads to the inference that clay content of soil plays an important role in building the SOC stock in the hydromorphic soils of Tripura.

The five soils taken up for study have been interpreted for crop production based on the limiting factors. Based on their limitations and production potential, the land use plan has been suggested to keep the soil fertile and productive.

Goachand soils: These are loamy, with abrupt increase in clay content at the surface. Due to high silt and clay content in the subsurface, the drainage is impeded. These soils are grouped under land capability subclass-IIw3 and land irrigability subclass-1 with medium to high production potential. Deep-water rice is the best option during *kharif* season and can potentially be used for vegetables, horticultural crops, viz., melon, water melon and cucumber during winter season.

Dukli II soils: These are heavier in texture in the surface causing water stagnation. These soils are grouped under land capability subclass-IIw4 and land irrigability subclass-2ds indicating drainage as the major limiting factor. The soils are acidic and poor in nutrient-holding capacity. The production potential of the soils is low to medium. Deep-water rice is the best option for these soils in *kharif* season.

Nayanpur soils: Fine texture and high groundwater level make these soils prone to flooding during rainy season. These are grouped under land capability subclass-IIw3 and land irrigability subclass-2ds indicating drainage as the major limitation for crop production. The production potential of the soils is medium to high. Deep-water rice is the best option during *kharif* season.

Dharaichherra soils: These are poorly drained with high clay and silt content. The soils have high nutrient status as indicated by high cation exchange capacity values. The soils have been grouped under land capability subclass-IIw4 and land irrigability subclass-2d showing drainage as the major limiting factor for crop production. The production potential is high. Deep-water rice is the best option during *kharif* season. However, it can be potentially utilized for growing vegetables during winter season.

Dukli I soils: These are developed in the river alluvium. The soils are relatively coarse in texture and poor in nutrient-holding capacity. These soils have been grouped under land capability subclass-IIw4 and land irrigability subclass-2ds indicating drainage as the major limiting factor for crop production. The production potential of these soils is medium to high. Deep-water rice is the best option in the rainy season. In the winter and summer season, vegetables and horticultural crops may enhance crop production.

The acidic hydromorphic soils of Tripura developed on the gently to very gently sloping plains through the deposition of alluvium/colluvium derived from the sedimentary rocks, viz. sandstone, shale and clay belonging to the Surma, Tipam and Duptila Groups are brought down by the flowing water from the surrounding uplands. Also, most of the rivers originating from the hill ranges of Tripura flow towards north and west and ultimately reach Bangladesh. Like many other rivers in the humid tropics, the riverbed of Tripura is also covered with alluvium, which has been defined as unconsolidated sediment of Recent geologic age. These sediments are deposited as a result of lateral erosion as well as alluvium brought by the rivers from the different geomorphic features as found in the Brahmaputra valley of Assam[10,11]. Erosion takes place at the convex curves of the meanders, whereas deposition occurs simultaneously on the concave side downstream. At the concave bends, the valley slope is undercut, leading to mass movement. Since this occurs at all the meander bends and as meandering naturally migrates downstream, the valley floor gets continuously widened to form a flood plain. The river systems in Tripura have thus widened their valleys, which are invariably enriched with alluvium varying both in thickness and composition as evidenced by different kinds of soils formed in the valley. The seasonal submergence and drying set the conditions for alternate oxidation and reduction, which is the striking feature of the pedochemical environment of these soils. The presence of gleys, rusty thread-like mottles, etc. indicates that there is hydromorphism in these soils. The process of hydromorphism in these soils is mainly attained due to reduction and/or release of Fe from iron-bearing minerals, which in turn was precipitated and fixed in the form of mottles in the subsurface horizons of soils developing grey colour. This kind of mobilization and fixation of iron indicates that gleyed horizons occur in the deeper layers of the soils in the permanent groundwater zone. Gleying can possibly be designated as the major pedogenic process in these soils[40].

Hydromorphic soils of Tripura under humid tropical climate are unique with dominant gleying characteristics and soil acidity compared to soils in the other parts of India. Gleying can possibly be designated as the major pedogenic process in these soils. Translocation of clay and free iron oxide influences the hydromorphic nature of the soils. These soils preferentially accumulate organic matter and are, therefore, important for sequestering atmospheric carbon dioxide. The landscape represents the granary of the state and should be managed and preserved judiciously for future, not only to maintain soil health for increasing crop production, but also to address the global warming issue. The present alarming situation of decreasing the land resources because of degradation, encroachment and also faulty management practices, requires scientific intervention to increase crop production.

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