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Pedogenesis of Some Hydromorphic Soils of Upper Brahmaputra Valley Region, Assam, India

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Abstract–*Hydromorphic soils and their properties are key to address various issues of the waterlogged regions related to its productivity and conservation. The present investigation is aimed to investigate the pedogenesis of some hydromorphic soils of the Upper Brahmaputra valley region of Assam. Six pedons from North West Jorhat Development block were selected and examined for the purpose. Detail morphological, physical and chemical characteristics of the hydromorphic soils under different landforms and land uses were done through land resource inventorization (at 1:10000 scale) using and fine resolution satellite image. The study showed change in soil characteristics with micro-topographic variation. Wide variability in particle size is attributed to frequent occurrence of lithologically discontinued soil horizons in active flood plains due to fluvial processes and changes in the course of Brahmaputra river. Soils were characterized by strongly acidic (pH 4.74) to neutral (pH 6.7) in soil reaction, low (0.48%) to high (1.14%) in organic carbon, low [3.13 cmol (p^+) kg^{-1}] to medium [11.90 cmol (p^+) kg^{-1}] in CEC and low (26%) to high (71%) in base saturation status. Active flood plains were endowed with* Typic Endoaquents, *whereas in the younger and older flood plains, soils formed were* Fluventic Endoaquepts *and* Typic Endoaqualfs, *respectively. The vertical distribution of different pedogenic indices were computed and discussed.*

Key words: Brahmaputra valley, Hydromorphic soils, Landforms, Land uses, Pedogenic indices, Soil maturity, etc.

The genesis of hydromorphic soils have been studied world-wide (Bouma, 1983; Bouma *et al.*, 1988; 1990). These soils varied in wide spectrum of orders from Entisols to Histosols. They have been locally classified under peat, muck and bog soils with occurrence of characteristics *Sapric* materials (Soil Survey Staff, 2003). In India, such hydromorphic soils are mainly distributed along the coasts, river deltas, river islands and their tributaries (Soil Resource Mapping, 1994). Some are also confined to anthropogenic water bodies. The Indian hydromorphic soils are mostly confined to Entisols and Inceptisols orders with aquic moisture regime (*aquepts*) (Bhattacharyya *et al.*, 2004; 2013a) and mostly spread over the Indo-Gangetic Plains and the Brahmaputra valley of Assam (Bhattacharyya *et al.*, 1997). However, soils belonging to other orders also exist in a scattered form (Ray *et al.*, 1997; Bhattacharyya *et al.*, 2004). These soils have endo-saturated sub-surface horizons with dark gray to light gray coloured matrix (2.5 Y to 10 YR hue, chroma of 2 or less). The lower sub-surface horizons are often gleyed with formation of reduction mottles and depletions of iron and manganese. The gleyed sub-surfaces horizons are often stratified with alternate sand and silt deposits due to fluvial cycles. The hydromorphic soils of Brahmaputra valley region are confined to marshy lands and younger, older and active flood plains (Vadivelu

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et al., 2003; Bhaskar *et al.,* 2007; 2010) and are mainly classified to *Typic Endoaquepts* and *Fluvaquentic Endoaquepts* sub group. However, these informations are limited to small scale dataset (Sen *et al.,* 1999) and lack detailed information on their genesis. These soils are formed as a result of continuous cycles of saturation (dominantly Endosaturation). But the knowledge about the factors responsible for their formation and pedogenesis requires investigation of pedogenic indices. It is noteworthy that among the pedogenic indices, obtained from ratios, *viz.,* exchange ratio (ER) (Pratt and Alvahydo, 1966), fine sand/ total sand (FS/ TS) and very fine sand/ total sand (VFS/ TS) (Schaetzl and Thompson, 2015) are the direct indicators influencing pedogenesis, whereas, the indices obtained from the ratios like sand/ silt, silt/ clay (Schaetzl and Thomson, 2015), index of weathering (IW) (Martini, 1970) and CEC/clay (Smith, 1986) influence inversely the pedogenesis in soils. An attempt has been made here to understand the variability of these direct and inversely related pedogenic indices on soil formation of the hydromorphic soils. Therefore, the present study has been undertaken to understand the characteristics of saturated soils with the objectives (i) to characterize and classify some hydromorphic soils of upper Brahmaputra valley region of Assam and (ii) to study their pedogenesis by pedogenic indexing.

Materials and Methods

Study Area

The study was concentrated in North West Jorhat Development Block of Jorhat District, Assam in between the geographic extent from 26°35'N to 26°55'N Latitudes and 93°55'E to 94°15'E Longitudes and covering an area of about 30,700 ha (Fig. 1). The general topography varied from almost flat to very gently sloping (slope varied from 0-1% to 1-3%). The climate is humid sub tropical with mean annual rainfall of 2262 mm (ACP, 2015). The mean annual soil temperature is 24.5°C, mean summer soil temperature is 26.3°C and mean winter soil temperature is 19.1°C. The soil temperature regime is *Hyperthermic* and soil moisture regime is *Aquic* (Soil Survey Staff, 2003). The agro-ecological sub region is 15.4 (Upper Brahmaputra Valley Zone, hot, moist per-humid climate with length of growing period of more than 300 days) (Velayutham *et al.,* 1999). The study area is under rain-fed paddy (*kharif*) as the major crop along with sporadically grown mustard / vegetables (*rabi*). Irrigation is mainly open sourced (*viz.,* open well, scattered water bodies, drainage streams and rivulets of Brahmaputra) (Statistical Handbook, 2015). The study area is characterized by three broad landform units viz., (i) very gently sloping active flood plains (AFP) (1-3% slope), (ii) nearly level younger flood plains (YFP) (0-1% slope) and (iii) very gently sloping older flood plains (OFP) (1-3% slope). Each of older and younger flood plains comprise two types of land use systems viz., paddy (*Kharif*)-fallow (*Rabi*) and currently fallow marshy lands, while, active flood plains consist of two land uses namely, mustard/ vegetables (*Rabi*)-fallow (*Kharif*) and currently fallow marshy lands. Six hydromorphic pedons were identified from each of the landform and land use units for examination of their morphological, physical and chemical characteristics (Fig. 2).

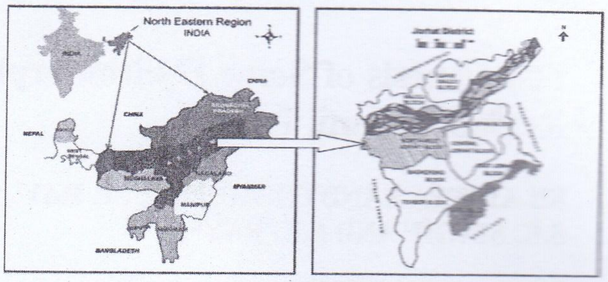

Fig. 1. *Location map of the study area*

Methodology of soil survey

A detailed soil survey on 1:10,000 scale was undertaken in the study area using Survey of India

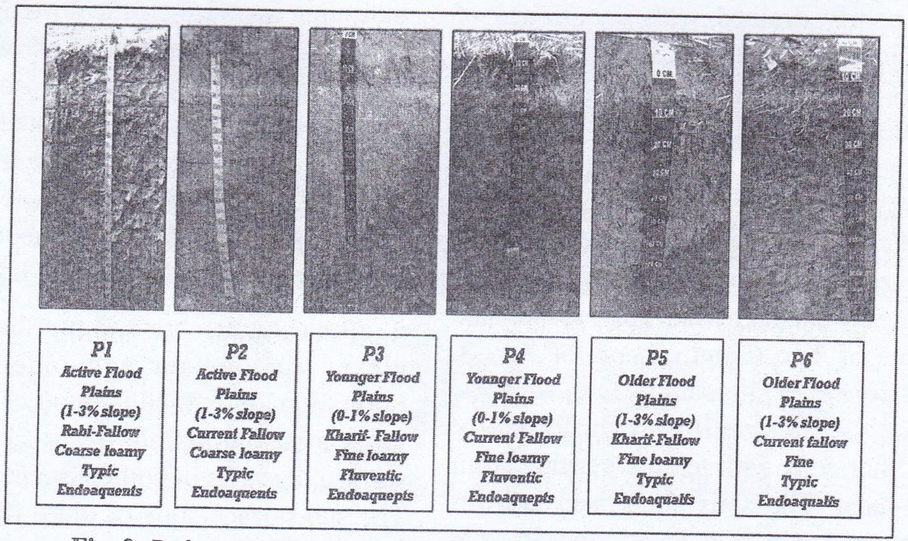

Fig. 2. *Pedons in different landforms and land use systems of the study area*

(SoI) topographical sheets (83 F/13, 14, J/1, 2), IRS (LISS-IV) multispectral data and Cartosat-1 data as base maps (Srivastava and Saxena, 2004, Nagaraju *et al.*, 2014). The landforms corresponding to the hydromorphic soils were identified on the base map by ground truth verification. The morphological characteristics of soils were studied by soil profile examination at specific sites where hydromorphic soils existed (Buol *et al.*, 1997; Soil Survey Staff, 2003) taking special care to note the soil hydromorphological indicators. Laboratory analysis of soil physical and chemical parameters were done which included mechanical analysis by International Pipette method (Jackson, 1973), pH (1: 2.5 H_2O) (Piper, 1966), soil organic carbon (SOC) by wet digestion method (Walkley and Black, 1934), cation exchange capacity (CEC) and exchangeable bases by neutral 1 *N* ammonium acetate solution (Sparks, 1996; Page *et al.*, 1982) and exchangeable aluminium was done by 1 *N* KCl (van Reeuwijk, 1993). Base saturation was calculated by both sum of cations as well as by sum of cations method (Soil Survey Staff, 1998). ECEC by sum of extractable bases plus exchangeable aluminium, pH dependent CEC by CEC of sum of cations subtracted from ECEC) (Pratt and Alvahydo, 1966) and base saturation by sum of bases divided by CEC and multiplied by 100. Soils were classified after interpretation of morphological, and laboratory analytical data using Soil Survey Staff (2003, 2014).

Pedogenic index

The 'pedogenic index', originally used to quantitatively express the changes which occurred in soils during their development, has been applied essentially in study of pedogenesis (Arnaud, 1988). In the present study, pedogenic indices have been calculated to throw some light on the genesis of soils of the study area. This was obtained by computing various indices from some soil properties, *viz.*, particle size ratios including sand/silt, silt/clay, fine sand/total sand (FS/ TS), very fine sand/total sand (VFS/ TS) (Schaetzl and Thompson, 2015), CEC/Clay, ECEC (sum of cations plus exchangeable aluminium), exchange ratio (ER) (pH dependent CEC/ ECEC) (Pratt and Alvahydo, 1966) and weathering index (CEC/ square of clay and multiplied by 100) (IW) (Martini, 1970).

Results and Discussions

Morphological characteristics of soils

Soils occurring on active flood plains were very deep, poorly drained with occurrence of redoximorphic depletions started below 20 cm from surface and continued beneath it. Gleying started at a depth below 20 cm in P1 and 40 cm in P2. The matrix colour in surface ranged from yellowish grey to grayish yellow with hue of 10 YR, value 5 and chroma 2 to 3. Soils in sub surface horizons comprised different sets of colour matrices with increased grayness of hue (2.5 Y), value of 4 to 6 and chroma of 2 to 3. Surface soils consist of silt loam texture, whereas, sub surface soils exhibit lithologically discontinued horizons with texture varying from silt loam to sand. The soils comprised horizon sequence of Ap-2ACg-3Cg in P1 and P2. On younger flood plains, the soils were very deep and imperfectly drained with occurrence of strong and brownish redoximorphic mottling started at a depth of 18 cm in P3 and 23 cm in P4. The soils comprised yellowish brown to dark gray colour with hue of 10 YR in surface and 10 YR to 2.5 Y in sub surface, value of 4 to 5 and chroma of 1 to 3. The surface soils have silt loam texture, whereas, sub surface soils varied from sandy loam to silty clay loam texture. The horizon sequence of P1 was Ap-Bwg-2Bwg and P2 was Ap-Bwg, signifying the occurrence of deep gleyed cambic horizons below surface. Sudden increase in clay content below 90 cm in P3 indicated profile discontinuity. Soils on older flood plains were very deep and very poorly drained with occurrence of redox depletions below 25 cm. The colour of the matrix ranged in hue of 2.5 Y to 5Y with value of 4 to 7 and chroma of 1, exhibiting dark gray coloured soil matrix. Occurrence of stress features and faint and patchy cutans in the forms of iron (Ferrans) and manganese concentrations (Mangans). In sub surface layers gleyed cambic (Bwg) followed by gleyed argillic (Btg) horizons were formed indicates gradual clay illuviation processes. The horizon sequences were Ap-Bwg-Btg-2Cg ad Ap--Btg for P5 and P6, respectively (Table 1). It is noteworthy that lithological discontinuity has been seen in P5 below 100 cm from the surface, indicating impeded profile development, whereas, the horizon sequence of P6 showed gradual soil development. Lithological discontinuity of P1, P2, P3 and P5 may be attributed to the juvenile stages of soils formation due to frequent flooding cycles and their genesis from recent origin *i.e., Quaternary* deposits of Brahmaputra alluvium of Holocene period (GSI, 2009; Gazetteers, 1979).

Both the cambic and argillic horizons were gleyed in younger and older flood plains. Formation of reduction mottles with iron and manganese depletions were common in sub-surface horizons of soils of younger flood plains. The sub-surface soils of older flood plains were characterized by formations of stress features followed by ferrans and mangans indicating that the process of agrillization preceeded much earlier than the process of gleyization (Bhaskar *et al.,* 2007; Vadivelu *et al.,* 2003). On the other hand, soils of active flood plains showed negligible horizon development because of the frequent fluvial influence of Brahmaputra river as evidenced by lithologic discontinuity (LD). Micro-depressions in the southern bank of the river may be attributed to faster gleyization process in active flood plains, which probably retarded the pedogenic processes. LD in these soils is one of the major factors influencing pedogenesis, particularly in soils of active and younger flood plains, where LD was found to decline from active flood plains to older flood plains. Thus LD can be attributed as an indicator of soil formation in the Brahmaputra valley; more frequent is the presence of LD, younger is the soil.

Physical and chemical characteristics of soils

The sand, silt and clay content of soils ranged from 1.0 to 90.8%, 5.2 to 74.3% and 3.8 to 52.4%, respectively. Such wide range of variability in particle size clearly depicts textural versatility of soils and lithological discontinuity due to frequent fluvial activities of the mighty river Brahmaputra. Older flood plains have

Table 1. Morphological characteristics of soils of the study area

Landforms	Pedons	Depth (cm)	Horizon	Matrix colour	Texture	Diagnostic features of sub-surface (mottles/ cutans/ stress features/ depletions)			
						Kind/ type	Abundance	Size	Contrast
Active flood plains (1-3% slope)	P1	0-20	Ap	10 YR 5/2 (M)	Silt loam	Nil	Nil	Nil	Nil
		20-40	2Acg1	2.5 Y 5/2 (M)	Silt loam	Fe-Mn depletion	Common (2-20%)	Medium	Distinct
		40-75	2Acg2	2.5 Y 4/2 (M)	Loamy sand	Fe-Mn depletion	Common (2-20%)	Medium	Distinct
		75-105	3Cg1	2.5 Y 4/2 (M)	Loamy sand	Fe-Mn depletion	Few (< 2%)	Medium	Faint
		105-130	3Cg2	2.5 Y 6/2 (M)	Loamy sand	Fe-Mn depletion	Few (< 2%)	Medium	Faint
Active flood plains (1-3% slope)	P2	0-20	Ap	10 YR 5/3 (M)	Silt loam	Fe-Mn depletion	Common (2-20%)	Medium	Distinct
		20-40	2Acg1	10 YR 5/2 (M)	Silt loam	Fe-Mn depletion	Common (2-20%)	Medium	Distinct
		40-60	2Acg2	2.5Y 5/3 (M)	Sandy loam	Fe-Mn depletion	Common (2-20%)	Medium	Distinct
		60-75	3Cg1	2.5Y 6/2 (M)	Loamy sand	Fe-Mn depletion	Few (< 2%)	Medium	Faint
		75-125	3Cg2	2.5 Y 6/2 (M)	Sand	Fe-Mn depletion	Few (< 2%)	Medium	Faint
Younger flood plains (0-1% slope)	P3	0-18	Ap	10YR 5/3 (M)	Silt loam	Not observable	Nil	Nil	Nil
		18-40	Bwg1	10YR 5/3 (M)	Sandy loam	Redox mottles	Common (2-20%)	Medium	Distinct
		40-70	Bwg2	10YR 5/2 (M)	Silt loam	Redox mottles	Many (> 20%)	Medium	Prominent
		70-90	Bwg3	10YR 5/2 (M)	Silt loam	Redox mottles	Many (> 20%)	Medium	Prominent
		90-136	2Bwg1	2.5Y 4/1 (M)	Silty clay loam	Redox mottles	Many (> 20%)	Coarse	Prominent
Younger flood plains (0-1% slope)	P4	0-23	Ap	10YR5/3 (M)	Silt loam	Not observable	Nil	Nil	Nil
		23-46	Bwg1	10YR5/3 (M)	Silt loam	Redox mottles	Common (2-20%)	Medium	Distinct
		46-90	Bwg2	10YR5/3 (M)	Silt loam	Redox mottles	Common (2-20%)	Medium	Distinct
		90-121	Bw3	10YR5/2 (M)	Sandy loam	Redox mottles	Many (> 20%)	Medium	Prominent
		121-153	Bwg4	10YR5/2 (M)	Sandy loam	Redox mottles	Many (> 20%)	Medium	Prominent
Older flood plains (1-3% slope)	P5	0-25	Ap	2.5Y 4/1 (M)	Loam	Not observable	Nil	Nil	Nil
		25-48	Bwg1	2.5Y 5/1 (M)	Silty clay loam	Fe-Mn depletion	Common (2-20%)	Medium	Distinct
		48-70	2Btg1	2.5 Y6/1 (M)	Silty clay loam	Ferrans/ Mangans	Few (2-25%)	Patchy	Faint
		70-100	Btg2	2.5 Y6/1 (M)	Silty clay loam	Ferrans/ Mangans	Few (2-25%)	Patchy	Faint
		100-115	2Cg1	2.5Y 7/1 (M)	Loamy sand	Fe-Mn depletion	Few (< 2%)	Medium	Faint
Older flood plains (1-3% slope)	P6	0-25	Ap	5Y 5/1 (M)	Silty clay loam	Not observable	Nil	Nil	Nil
		25-55	Btg1	5Y 5/1 (M)	Silty clay	Stress features	Few (2-25%)	Patchy	Faint
		55-85	Btg2	5 Y6/1 (M)	Silty clay	Ferrans/ Mangans	Few (2-25%)	Patchy	Faint
		85-120	Btg3	5 Y6/1 (M)	Silty clay	Ferrans/ Mangans	Few (2-25%)	Patchy	Faint

generally more clay content in sub surface (28.1-52.4%) compared to that younger (10.0-38.2%) and active flood plains (3.8-20.1%). Lithological discontinuity has been found more prominent in sub-surfaces of soils on active flood plains with high sand contents (75.6-90.8%) compared to that in other landforms. Thus, it is noteworthy to say that varying particle size fractions are good enough to explain the micro-topographic variability of the study area (Birkland, 1984; Gerrard, 1992). The soils were slightly acidic to neutral in reaction (pH 6.3-6.7) on active flood plains, strongly to moderately acidic (pH 5.3-6.1) on younger flood plains and very strongly to moderately acidic (pH 4.7-6.1) on older flood plains. Strong to moderate soil acidity in older and younger flood plains may be attributed to little influence of exchangeable aluminium {0.11-0.59 cmol (p^+) kg^{-1}. Higher side of pH in soils of active flood plains may be attributed to presence of considerable amount of bases in coarser particle size (sand and silt) fraction of soils. The soils comprise low (0.48%) to medium organic carbon (0.64%) on active flood plains, medium (0.62%) to high (0.79%) on younger flood plains and high (0.89-1.14%)-on older flood plains. The gradual increase in organic carbon from P1 to P6 indicates that the older is the landform the more is the soil aggregation. Frequent fluvial activities and flooding hazards by Brahmaputra appears to hinder organic matter accumulation and thereby restrict the process of humification in surface soils of active flood plains. CEC of soils varied from 3.13 cmol (p^+) kg^{-1} on active flood plains to 10.56 cmol (p^+) kg^{-1} on older flood plains (Table 3). CEC of sum of cations ranged from 4.35 cmol (p^+) kg^{-1} in active flood plains to 10.73 cmol (p^+) kg^{-1} in older flood plains. CEC of sum of cations was more than CEC by ammonium acetate method is most of the horizons of all the pedons (P1 to P6), attributing to the little influence of exchangeable aluminium in soils, even at higher pH. Lower CEC in soils on active flood plains and its subsequent increase in soils of younger and older flood plains may again attribute to the subsequent increase in clay content of soils. The soils comprised medium to high base saturation in active flood plains (42-71%), high base saturation on younger flood plains (51-71%) and low to medium base saturation in older flood plains (26-44%). The base saturation percentage had a general declining trend from active flood plains to older flood plains. Relatively low base saturation status in soils older flood plains may be attributed to low CEC content, which reflects the presence of considerable amount of low activity clays in these soils (Bhattacharyya *et al.*, 2010; 2013b). On the contrary, younger and active flood plains comprise soils with relatively higher base saturation status due to presence of considerable amount of extractable bases, especially calcium and magnesium (Bhaskar *et al.*, 2007).

Among the physical and chemical characteristics of the soils, silt, clay, CEC and base saturation were the major influencing factors for the formation of hydromorphic soils. High CEC and base saturation of soils in younger flood plains may be attributed to higher silt and clay content, resulting in impeded sub-surface drainage condition in all the soils (Table 2). The soils of older flood plains have high clay and low sand and silt fractions with low CEC/ clay ratio compared to that in other two landforms (Table 2). This may justify the presence of considerable amount of low activity clays in these soils with presence of kaolin group of minerals being interstratified with HIV (Bhattacharyya *et al.*, 2010; 2013b). This favours the assumption that these soils were formed much earlier (during *Pleistocene* period or more older) the soils of younger and active flood plains. The hydromorphic characters of these soils might have built-up recently *i.e.*, during the late *Holocene* period (GSI, 2009; Gazetteers, 1979) due to shifting of courses of Brahmaputra more and more towards southern direction.

Table 3. *Physical and chemical characteristics of soils of the study area*

Pedons	Depth (cm)	Sand	Silt	Clay	pH (1: 2.5 H$_2$O)	O.C. (%)	CEC			Sum of bases	Exch. Aluminium	ECEC	BS (%)
							1*N* NH$_4$Oac	Sum of cations	pH dependent				
		%					cmol (p$^+$) kg^{-1}						
P1	0-20	35.2	52.5	12.3	6.6	0.64	7.04	7.14	3.12	3.80	0.22	4.02	54
	20-40	16.7	65.4	17.9	6.4	0.49	7.34	7.99	3.12	4.55	0.32	4.87	62
	40-75	75.6	18.0	6.4	6.4	0.13	4.41	5.46	2.71	2.53	0.22	2.75	57
	75-105	80.7	14.2	5.1	6.6	0.05	4.45	5.53	2.49	2.88	0.16	3.04	65
	105-130	87.7	6.9	5.4	6.7	0.13	4.59	4.35	1.69	2.55	0.11	2.66	56
P2	0-20	15.2	71.3	13.5	6.5	0.48	6.77	7.45	3.72	3.42	0.31	3.73	51
	20-40	15.2	64.7	20.1	6.4	0.43	7.47	6.57	3.19	3.16	0.22	3.38	42
	40-60	58.3	32.5	9.2	6.3	0.16	4.95	6.4	3.19	3.10	0.11	3.21	63
	60-75	87.7	6.1	6.2	6.5	0.14	3.13	5.14	2.80	2.23	0.11	2.34	71
	75-125	90.8	5.4	3.8	6.5	0.11	3.23	4.52	2.66	1.75	0.11	1.86	54
P3	0-18	28.3	52.4	19.4	6.1	0.79	5.83	7.82	3.89	3.68	0.25	3.93	63
	18-40	63.1	26.9	10.0	5.9	0.11	5.23	7.12	3.79	3.02	0.31	3.33	58
	40-70	3.0	74.3	22.8	6.0	0.32	5.77	7.84	4.27	3.26	0.31	3.57	56
	70-90	41.9	47.9	10.2	5.6	0.17	4.97	7.16	4.01	2.84	0.31	3.15	57
	90-136	6.8	55.0	38.2	6.0	0.72	9.29	12.41	6.49	5.41	0.51	5.92	58
P4	0-23	15.1	58.4	26.5	5.4	0.62	6.98	9.24	3.69	4.96	0.59	5.55	71
	23-46	21.5	57.6	20.9	5.4	0.18	4.67	7.47	4.40	2.76	0.31	3.07	59
	46-90	16.2	59.6	24.2	5.3	0.25	4.72	7.25	4.11	2.83	0.31	3.14	60
	90-121	83.5	5.2	11.3	5.5	0.04	3.36	6.28	4.25	1.78	0.25	2.03	53
	121-153	72.3	10.2	17.5	5.4	0.22	3.90	6.31	4.01	1.99	0.31	2.3	51
P5	0-25	56.7	27.2	16.1	4.7	0.89	5.05	6.14	3.93	1.86	0.35	2.21	37
	25-48	15.8	55.4	28.8	5.1	0.23	5.45	5.43	3.69	1.44	0.30	1.74	26
	48-70	17.2	51.5	31.3	5.4	0.14	5.96	6.23	4.27	1.66	0.30	1.96	28
	70-100	14.1	55.3	30.6	5.2	0.09	6.67	7.47	4.36	2.65	0.46	3.11	40
	100-115	80.7	14.2	5.1	5.3	0.04	4.76	4.63	1.36	2.11	0.16	2.27	44
P6	0-25	1.0	74.0	25.0	5.3	1.14	10.56	10.73	5.82	4.64	0.27	4.91	44
	25-55	4.3	46.2	49.6	6.1	0.42	9.79	9.33	5.45	3.72	0.16	3.88	38
	55-85	6.4	41.2	52.4	6.0	0.29	7.87	9.78	6.45	3.22	0.11	3.33	41
	85-120	4.0	53.9	42.1	6.1	0.18	5.47	8.23	5.82	2.25	0.16	2.41	41

Pedogenic index

The vertical distribution of some soil properties in each pedon as well as across the landforms was the basis for development of pedogenic indices (Table 3, Fig 3) and are described below:.

Particle size ratio

The average sand/silt ratio followed the sequence of P2 (6.69) > P4 (4.81) > P1 (4.70) > P5 (1.73) > P3 (0.78) > P6 (0.08). The lower the sand/silt ratio, the higher is the maturity of soils indicating relatively higher profile development as is evidenced in soils of older flood plains under current fallow land use (P6). Whereas, soils of active flood plains under current fallow land use have least developed horizons. The sand/ silt ratio had a gradual increasing trend with depth in soils of active flood plains (P1 and P2) (Sidhu *et al.*, 1976; Ray *et al.*, 1997). Vertical distribution of sand/ silt ratio in soils of younger flood plains had an irregularly increasing trend with depth of soils, indicating little influence of pedogenic processes in the formation of soils of active flood plains. In soils of older flood plains, lithological discontinuity has only been seen in P5 at a depth below 100 cm, which was absent in P6. As a result, a gradual increasing trend of sand/ silt ratio with depth of soil has been observed in both P5 and P6 in soil control section, showing relatively higher degree of maturity as compared to soils of the other two landforms. Silt/ clay ratio had a sequence of P1 (2.96) = P3 (2.96) > P1 (2.89) > P5 (1.97) > P4 (1.69) > P6 (1.49). Though, soils on older flood plains had lower silt/ clay ratio as compared to that in younger and active flood plains, an irregularity in their vertical distribution was observed in all the profiles. Secondly, the dominance of silt fraction over the clay in most of the sub-surface horizons of younger and older flood plains resulted in irregularity in silt/clay ratios with increasing depth. VFS/ TS (0.44-2.98) and FS/ TS (0.24-1.12) showed an increasing trend from active flood plains to older flood plains. Average value of FS/ TS followed the sequence of P6 (0.70) > P5 (0.69) > P4 (0.58) > P2 (0.54 > P3 (0.51) > P1 (0.31), whereas, VFS/ TS follows the order of P6 (2.11) > P3 (2.05) > P5 (1.83) > P4 (1.21) > P2 (1.08) > P1 (0.58). Least values of VFS/ TS and FS/ TS in active flood plains were indicative of least profile development and hence least maturity of soils. Presence of finer sand fraction in soils of older flood plains is once again, indicative of their more relative maturity of soils as compared to other landforms.

The interpretation of particle size ratio showed that there was a relative increase in coarse fractions (sand and silt) soils in active flood plains and finer fractions (clay, fine and very fine sands) in younger and older flood plains. The

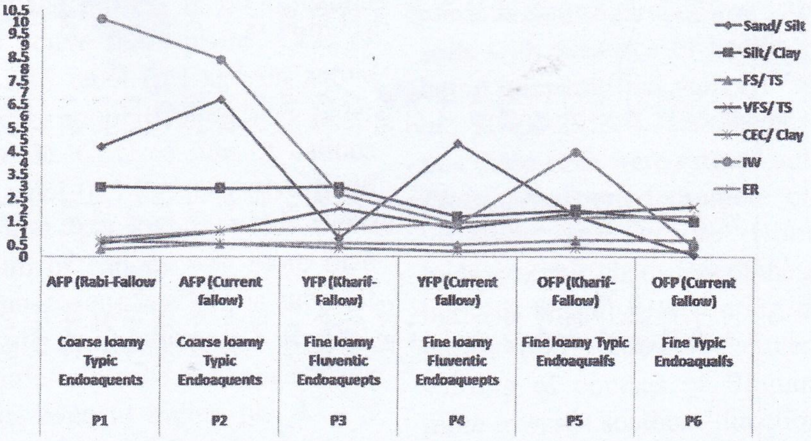

Fig. 3. *Distribution of pedogenic indices in soils under different landforms*

hydromorphic behaviour was persistent even under the predominance of coarse fractions of soils due to prolonged inundation of soils under active flood plains. On the other hand, translocation of finer fractions in soils of younger and older flood plains facilitates developing impeded drainage situations.

Chemical and exchange ratio

The weighted average of CEC/ clay ratio in control section (0-100 cm) all soils were more than 0.20, indicating mixed mineralogy of soils in P1 to P6 (Smith, 1986). The higher values of average CEC/ clay ratio (0.55-0.68) in soils of active flood plains may be attributed to the presence of hydroxy-interlayered vermiculite (HIV) (Bhattacharyya *et al.,* 1997), whereas, in younger and older flood plains, the average values of the same were lower (0.23-0.37), indicating the presence of low activity clays in terms of kaolinite interstratified mixed minerals (Bhattacharyya *et al.,* 2010; 2013b). The CEC/ clay ratio followed the sequence of P1 (0.68) > P2 (0.68) > P5 (0.37) > P3 (0.36) > P4 (0.24) > P6 (0.23). Occurrence of low activity clays in soils of older flood plains (P6) indicates that the soils of this landform are relatively mature compared to the other landforms. It is interesting to note that weathering index followed similar trend that of the CEC/ clay ratio in the sequence, P1 (10.11) > P2 (8.38) > P5 (4.46) > P3 (2.66) > P4 (1.35) > P6 (0.40). It is noteworthy that P5 had an intermediate position, which may be attributed to the occurrence of lithological discontinuity below 100 cm depth. Exchange ratio followed the sequence, P6 (1.74) > P5 (1.64) > P4 (1.45) > P3 (1.14) > P2 (1.11) > P1 (0.77) indicating that soils of active flood plains showed least profile development, whereas soils of older flood plains exhibited higher degree of profile development. The weathering index (IW) values followed the trend, P1 > P2 > P5 > P3 > P4 > P6 (Martini, 1970) indicating that the soils of the older alluvium in general, show higher maturity in profile development compared to the active alluvial plain. There is an exception in the IW value for profile P5 which is higher compared to P3 and P4 which may be attributed to the presence of higher clay per cent.

Classification of hydromorphic soils

Soils on active flood plains (P1 and P2) belonged to coarse loamy textural family owing to having weighted average of clay in the soil control section (0-100 cm) of less than 18%, whereas as, soils on younger flood plains were characterized by fine loamy textural class with weighted average clay content between 18 to 35%. On older flood plains, both fine loamy and fine textural classes (> 35% of weighted average of clay in soil control section) were found. Higher clay content on older flood plains and their increasing trend with depth of soils clearly indicated that clay illuviation is one of the major soil forming processes and the clay increase and its distribution suffices to classify these soils as Alfisols. On the other hand, lithological discontinuity in active flood plains appears to have restricted clay illuviation processes resulting in the formation of Entisols. Soils of younger flood plains showed the presence of cambic B horizon and thus these soils were classified to Inceptisols. Whereas the soils of P1 and P2 (Ap-2ACg-3Cg type of horizon) with hue of 2.5 Y and chroma of 2 or less in sub-surface horizon, having an aquic moisture regime, enabled to classify these soils to Entisols and can be generalized as *Coarse loamy, mixed, hyperthermic* family of *Typic Endoaquents.* Soils of younger flood plains were Inceptisols having cambic and gleyed (Bwg) sub surface horizons with horizon type of Ap-Bwg with aquic moisture regime and presence of endo-saturation were classified as *Fine loamy, mixed, hyperthermic* family of *Typic Endoaquepts,* showing their more relative maturity over the soils on active flood plains. Soils on older flood plains were more matured than younger flood plains as they have both gleyed cambic (Bwg) as well as gleyed argillic (Btg) horizons with dark gray hue (2.5-5Y) and chroma of 1. Formation of stress features in sub surface horizons with occurrence of faint and patchy ferrans and mangans indicate that these soils are Alfisols and can be classified as *Fine loamy, mixed, hyperthermic* family of *Typic Endoaqualfs* (P5) and *Fine, mixed, hyperthermic* family of *Typic Endoaqualfs* (Vadivelu *et al.*, 2003; 2004). The fact that these soils could also be Alfisols has been a revelation in this study (Bandyopadhyay *et al.*, 2014; 2018).

Discussions

It is noteworthy that all these soils comprised endo-saturation with hue 5Y to10 YR and

Table 4. *Pedogenic considerations of soils of the study area*

Pedons	Depth (cm)	Sand/ Silt	Silt/ Clay	FS/ TS	VFS/ TS	CEC/ Clay	ER	IW
P1	0-20	0.67	4.27	0.24	0.44	0.57	0.78	4.65
	20-40	0.26	3.65	0.36	0.67	0.41	0.64	2.29
	40-75	4.20	2.81	0.38	0.70	0.69	0.99	10.77
	75-105	5.68	2.78	0.26	0.48	0.87	0.82	17.11
	105-130	12.71	1.28	0.32	0.59	0.85	0.64	15.74
	Average	**4.70**	**2.96**	**0.31**	**0.58**	**0.68**	**0.77**	**10.11**
P2	0-20	0.21	5.28	0.24	0.47	0.50	1.00	3.71
	20-40	0.23	3.22	0.52	1.03	0.37	0.94	1.85
	40-60	1.79	3.53	0.71	1.41	0.54	0.99	5.85
	60-75	14.38	0.98	0.82	1.63	0.50	1.20	8.14
	75-125	16.82	1.42	0.43	0.86	0.85	1.43	22.37
	Average	**6.69**	**2.89**	**0.54**	**1.08**	**0.55**	**1.11**	**8.38**
P3	0-18	0.54	2.70	0.45	1.58	0.30	0.99	1.55
	18-40	2.35	2.69	0.45	1.58	0.52	1.14	5.23
	40-70	0.04	3.26	0.78	2.76	0.25	1.20	1.11
	70-90	0.87	4.70	0.67	2.37	0.49	1.27	4.78
	90-136	0.12	1.44	0.56	1.97	0.24	1.10	0.64
	Average	**0.78**	**2.96**	**0.58**	**2.05**	**0.36**	**1.14**	**2.66**
P4	0-23	0.26	2.20	0.40	0.95	0.26	0.66	0.99
	23-46	0.37	2.76	0.48	1.13	0.22	1.43	1.07
	46-90	0.27	2.46	0.48	1.13	0.20	1.31	0.81
	90-121	16.06	0.46	0.56	1.32	0.30	2.09	2.63
	121-153	7.09	0.58	0.64	1.51	0.22	1.74	1.27
	Average	**4.81**	**1.69**	**0.51**	**1.21**	**0.24**	**1.45**	**1.35**
P5	0-25	2.08	1.69	0.46	1.22	0.31	1.78	1.95
	25-48	0.29	1.92	0.49	1.29	0.19	2.12	0.66
	48-70	0.33	1.65	0.74	1.97	0.19	2.18	0.61
	70-100	0.25	1.81	0.64	1.69	0.22	1.40	0.71
	100-115	5.68	2.78	1.12	2.98	0.93	0.72	18.30
	Average	**1.73**	**1.97**	**0.69**	**1.83**	**0.37**	**1.64**	**4.46**
P6	0-25	0.01	2.96	0.70	2.11	0.42	1.19	0.40
	25-55	0.09	0.93	0.64	1.94	0.20	1.41	0.29
	55-85	0.16	0.79	0.61	1.86	0.15	1.94	0.31
	85-120	0.07	1.28	0.83	2.53	0.13	2.41	0.59
	Average	**0.08**	**1.49**	**0.70**	**2.11**	**0.23**	**1.74**	**0.40**

Abbreviations: FS/TS-Fine sand/ total sand; VFS/ TS-very fine sand/ total sand; ER-Exchange ratio; IW-Weathering index

Chroma of 2 or less in at least two or more sub-surface horizons. Formation of gleyed cambic and argillic horizons were common in these soils. The hydromorphic behaviour is indicated from gleyed sub-surface horizons in all the pedons with occurrence of reduction mottles, iron and manganese depletions in P1, P2, P3 and P4, as well as stress features, ferrans and mangans in P5 and P6. They have been classified under Entisols, Inceptisols and Alfisols orders in successive stages of pedogenesis from active flood plains, younger flood plains to older flood plains. Worldwide, hydromorphic soils are known in varying orders with the commonest one as Histosols (Bouma *et al.,* 1990). Though, in Brahmaputra valley region of Assam, the hydromorphic soils were confined only to three soil orders. The humid sub-tropical climate of the study area may not be conducive for the formation of Histosols, since the soils experiences rapid pedogenic events. Thus, it is apparent that there is a steady pedogenic change in these hydromorphic soils from *Endoaquents* to *Endoaqualfs* with micro-topographic variability of the landscapes. The relatively higher elevation and being at a distance proximity from the fluvial agents, facilitated clay illuviation compared to that for the younger and active flood plains which are in close proximity to the agents of fluvial action.

The hydromorphic behaviours in soils under three different landforms are very complex in nature. The endo-saturation in older flood plains occurred much earlier than it happened in younger and active flood plains. In active flood plains, micro-climatic depressions may be responsible for hydromorphic behaviour of soils. Soils of younger flood plains show an intermediate stage of endo-saturation between that of active and older flood plains. Hence, this study shows that local topographic and micro-climatic variability in the region can greatly influence the hydromorphic behaviour of soils *vis-a-vis* their pedogenesis.

Conclusions

The presence investigation stresses that micro-topographic variations, changes in textural and exchange properties and lithological discontinuity have been identified as the recognizable factors to describe the pedogenesis of hydromorphic soils. The relative elderliness of soils depended upon the pedogenic indices across the landforms and land uses of the study area. The vertical distribution of these indices showed lithological discontinuity in the younger and soils of the active plains was detrimental for the higher pedogenic development in such soils. This type of study can unveil the crucial information needed for proper management and restoration of these soils for their optimal use.

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