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Full Length Research Paper

Pedological perspective of gully erosion sites within Kendu escarpment-Sondu Miriu Region, West Kenya

D. O. Sigunga[1]*, M. Hoshino[2], J. C. Onyango[1], S. Asanuma[2] and M. Kimura[2]

[1]Faculty of Science, Maseno University, Kenya.
[2]Graduate School of Bioagricultural Science, Nagoya University, Japan.

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Gully erosion is a common feature in western Kenya, rendering large expanses of otherwise arable land uncultivable and uninhabitable. Gully erosion in the area was classified into two types: the Awach-type and the Sondu-type. The current study aimed at providing insight into physical and chemical properties of soil that promote soil erosion and determine the gully formation type. Field studies were conducted at 4 sites (3 eroded and 1 non- eroded). Physical (particle size distribution, structure stability, infiltration rate, dispersibility, and soil hardness), and chemical (pH, exchangeable cations, total-C, and total-N) properties of soil samples collected from the sites were analyzed in the laboratory. The results showed alkaline pH; high exchangeable sodium (Na) percentage (ESP); fragile soil structure; high dispersibility; and low infiltration rate are major factors contributing to the formation of Awach-type of gully. In contrast, impermeable top layer of hard crust and coarse-textured soil layers beneath it in addition to high ESP facilitated the formation of Sondu-type of gully. Soils of the eroded sites and the non-eroded sites differed mainly in the ESP, which influenced the soil structure stability, water infiltration rate, and soil dispersibility. Susceptibility of soil layers to erosion depended on the magnitude of ESP and sand content.

Key words: Exchangeable sodium percentage, gully erosion, infiltration rate, Kenya, soil dispersion, soil structure.

INTRODUCTION

Per capita food production in Kenya has declined over the past several years (Central Bureau of Statistics, 2006). One main cause for the decline was the mismanagement of land/soil resources (Lal, 1987; 1988; Sanchez et al., 1997). Soil erosion was the most extensive and serious land degradation problem undermining crop production resulting in increased food insecurity in Kenya (FAO, 2010). Soil erosion was noticed in Kenya as early as the 1930s, and the organized soil conservation program started in the country in 1937 (Erikkson, 1992). However, soil erosion control was not successful, partly because the recommended soil-erosion control measures were not sufficiently evaluated in terms of their technical effectiveness, economic benefits, and societal suitability across different levels of the landscape hierarchy (Sigunga, 1998; Okoth, 2003).

Erosion is the process by which the soil or rock formation is loosened and carried away by wind, water, freeze and thaw or biological activities (Fairbridge, 2008). Gully erosion, also known as ephemeral gully erosion, occurs when water flows in narrow channels during or after heavy rainfall or melting snow. The channels or gullies range in depth from 30 to 3,000 cm and only contain water during and immediately after precipitation events (Termwiki, 2010). Gully erosion in this region is caused by water.

Gully erosion is a common feature in the Kendu escarpment and on the slope of Sondu-Miriu range; rendering large expanses of otherwise arable land uncultivable and uninhabitable in western Kenya (Figure 1). Gullies occur sporadically covering over 100 ha of land in some parts of this region. The damage due to gully erosion results not only in loss of land for crop and pasture production but also in land for establishing homesteads and roads leading to displacement of many

*Corresponding author. E-mail: dalsigunga@yahoo.com.

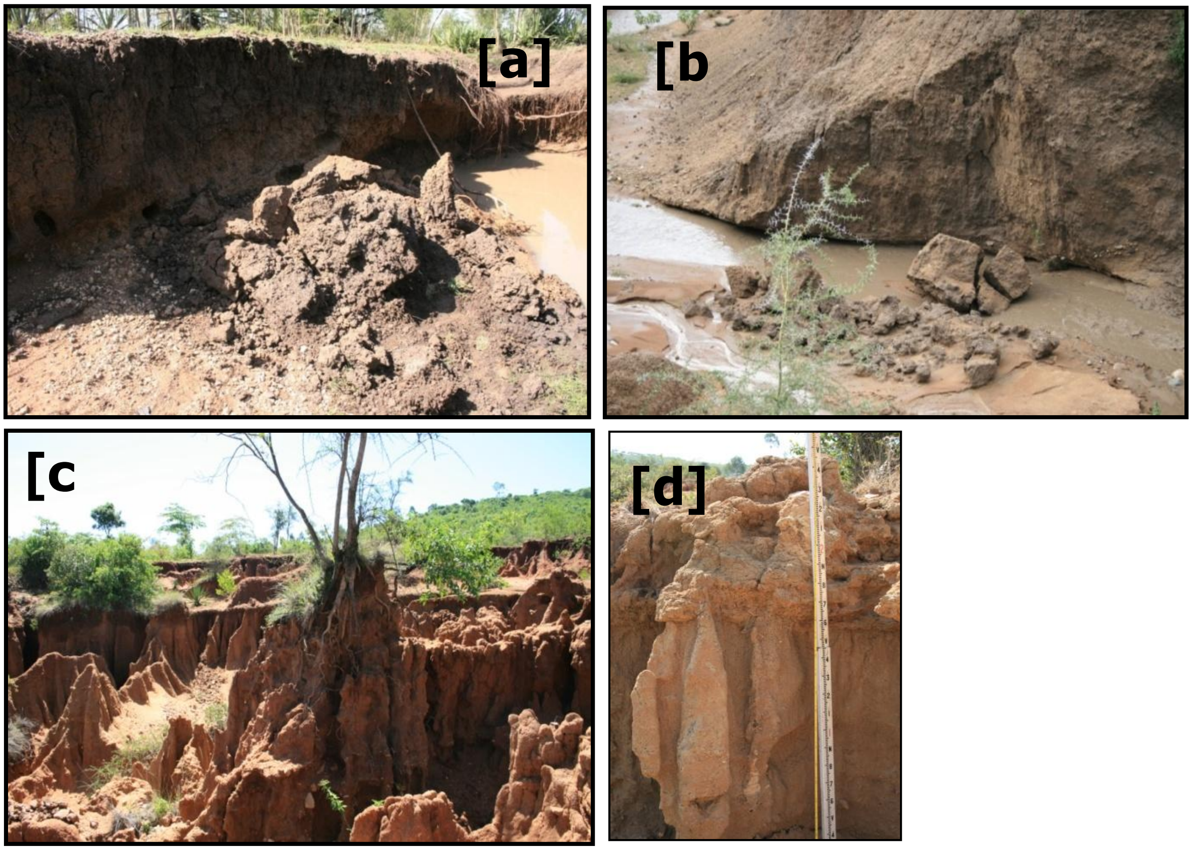

Figure 1. Two types of gully erosion in western Kenya. Awach type: (a) Kokal and (b) Katuk kodeyo and Sondu type: (c) Kadiang'a and (d) Odino.

families. The displaced families face serious social and economic hardships since they are compelled to resettle elsewhere away from home. Gully erosion in the area is classified into two erosion pattern types: Awach-type and Sondu-type (Figure 1). A deep single channel, perpendicular banks, and distinct head-cuts presumably formed by stream flows and mass wasting characterized Awach-type gullies. Due to their steep geomorphic conditions, slumping of bank walls occurred in places along the gully (Figure 1a and b). In contrast, braided shallow channel beds characterized Sondu-type gullies (Figure 1c and d). They are in general less than 10 m in depth. Banks ranged from nearly perpendicular to gently declining, and plenty of earth pillars developed along the gullies (Hoshino et al., 2004; Hoshino, 2006; Katsurada, 2007; Katsurada et al., 2007).

Interaction among such factors as soil conditions, climatic constituents, and anthropogenic activities cause gully erosion (Burkard and Kostaschuk, 1995; Morgan et al., 1997). Hoshino (2006) proposed the possible mechanisms of gully erosion based on geological and geographical factors. In the current study, pedological namely physical and chemical characteristics of eroded sites were compared with those of non-eroded sites in the Kendu escarpment Lake Victoria delta of western Kenya to understand the characteristics of lands/soils prone to gully erosion processes.

MATERIALS AND METHODS

Study sites

The study area was located between Kendu escarpment (1,200 to 1,600 m above the sea level, masl) and Lake Victoria (surface elevation of 1,133 masl) (Figure 2). The study area was characterized by monomodal rainfall patterns with the peak in April (Jaetzold and Schmidt, 1983). Field studies were conducted at four sites: Kokal (S00°16'35.3", E34°58'46.6"), Kadiang'a (S00°21'48.4", E34°53'28.5") and Katuk kodeyo (S00°18'24.64'', E35°1'2.37'') with extensive gully erosion while Kapkatet (S00°23'15.7", E35°03'26.1") was a non-eroded site. Awach-type of gully erosion was represented by Kokal and Katuk kodeyo sites, while Kadiang'a represented the Sondu-type of gully erosion. Kapkatet, a non-eroded site, was used for comparison with the eroded sites. Soil samples were taken from 7, 6, 13, and 5 layers along the soil profiles at Kokal, Kadiang'a, Katuk kodeyo, and Kapkatet sites, respectively. The layers of each soil profile were differentiated on the basis of soil texture, soil colour, and plant root development. Soil samples were air-dried and passed through a 2 mm sieve. Physical properties determined were particle size distribution, structure stability, dispersibility, water infiltration rate, and soil hardness. Chemical properties determined were pH,

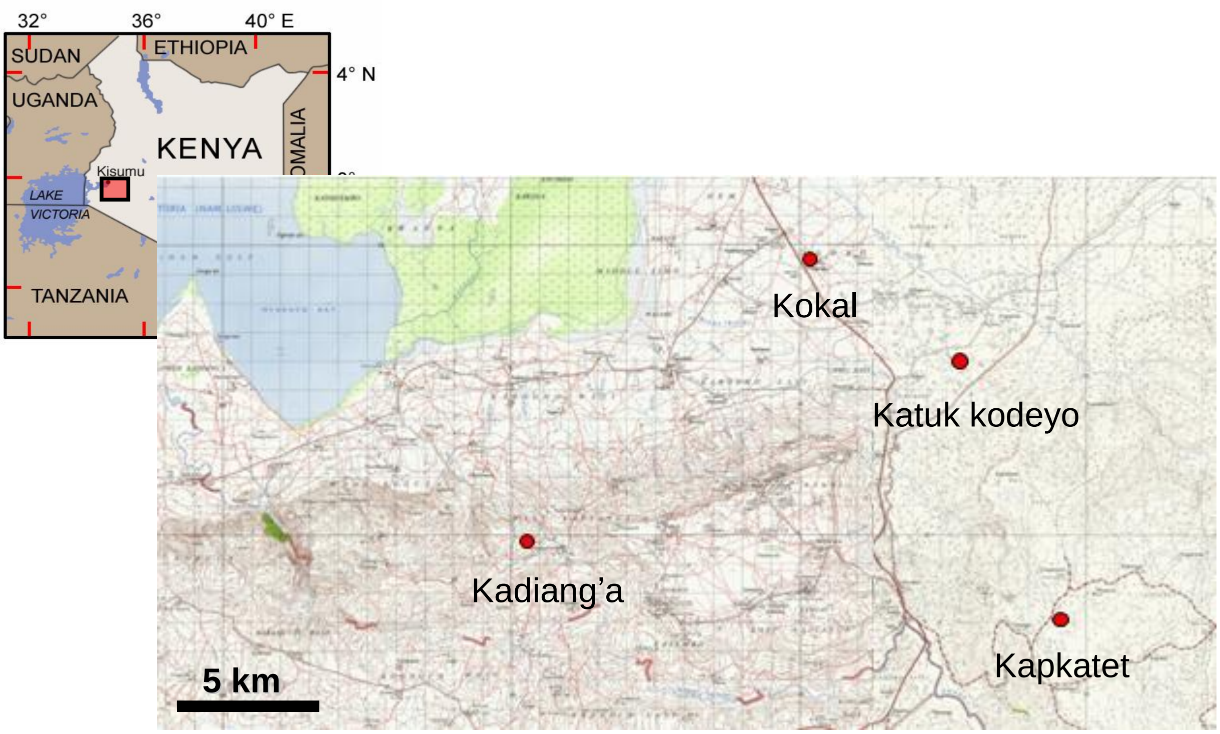

Figure 2. Study area.

exchangeable cations, total carbon (total-C), and total nitrogen (total-N).

Physical properties

Particle size distribution was determined with a bouyoucos hydrometer after digesting soil organic matter with hydrogen peroxide and soil dispersion with sodium hexametaphosphate (Okalebo et al., 2002). Structure stability of soil aggregates was compared among the soil samples in the laboratory. Air dried soil particles with the size between 0.5 and 2 mm were placed on a 0.5 mm sieve; excess amount of distilled water was added drop by drop to submerge the soils. Five min after soil submergence, excess water was absorbed by tissue paper from the bottom of the screen. The soil structure was then compared with that of air dry soil samples.

Soil dispersibility was evaluated with 3 g of air-dry soil that was placed in a glass column (diameter 1.0 cm, height 10.0 cm) that was plugged with cotton wool at the bottom. The soil was percolated with distilled water under a controlled water-head condition. Five milliliter (5 mL) of leachate was collected with a fraction collector (CHF 100AA, Toyo Seisakusho Kaisha Limited, Japan), and its turbidity was determined at 660 nm wavelength with a spectrophotometer (NOVASPEC II, Pharmacia Biotec, Sweden). As water permeability of the soil samples collected, from the 6th to 13th layers from Katuk kodeyo site were very slow, 3 g of soil samples were mixed with 6 g of quartz sand to increase the permeability (Topark-Ngarm et al., 1990). To determine water infiltration rate in different soils, 3 g of air dry soil was parked in a glass column as described for soil dispersion evaluation. Time taken to collect 50 mL of filtrate from each soil samples was recorded (Patcharapreecha et al., 1989). Soil hardness was determined using soil penetrometer.

Chemical properties

Soil pH, exchangeable cations, total-C, and total-N were determined following procedures described by Okalebo et al. (2002). Soil pH (H_2O) was determined in soil: water ratio of 1:2.5 using pH meter. Exchangeable cations (Ca, Mg, K, and Na) were extracted using 1M NH_4OAc. Extracted Ca and Mg were determined with an atomic adsorption spectrophotometer and exchangeable K and Na with a flame photometer. Total C and total-N in soil samples were determined using the NC analyzer after grinding to 100 to 200 μm.

Statistical analysis

Chemical and physical properties of soil samples collected from the first five layers from the ground surface of the soil profiles at the four sampled sites were subjected to statistical analysis using ARM 8 statistical software (Gylling Data Management, 2008). The number of layers per site subjected to statistical analysis was limited to five since the soil profile at Kapkatet site had only five layers (Figure 2).

RESULTS

Particle size distribution

Particle size distribution significantly ($p > 0.05$) varied between and within sites (Table 1). Sand fractions of Kokal, Kadiang'a, Katuk kodeyo, and Kapkatet sites

Table 1. Textural and chemical properties of soils at the four research sites.

Village site	Soil layer and depth (cm)	Sand (%)	Silt (%)	Clay (%)	Texture	pH (water)	Ca cmol kg^{-1}	Mg cmol kg^{-1}	K cmol kg^{-1}	Na cmol kg^{-1}	ESP§	Total-C g kg^{-1}	Total-N g kg^{-1}
	1 (0-3)	64.7^{e}	14.0^{gh}	21.3^{g}	SCL	7.2^{h}	18.8^{e}	3.3^{e}	1.5^{g}	0.7^{cd}	3^{h}	14.7^{g}	0.6^{b}
	2 (3-29)	65.1^{e}	11.5^{i}	23.4^{f}	SCL	7.7^{f}	22.0^{d}	3.3^{e}	1.2^{i}	1.6^{a}	6^{g}	5.6^{j}	0.3^{b}
Kokal	3 (29-96)	63.1^{f}	9.5^{j}	27.4^{e}	SC	7.9^{e}	24.8^{c}	3.5^{d}	1.1^{ij}	3.0^{bcd}	9^{f}	6.2^{i}	0.6^{b}
	4 (96-131)	61.1^{g}	15.5^{fg}	23.4^{f}	SCL	8.3^{cd}	29.7^{b}	3.3^{e}	1.0^{jk}	3.2^{bcd}	9^{f}	4.3l	0.3^{b}
	5 (131-147)	61.1^{g}	17.5^{e}	21.4^{g}	SCL	8.4^{c}	31.2^{a}	3.6^{d}	0.9^{k}	3.6^{a-d}	9^{f}	2.6^{o}	0.3^{b}
	1 (0-32)	80.7^{b}	13.8^{h}	5.4l	SL	6.3^{i}	7.7^{jk}	2.0^{j}	4.2^{b}	4.6^{a-d}	25^{b}	1.7^{p}	0.3^{b}
	2 (32-53)	82.4^{a}	7.8^{k}	9.8^{k}	SL	6.0^{j}	5.5l	1.8^{k}	1.6^{g}	2.7^{bcd}	23^{cd}	3.1^{n}	0.3^{b}
Kadiang'a	3 (53-76)	81.9^{a}	11.8^{i}	5.8l	SL	7.8^{ef}	6.7^{kl}	2.0^{j}	3.4^{d}	4.1^{a-d}	25^{b}	4.2l	0.4^{b}
	4 (76-96)	80.4^{b}	10.2^{ij}	9.4^{k}	SL	7.5^{g}	10.7^{i}	3.1^{fg}	4.7^{a}	4.6^{a-d}	20^{e}	5.0^{k}	0.4^{b}
	5 (96-147)	76.7^{c}	14.0^{gh}	9.3^{k}	SL	8.3^{d}	8.5j	2.4^{i}	2.0^{f}	3.7^{a-d}	22^{d}	3.7^{m}	0.4^{b}
	1 (0-10)	67.3^{d}	16.7^{ef}	16.0^{h}	SCL	7.4^{g}	29.5^{b}	4.9^{b}	1.4^{h}	0.1^{d}	0^{i}	39.2^{c}	2.1^{b}
	2 (10-30)	54.7^{j}	16.0^{ef}	29.3^{d}	SC	7.5^{g}	31.7^{a}	4.2^{c}	1.0^{jk}	0.5^{d}	1^{i}	22.1^{f}	1.0^{b}
Katuk kodeyo	3 (390-461)	67.6^{d}	20.2^{d}	12.2^{j}	SL	8.9^{a}	12.1^{h}	2.8^{h}	1.2^{i}	6.8^{ab}	30^{a}	2.5^{o}	0.2^{b}
	4 (461-580)	47.6^{k}	20.2^{d}	32.2^{c}	LiC	8.9^{a}	13.7^{g}	3.3^{e}	1.6^{g}	7.6^{ab}	29^{a}	1.0^{q}	0.1^{b}
	5 (580-588)	67.1^{d}	20.3^{d}	12.7^{j}	SL	8.6^{b}	14.3^{g}	3.2^{ef}	2.4^{e}	6.4^{abc}	24b^{c}	3.2^{n}	0.3^{b}
	1 (-5-0)	58.4^{h}	26.0^{b}	15.6^{h}	CL	6.0^{j}	16.2^{f}	6.4^{a}	4.2^{b}	0.1^{d}	0^{i}	55.0^{a}	4.3^{ab}
	2 (0-30)	56.7^{i}	29.6^{a}	13.6^{i}	L	6.0^{j}	11.3^{hi}	3.0^{g}	3.9^{c}	0.1^{d}	1^{i}	45.4^{b}	2.7^{b}
Kapkatet	3 (30-50)	54.7^{j}	23.6^{c}	21.6^{g}	CL	5.4^{k}	6.2l	2.3^{i}	1.9^{f}	0.1^{d}	1^{i}	36.3^{d}	2.0^{a}
	4 (50-79)	42.7^{l}	15.3^{fgh}	41.8^{b}	LiC	5.1l	3.1^{m}	1.4l	0.7l	0.1^{d}	2^{i}	25.8^{e}	1.2^{ab}
	5 (79-155)	40.4^{m}	7.6^{k}	52.0^{a}	HC	5.0l	3.8^{m}	1.9^{jk}	0.5^{m}	0.1^{d}	2^{i}	6.7^{h}	0.6^{b}
LSD (.05)	-	1.10	1.46	0.83	-	0.14	1.23	0.13	0.14	5.09	1.80	0.30	7.40
Standard Dev.	-	0.524	0.70	0.40	-	6.71	0.59	6.28	6.68	2.43	0.86	0.14	3.54
CV	-	0.82	4.34	1.96	-	0.93	3.82	2.04	3.30	79.27	7.06	0.98	208.16
Total df (39)	-	***	***	***		***	***	***	***	**	***	***	**

§ Exchangeable sodium percentage (ESP) is given by [Na]/ {[Ca] + [Mg] + [K] + [Na]} x 100; In each column means followed by different letters are significantly different (Duncan's MRT, P = 0.05); *** denotes significant difference (P ≤ 0.001); ** denotes significant difference (P ≤ 0.01) but CV value is too high due to data range.

ranged from 61 to 65%; 76 to 82%; 47 to 68%, and 40 to 58% respectively. The top two layers had significantly (p > 0.05) higher sand content than the lower layers. The soil at Kokal was sandy clay loam in all the layers, with the clay fraction ranging from 21 to 27%. The clay content of the layers significantly varied from one layer to the other. These results indicate that the origins of the five layers were different from each other. The texture of the soil at Kadiang'a site was sandy loam throughout the layers with clay fraction ranging from 5 to 10%. Many small shiny flakes of mica were also observed on the soil surface, both of which suggest the granitic origin of this soil.

The soil at Katuk kodeyo was generally loamy with the clay fraction ranging from 12 to 32%. The wide range of sand fraction at this site was due to the multiple depositions of soil materials by alluvial processes, which was recognized from the insertion of thin fine-textured layers and drastic change in soil texture between the adjacent layers. For example, clear lines were observed between the 3rd and 4th layers. In addition, the 3rd and 5th layers were the intercalated layers. Furthermore, the sand fraction was significantly larger in the 1st, 3rd, and 5th layers than in the 2nd, and 4th layers, which suggested the deposition event of the 1st, 3rd, and 5th layers were different in time from that of the 2nd and 4th layers. The texture of the soil at Kapkatet site was loamy in the first four layers and clayey in the 5th layer; the clay fractions ranged from 14 to 22% in the top four layers, while they were from 42 to 52% in the lower layers. These results indicated that the origin of top four layers and below them were different in parent materials.

Stability of soil structure

Stability of soil structure varied within each soil profile at the three erosion sites (Figure 3). Soil samples collected from the 3rd to 7th layers at Kokal site became fragile when submerged in water and were destructed from the original structure. In contrast, soil samples from the 1st and 2nd layers at the site retained their original structures (Figure 3a). At Kadiang'a site the soil samples from the 1st to 5th layers remained stable. Only the soil sample from the 6th layer showed the considerable destruction of structure (Figure 3b). Since soil samples from layers at Katuk kodeyo site were used out during chemical analyses, only soil samples from six layers were subjected to this study. The soil sample from the 2nd layer was stable to submergence in water, while samples from five layers underneath were very fragile to submergence (Figure 3c). Only two soil samples, the 2nd and 5th layers, from Kapkatet site were available for this study. Although they were stable to submergence, each of them showed different reaction to the submergence: soil sample from the 2nd layer was stable to submergence, whereas the sample from 5th layer was destructed to smaller particles but remained stable at the smaller size (Figure 3d).

Soil dispersibility

The optical density (OD) at 625 nm in 5 ml filtrate was integrated along the fractions (Figure 4). The more soil the was dispersed the higher the turbidity of the filtrate and, hence, the higher the OD. Soil dispersion was very small for the soils from Kapkatet site with less than OD 2 soil was dispersed the higher the turbidity of the filtrate of the integrated values except for the second layer (integrated OD = 4.9). Integrated OD was also low for soils from Kokal and Kadiang'a sites. In contrast, integrated OD was very high for the soils from the sixth layer at Katuk kodeyo site except for the 8^{th} layer. In general, soil dispersibility was greater at the lower layers than at the surface layers at every gully-erosion site (Kokal, Kadiang'a and Katuk kodeyo), especially at Katuk kodeyo site.

Water infiltration rate

The water infiltration rate was very low in some layers at the Kokal and Katuk kodeyo sites in comparison with those at Kadiang'a and Kapkatet sites and the layers of low infiltration rate were from the deeper horizons (Figure 5). All the layers at Kapkatet site showed high water infiltration rates (Figure 5) indicating high soil porosity and rapid water movement vertically down and horizontally indicating no horizon/layer preventing water movement that is, water stagnation.

Soil reaction

Soil pH (H_2O) varied significantly between the sites, and within the individual profiles at the sites (Table 1). At the Kokal site, the pH was 7.2 at the top layer increasing to pH 8.4 in the 5th layer of 131 to 147 cm depth. The pH of the soils at Kadiang'a site ranged from weakly acidic (6.0 to 6.3) in the top two layers to alkaline (7.5 to 8.3) in the layers below. The soil pH of each layer at the Katuk kodeyo site was constantly alkaline from 7.4 to 8.9 throughout the soil profile. In contrast, the soils at Kapkatet site were acidic throughout the soil profile (5.0 to 6.0). Alkaline soil pH of the Kokal, Kadiang'a and Katuk kodeyo sites seemed to accelerate soil dispersion and decrease the infiltration rates in these soils.

Exchangeable cations

Dominant exchangeable cation was Ca in all the layers of the profile at each site (Table 1). At the Kokal site Ca was followed by Mg and Na in this order, while Na and K followed Ca at the Kadiang'a site. At Katuk kodeyo K and Na followed Ca in the upper and lower layers, respectively. In contrast, exchangeable Na content was very low in every layer of the profile at the Kapkatet site. At the Kokal site, the exchangeable Na content was 0.7 cmol kg^{-1} of soil in the first layer, and increased to 3.6 cmol kg^{-1} of soil in the 5th layer with exchangeable Na percentage (ESP) in the four main cations (Ca, Mg, K and Na) of 3% in the first layer and of 9% in the 5th layer (Table 1). At the Kadiang'a site, exchangeable Na content was very high, ranging from 2.7 to 4.6 cmol kg^{-1} of soil and ESP was from 20 to 26%. As the soil with ESP

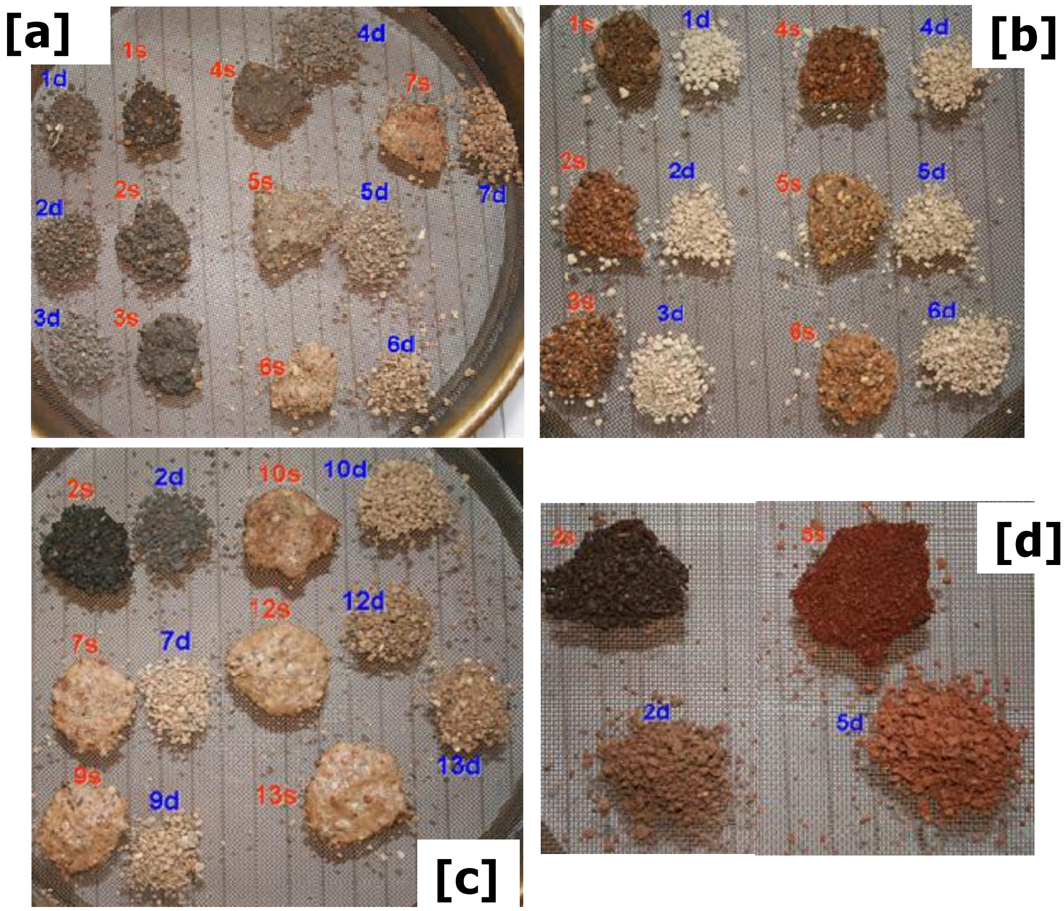

Figure 3. Soil particles (0.5 – 2.0 cm) under submerged conditions (s) compared with air dry soil particles (d). The Arabic numbers indicate the respective soil layers. The soil samples were collected from Kokal [a], Kadiang'a [b], Katuk kodeyo [c] and Kapkatet [d] sites.

over 15% and above is grouped as alkaline (Brady and Weil, 2009), the high ESP strongly indicated that the soil at the site was Alkaline. At Katuk kodeyo site exchangeable Na content was low at the first 2 layers and significantly higher in the layers below. At least, the soil layers from the 3rd layer had the properties of alkaline soils. In contrast, exchangeable Na content was significantly lower at Kapkatet site than at the other sites and ranged from 0.09 to 0.11 cmol kg^{-1} of soil with the ESP ranging from 0 to 2%.

Total-C and total-N

Total-C content was 1.5% in the first layer, and decreased sharply to 0.6% from the second layer at the Kokal site (Table 1). At Kadiang'a site, total-C content in the soil was very low throughout the layers, ranging from 0.17% in the first layer to 0.37% in the 5th layer. The total C content at Katuk kodeyo site was significantly highest in the first layer (3.92%) and lowest in the 4th layer (0.10%).than the other layers underneath (0.10 to 032%). The high content of soil organic matter in the top two layers was also recognized from the dark color. The total C content of the soil at Kapkatet site was very high in the first four layers ranging from 2.58 to 5.45%, which seemed to suggest the volcanic ash origin (Andic properties).

DISCUSSION

Soil physical and chemical properties and the erodibility of study sites

Awach-type erosion (Kokal and Katuk kodeyo) sites

Particle size distribution in Table 1 showed that the Kokal and Kadiang'a (eroded) sites had significantly higher sand content than did the Kapkatet (non-eroded) site. Katuk kodeyo (also eroded) site contained significantly

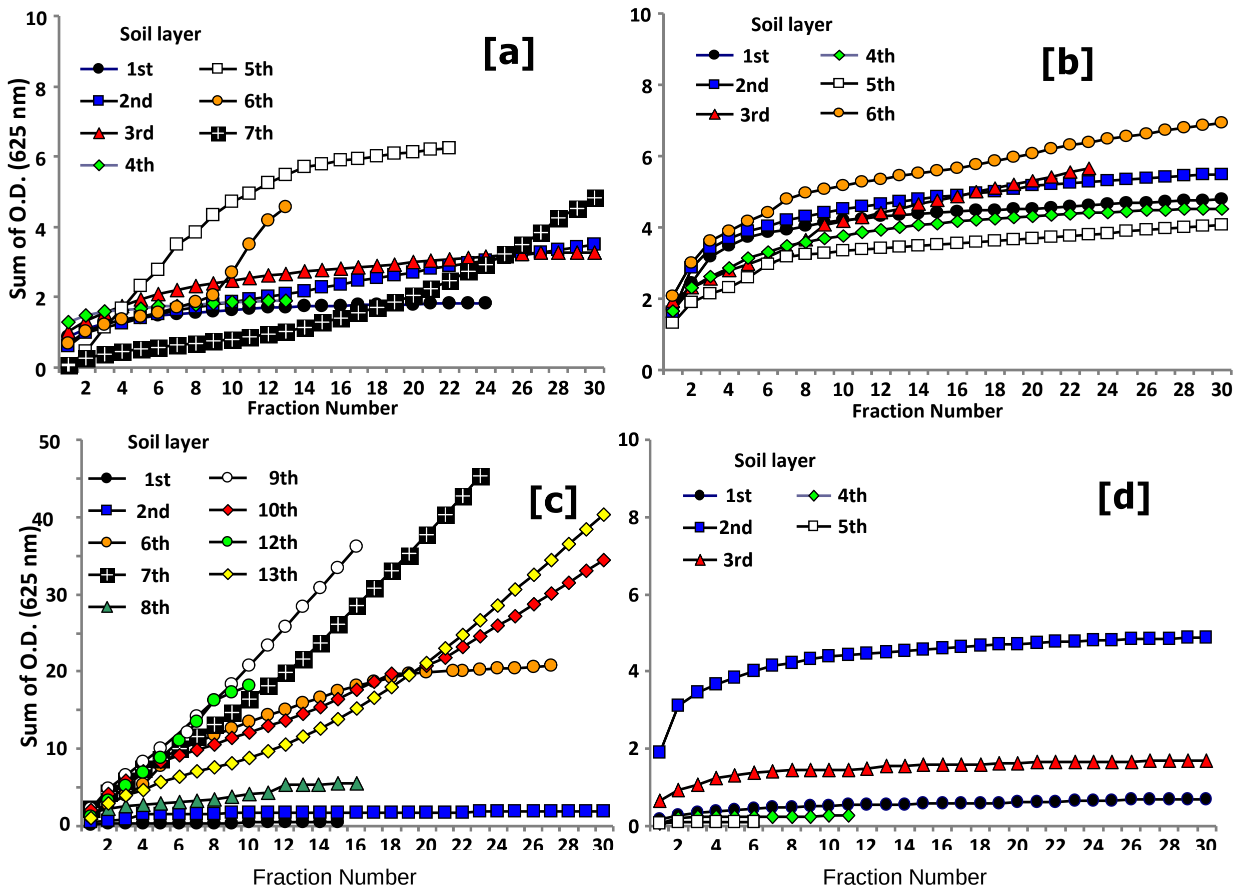

Figure 4. Dispersibility of soil particles as estimated from optical density of filtrate. The soil samples were collected from Kokal [a], Kadiang'a [b], Katuk kodeyo [c] and Kapkatet [d] sites.

higher sand fraction in some but not all layers compared to Kapkatet site, indicating that texture was not the only factor influencing erosion. However, sediments with high sand or silt contents erode more easily than those with lower sand and silt contents (Fairbridge, 2008). Soilstructures in the lower layers at the Kokal and Katuk kodeyo sites were very fragile with easy destruction by water in comparison with the upper layers and the soils at the Kapkatet site (Figure 2). Destruction of soil structure induced considerable soil dispersion in those soil layers (Figure 4). Markedly large soil dispersion of Katuk kodeyo soil samples was explained from the high ESP (Table 1). Dispersion is facilitated by a large number of water molecules associated with each micelle and with the adsorbed Na^+ ions. Highly hydrated monovalent Na^+ ions are not tightly held by the micelles enhancing clay dispersion (Brady and Weil, 2009).Very low infiltration rate was an additional factor causing serious gully erosion at the Katuk kodeyo site. Low water infiltration rate results in saturation of soil layers, leading to both surface and subsurface runoff facilitating soil erosion by water (Chesworth, 2008). As for the Kokal site, very low infiltration rate might be the predominant factor, as well as relatively higher percentage of exchangeable sodium, and higher soil dispersibility in the lower layers than in the upper layers (Table 1) that induced the Awach type soil erosion. Very low water infiltration rate and higher soil dispersibility at the Katuk kodeyo site, and in the lower layers at the Kokal site, indicate that dispersed soil (mainly clay fractions) might plaster and/or plug the pores and channels of water pass-way, which resulted in serious water stagnation at the Kokal and Katuk kodeyo sites. High pH coupled with high Na content (Table 1) is bound to accelerate soil dispersion and decrease infiltration rate. Heavy soil mass due to water stagnation, fragile soil structure, and hollow-out at the soil layer of stream-floor might induce the fall-down of the above soil mass successively (Figure 1a and b). Especially very low water infiltration rate from the 6th layer (Figure 5c) with the remarkable soil dispersion (Figure 4c) at the Katuk kodeyo site indicate the fall-down in billiard manner from the lower layers upwards. The process of Awach-type gully erosion may be explained from the very low water infiltration rate, and the serious soil dispersion in the lower soil layers. The higher C content in the surface layers than that of the lower layers suggested more

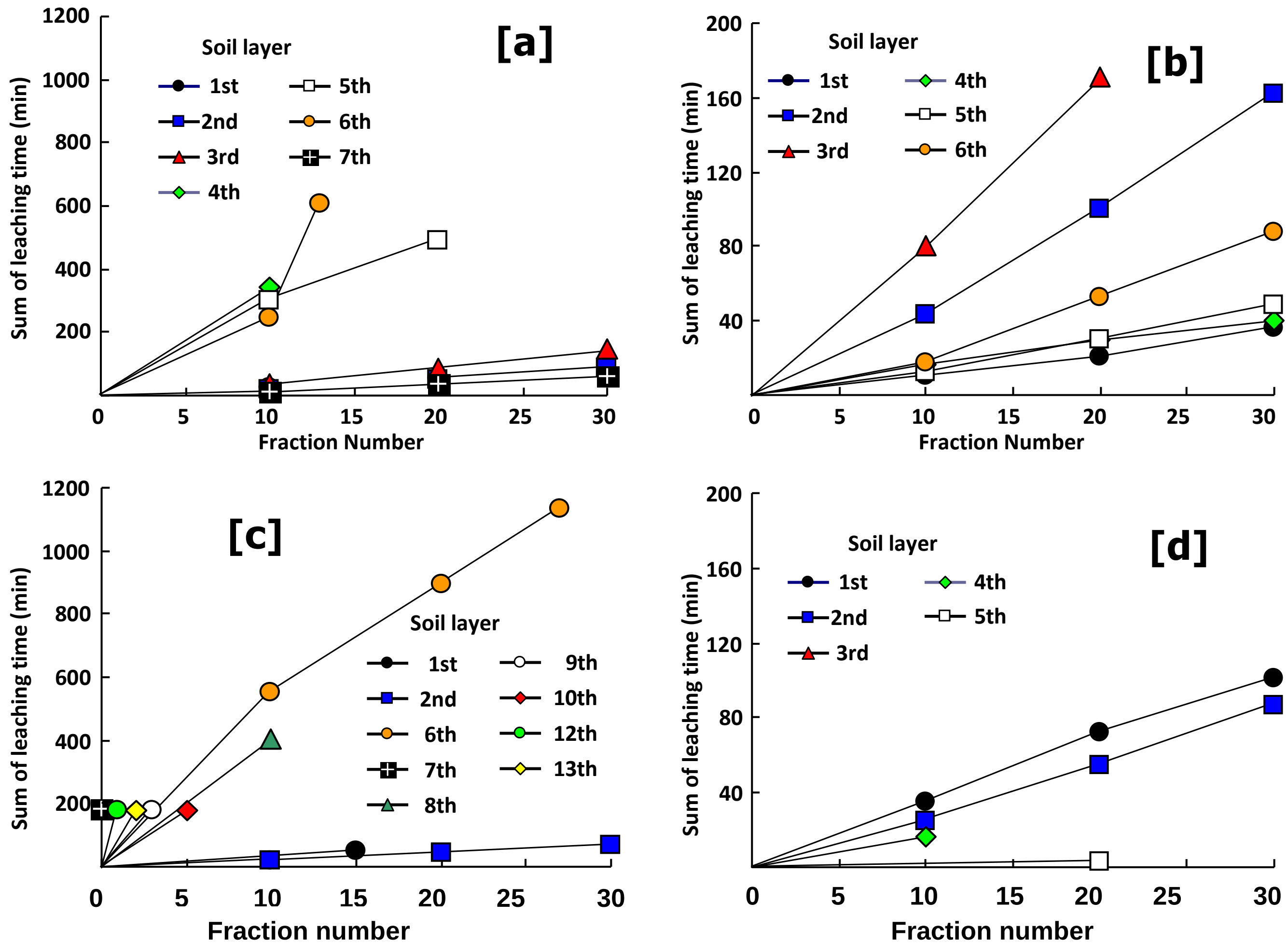

Figure 5. Water infiltration rates in soil samples collected from Kokal [a], Kadiang'a [b], Katuk kodeyo [c] and Kapkatet [d] sites.

stable soil structure in the surface layers than in the lower layers at the Kokal and Katuk kodeyo sites.

Sondu-type erosion (Kadiang'a) site

As the Sondu-type gully formation process at Kadiang'a site was difficult to explain from physical and chemical properties of soil layers only, field survey was complemented at the site. The Sondu type gully formation at this site seemed to proceed by two processes. The first process was the acceleration of surface run-off of rainwater along the slope after the disappearance of plant cover. Without plant cover, exposure of soil surface to the sun increased the soil hardness. For example, soil hardness along the transaction from the bare surface to the plant-covered surface decreased from 32.0 ± 1.2 at the former surface to 23.4 ± 1.7 at the latter surface (n = 10). The increase in soil hardness was due to the soil compaction, and the top soil layer became impermeable to rainwater at bare surface. The second process was the infiltration of run-off water into soil at the surfaces where the impermeable top layer was cracked or lost (Figure 1c and d). Cracks run vertically downwards from the surface layer. They were stained dark on the crack surface with the deposition of clay particles or made hollows and earth pillars. The clay dispersion due to high ESP and sandy texture accelerated the crack development and pillar formation. The pillars were very hard when dry and very fragile when moistened in contrast to the banks of Awach-type gully, which did not exhibit similar properties.

Clay types estimated from exchangeable cations and soil erodibility

Although clay fraction was not large, a large amount of exchangeable cations was observed for every layer except for the 4th and 5th layers at Kapkatet site (Table 1). The correlation coefficient between the sum of exchangeable cations (Ca+Mg+K+Na) and the percentage of clay fraction was 0.345 ($P < 0.01$)

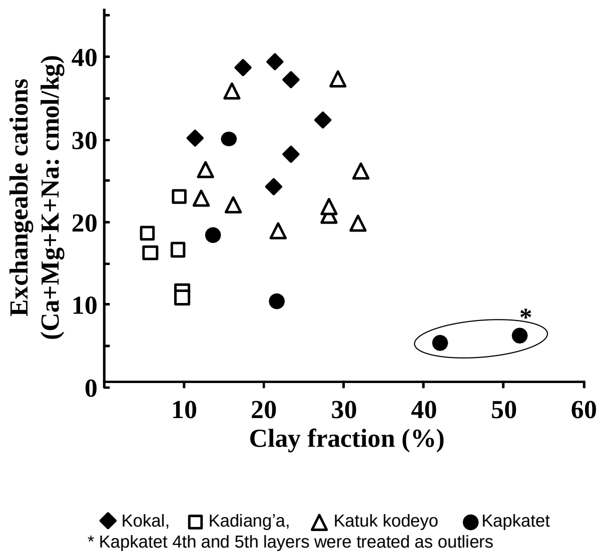

Figure 6. Correlation between sum of exchangeable cations and clay fraction

excluding the data from the 4th and 5th layers at Kapkatet site (Figure 6). The approximated line was $y = 0.368x + 17.9$, where y was the sum of exchangeablecations (meq/100 g soil) and x was the percentage of clay fraction. The extrapolation of the approximated line indicates that the soils in this area may have about 55 cmol kg^{-1} of soil in case the percentage of clay fraction reaches to 100%. As it is generally evaluated that cation exchange capacity (CEC) of kaolinite, halloysite, smectite and vermiculite are 2 to 10, 5 to 40, 60 to 100 and 100 to 150 meq per 100 g of clay, respectively (Brady and Weil, 2009), the clay minerals of these soils were estimated to be 2:1-type clay minerals. Only the 4th and 5th layers at Kapkatet site might consist mainly of 1:1-type clay minerals. The 2:1-type clay minerals expand in volume when moistened, especially those of high ESP (Brady and Weil, 2009), the property that brings about low water infiltration rate in the soil profile.

Conclusion

Gully erosion, a common feature in the Kendu escarpment, and on the slope of Sondu-Miriu range, rendering large expanses of otherwise arable land uncultivable and uninhabitable in western Kenya, was classified into two types from their patterns: the Awach-type and the Sondu-type. The present study showed that alkaline pH, high ESP, fragile soil structure, high dispersibility and low water infiltration rate, especially in the lower layers, brings about Awach-type gully erosion characterized by deep single channel, perpendicular banks, and mass wasting. In contrast, impermeable top layer of hard crust and coarse-textured soil layers beneath it, in addition to high ESP, brought about Sondu-type of gully erosion characterized by nearly perpendicular to gently declining banks and plenty of earth pillars. The main differences between the soils of the eroded sites and the non-eroded sites lay in the ESP, which influenced the soil structure stability, water infiltration rate, and soil dispersibility. Susceptibility of soil layers to erosion varied and depended on the magnitude of ESP and sand content.

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