Original Research Article

Drivers of gully erosion and its socio-economic and environmental effects in a tropical semi-arid environment

ABSTRACT

Gully erosion is a form of severe land degradation, which is more pronounced in semi-arid and arid environments due to their vulnerable ecosystems. Establishing the causes and effects of gully erosion is therefore fundamental in policy formulation and resource allocation for up-scaling context-specific gully mitigation and rehabilitation measures. Thus, this study aimed at assessing the causes and effects of gully erosion in semi-arid region, in the North-West part of Kenya. A cross sectional survey, field measurements, laboratory analysis, focus group discussions and key informants' interviews were used to collect data on drivers and effects of gully erosion. Descriptive statistics and content analysis were used to analyze the data. From the findings, 60 % of the respondents reported deforestation as the main driver of gully erosion. Further, 37 and 34 % of the respondents reported surface runoff and steep slopes, respectively, as major drivers of gully erosion. Based on soil analysis, it was confirmed that soils in the region had a high dispersion ratio, with values of between 0.3 and 0.9, making them highly erodible. About 66 and 55 % of the respondents reported that the major effects of gully erosion were reduction in arable land size and death of livestock due to fatal falls, respectively. Approximately 14 ha of arable land and 1,483,600 Mg of sediment have been lost to gully erosion at the rate of about 2,410 Mg ha^{-1} over a period of 45 years. The average growth rate and density of gullies in the study site stood at 154 Mg ha^{-1} yr^{-1} and 0.7 km km^{-2}, respectively. Four people and about 100 cattle had died due to fatal falls into the deep gullies. Nonetheless, gullies were reported to have provided a number of ecological services in the area. For example, it was reported that some gullies were a source of streams that provided water to surrounding households and livestock. In addition, they acted as sources of building sand, rocks and minerals that were exploited by the youth in the area. However, the negative effects were reported to outweigh the ecological benefits drawn from the gullies, and therefore urgent attention is required from all stakeholders. For effective mitigation of gully erosion, it is important to upscale integrated measures that reduce surface runoff and increase vegetation cover. Finally, it is also critical to find suitable and site-specific solutions to rehabilitate existing gullies aimed at preventing death of more livestock and people, and thus providing alternative ways of utilizing the badlands while mitigating further negative effects that could be brought about by climate change.

Keywords: Erodibility, Cambisols, Deforestation, Dispersion ratio, Gully morphometry, Land degradation, Lixisols, Overstocking

1.0 INTRODUCTION

Gullies are geomorphic features deeper than 0.5 m caused by concentrated water flow from surface runoff eroding the soil [1]. Due to their depth, gullies are difficult to rehabilitate using tillage implements. Thus, gully erosion is one of the most devastating forms of land degradation across various agroclimatic zones of the world [2-10]. Nonetheless, their effects are more pronounced and hard felt in the arid and semi-arid areas (ASALs) due to the vulnerability of these ecosystems which is attributed to the scarce vegetation cover, highly erodible soils and little emphasis on soil conservation [11-13]. Assessing and characterizing gully erosion is more complex than that of sheet erosion which can easily be modelled [14]. Various modern methods such as geographic information systems (GIS) have enabled deployment of machine learning in determination of gully susceptibility and the role of land use and cover changes on gully erosion [15]. In addition, models such as Digital Elevation Models (DEM), Digital Surface Models (DSM), Alternating Decision Tree (ADTree), Naïve-Bayes tree (NBTree), and Logistic Model Tree (LMT), boosted regression trees, support vector machines, random forest and logistic regression models have enabled use of machine learning to quantify and characterize gully erosion [15-19]. However, the models give varying results especially for the narrow and very deep, short or shallow, or gullies with very steep sides [16, 18]. This is attributed to the fact that gullies show different morphological characteristics with varying shapes and sizes. Further, growth of gullies continues through scouring of both gully walls and floor as well as head cut retreat [14, 20]. In addition, several factors, both anthropogenic and natural, have been associated with gully erosion across different agroclimatic zones. Some of these factors include deforestation, overgrazing,

inappropriate installation of soil conservation measures, prolonged droughts which reduce vegetation cover, landslides, erodible soils, steep slopes, and intense stormy rains [13, 21]. The contribution of any of these factors to gully erosion varies widely across agroclimatic zones. Hence, understanding the factors contributing to gully erosion and its effect in a particular watershed is critical in developing effective mitigation and rehabilitation plans [14, 21].
Elucidating the impact of gully erosion is equally critical in understanding the severity and extent of the situation for resource allocation. Several socio-economic and environmental effects of gully erosion have been documented across various countries. Among the extreme effect are loss of lives, displacement of people, reduction in crop yields, massive loss of soils and conversion of arable land into badlands [5, 8, 21-23]. In some regions, positive effects of gully erosion have been reported such as linear oasis during the dry seasons [24]. However, in the wake of growing global concerns on climate change and given the crucial role gully erosion plays in the aridification and desertification processes, it is critical to evaluate the qualitative and quantitative effects of gully erosion on the environment and socio-economic activities. This will greatly help to elevate discussions on gully erosion to international levels and hence aiding in fast tracking resource mobilization and policy formulations necessary for gully mitigation and rehabilitation.

Due to the complex nature of gully erosion, it is inevitable to deploy mixed methods for explicit elucidation of the drivers and dynamics of gully erosion [13, 25, 26]. However, only a few studies have partially managed this approach [21, 25]. Thus, there is scanty information on causes of gully erosion in semi-arid environments, their effects on the environment and socio-economic activities and more importantly characterizing the physico-chemical properties predisposing soils to gully erosion. Such information is not only critical in formulating effective gully mitigation and rehabilitation measures, but is also important in effective resource mobilization and allocation. Hence, this study aimed at assessing the drivers and impact of gully erosion in semi-arid areas through deployment of mixed methods. Therefore, the objectives of this study were to determine i) physico-chemical and human-induced drivers of gully erosion, ii) socio-economic effects of gully erosion to communities in the study site.

2. Materials and Methods

2.1 Study site characteristics

The study was conducted in Chepareria, West Pokot County in Kenya. The area is located between latitude 1°15′ N to 1°55′ N and longitude 35°7′ E to 35°27′ E. The area is undulating, semi-arid with several hills, which makes the area very susceptible to erosion. The mean annual rainfall is about 600 mm, distributed across two rainy seasons with the first season, often locally called ‘long rains’ occurring between March and June, while the second season, ‘short rains’ occurring between October and December. The area is dominated by four soil types; Leptosols, Lixisols, Cambisols and Luvisols. The research was conducted in two catchments; Senetwo and Ywalateke, purposefully sampled based on presence of severe gullies (Fig. 1). For effective elucidation of gully morphometry within the available resources, two sub catchments that were severely degraded were sampled. These were Sla and Senetwo sub-catchments. The area is inhabited by agro-pastoralists. Crops grown include maize and beans, and fruit trees such as mangoes and bananas. The dominant livestock kept are cattle, goats, sheep and poultry. Other economic activities in the area include sand mining, firewood and charcoal making and trading [27-29].

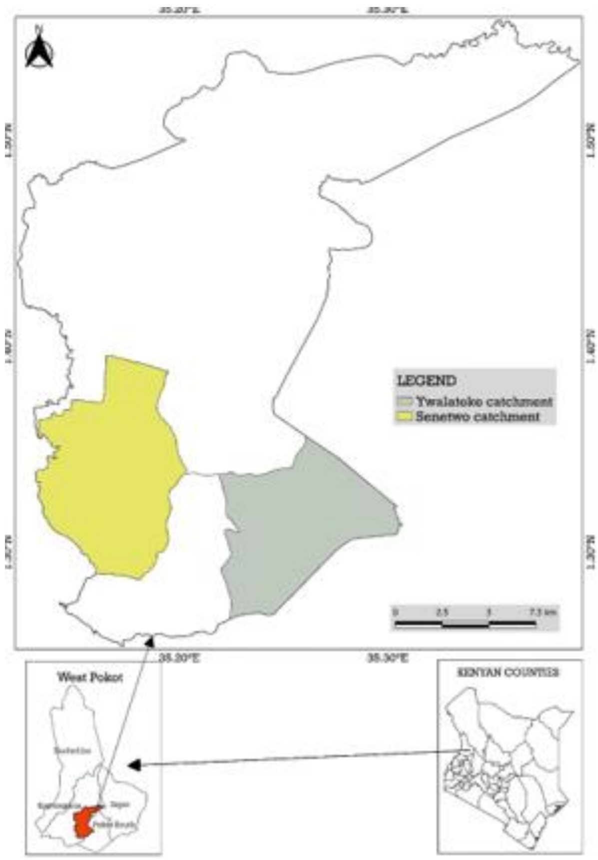


Figure 1: Map showing the study site

2.2 Study designs

The study used mixed methods to assess the causes and impacts of gully erosion. Among the methods deployed were cross-sectional household surveys, key informants' interviews, field observations and measurements, and laboratory analysis. Random sampling was used to identify households and to administer the questionnaires. Semi-structured questionnaire was administered to a sample size of 382 households obtained using the formula in (Eq. 1) [30].

$$n_0 = \frac{PQZ^2}{d^2} \qquad = \frac{0.5 \times 0.5 \times 1.96^2}{0.05^2} = 384 \qquad \text{Eq. 1}$$

where n_0 was the target sample size at 95% confidence interval, P was the estimated proportion of an attribute present in the population, in this case 0.5 was used; Q was given by 1-0.5, which was the probability for non-occurrence; Z^2 is the standard normal deviance of 1.96; d was the level of precision where 0.05 was adopted. The calculated n was adjusted to take into account 10% non-respondent rate. The two catchments sampled, (Senetwo and Ywalateke), had a total of 3,626 households according to Kenya National Population and Housing Census 2019 [31]. Since the required sample size in Eq. 1 exceeded 5% of the total population, it was adjusted using modified [30] equation by applying correction formula by [32] as provided in Eq. 2. The equation was again modified to take into account 10% non-respondent rate, giving a return sample size of 382.

$$n = \frac{n_0}{1 + n_0 \div population} = \frac{384}{1 + 384 \div 3626} \times 110\% = 382 \qquad Eq. 2$$

Key informants' interviews comprising of chiefs and elders born in 1960s were purposefully identified and interviewed on the causes, trends and impact of gully erosion using recall memory. Key informant interviews (KII) mainly aimed at documenting historical events associated with gully formation in the area such as *El Nino* events, deforestation, and droughts. In determination of gully characteristics, gullies were subdivided into representative trapezoidal segments for ease of determining the width and depths. Measurements of gully depth, height and width were determined manually using taping method. Gully volume (V) was determined based on Eq. 3 as described by Hassen and Bantider [21] and Yazie *et al.* [23].

$$V = L \times \frac{(W_t + W_h)}{2} \times Df \qquad \text{Eq. 3}$$

Where V = the displaced volume of soil in m^3, L is the length of gully in meters, W_t = the average top width of the gully in meters, W_h = the average bottom width of the gully in meters and Df = the average depth measured in meters.
The gully area was determined using Eq. 4.

$$Area\ (A) = L \times w \qquad \text{Eq 4}$$

Where L is the actual gully length and W is the average width.
Amount of soil loss due to gully erosion was calculated as shown in Eq. 5.

$$\text{Amount of soil loss (Mg)} = V \times Ds \qquad \text{Eq. 5}$$

Where V is the total volume of soil loss, Ds is the average soil bulk density (1.56 g cm^{-1}). Bulk density was calculated from an average of 18 samples obtained across the three soil types in the study area and from all layers to a depth of 150 cm.
The rate of gully erosion was determined using Eq. 6 as described by [25].

$$\text{Rate of gully erosion } (\text{Mg yr}^{-1}\text{ha}^{-1}) = \frac{\text{Amount of soil loss (Mg)}}{\text{Age of oldest gully} \times \text{area under gullies}} \qquad \text{Eq. 6}$$

Gully density was determined using Eq. 7 as described by [5] and [23].

$$\text{Gully density} = \frac{\text{Total length of gullies (km)}}{\text{sub catchment area (km}^2)} \qquad \text{Eq. 7}$$

2.3 Soil analysis

Soil samples were analyzed for physico-chemical properties that are said to be predisposing to gully erosion as described by [6, 13, 33, 34]. These included soil compaction, soil organic matter content, cation exchange capacity, clay dispersion ratio (CDR), and dispersion ratio (DR). Clay dispersion affects the soil physical and chemical properties including sealing, crusting, water-retention characteristics, and soil erodibility. The CDR and DR were analyzed based on Eq. 7 and 8 as described by [34];

$$CDR = \frac{WDC}{TC} \qquad Eq.7$$

$$DR = \frac{WDC + WDS}{TC + TS} \qquad Eq.8$$

Where WDC and WDS is water dispersible clay and silt, respectively, which is obtained without using soil dispersing reagents (Calgon). TC and TS is the total clay and silt, respectively, obtained using Calgon as a dispersion agent.

2.4 Data analysis

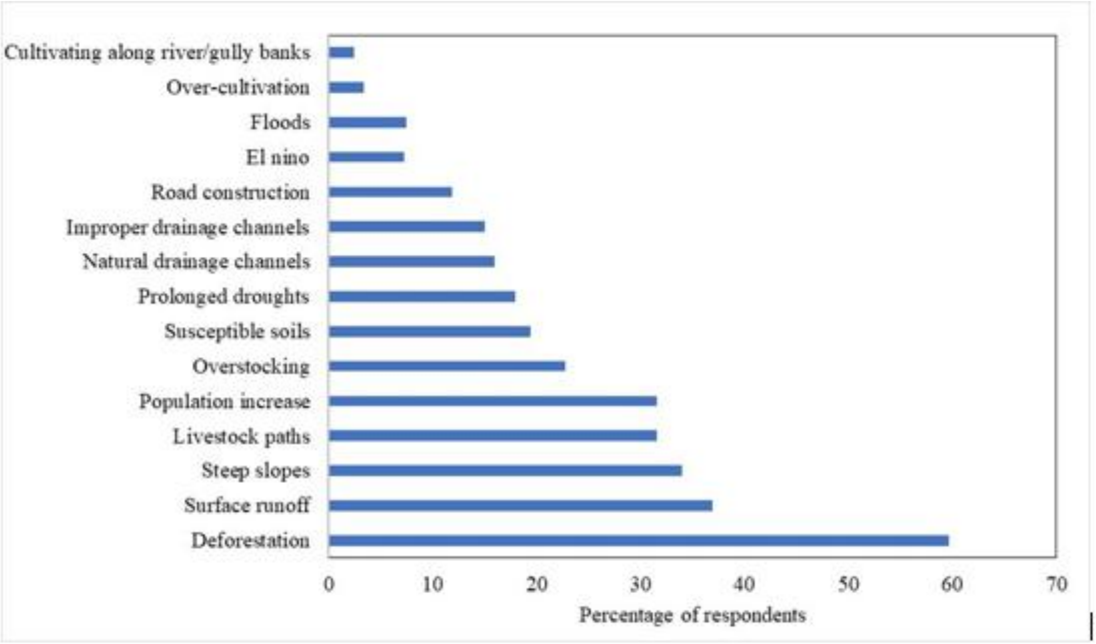
Survey data were analyzed descriptively. FGDs and KII videos were transcribed and translated in the case of speakers who used native language. Transcribed videos were content-analyzed in regard to the guiding questions used at the time of the discussions. Gully morphometry data were analyzed descriptively with focus on severity. All descriptive analysis were done using statistical package for social sciences (SPSS) package version 23.0.

3. Results

3.1 Anthropogenic drivers of gully erosion in the study area

Based on the data obtained, about 60% of the respondents reported deforestation to be the leading driver of gully eroson in the study area (Fig. 2). In addition, about 30% of the respondents also reported livestock paths and population increase to have contributed significantly to gully erosion. This was confirmed during the key informants interviews where participants indicated that the area was covered by dense forests in 1970s which was later deforested in 1980s and 1990s as population increased. According to some of the key informants, the droughts experienced in 1979 and 1984 led to a socio-economic shock as the community lost their livestock. To survive the impact, the community devised alternative livelihoods which were charcoal making and maize farming which

resulted to indiscriminate deforestation. With increased land subdivision due to population increase, shifting and contour cultivation were dropped thus increasing soil susceptibility to erosion. Firewood and charcoal remains one of the commonly traded commodities by women in the area.
In addition, the participants of FGD indicated that majority of the gullies developed along livestock paths which later transformed into drainage channels. Less than 25% of the respondents reported overstocking, road construction and improper drainage to be significant drivers of gully erosion. Only less than 5% of the respondents perceived cultivation along gullies or river banks as critical human induced factors contributing to gully erosion in the area.



3.2 Natural drivers of gully erosion in the study area

Figure 2: Drivers of gully erosion in Chepareria, West Pokot County

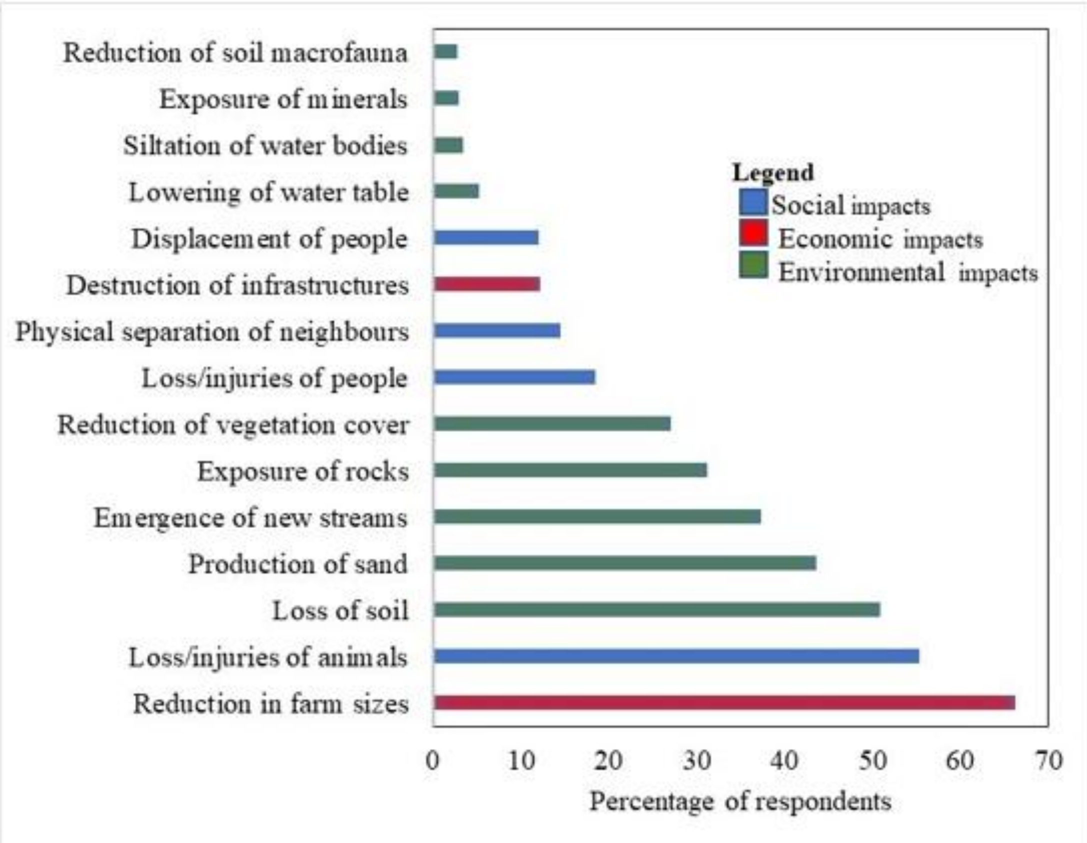
Besides anthropogenic drivers, the respondents identified several natural factors contributing to gully formation in the study area. About 37 and 34 % of the respondents reported that surface runoff and steep slopes, respectively, are significant natural drivers of gully erosion in study area (Fig. 2). Prolonged droughts and *El Nino* were reported by 18 and 7 % of the respondents to have contributed to gully erosion in the area, respectively. According to the participants of the FGD, there was five famine events (*La Nina*) experienced in the area which occurred in 1964, 1979, 1984, 1999 and 2009 resulting in massive loss of natural vegetation, hence losing important ground cover. During the key informants interviews the participants noted that, an increase in bareland resulted in an equal increase in surface runoff. One of the key informants noted that, "...*our soils harden during the prolonged dry season. Even digging becomes a problem. After the first rains, there is turbulent and massive surface runoff all over this area. Water hardly percolates into the ground*...". Natural drainage channels and susceptible soils were reported to be important drivers of gully erosion by 16 and 19 % of the respondents, respectively. Participants of the FGDs noted that most of the soils in the area were loose and deep and hence easily erodible.

3.3 Physico-chemical properties predisposing soils to gully erosion in the study area

Generally, the two locations are covered by four soil types; Leptosols, Cambisols, Lixisols and Luvisols. Luvisols had the highest bulk density of 1.6 g cm^{-3} in the surface horizon, which was 0.2 units higher than both Cambisols and Lixisols. These soils also had generally greater total organic carbon (TOC) with an average of 0.7%, whereas Cambisols had the lowest TOC with an average of 0.4%. The proportion of silt + clay to sand particles was low in Lixisols and Cambisols, both recording an average ratio of 0.3 and 0.4, respectively, while Luvisols had an average ratio of 0.5. The surface horizon in Lixisols had the lowest silt + clay to sand particles ratio of 0.3 while that in Cambisols had the highest value of 0.6. Cambisols had the highest exchangeable sodium percentage (ESP) with an average of 11.9 % while Luvisols and Lixisols had an average ESP of 2.4 and 1.7%, respectively. Generally, ESP in Lixisols had no general trend but it increased down the soil profile in Cambisols. Lixisols had high CDR and DR of 0.89 and 0.76, respectively in the surface horizon. However, Cambisols had low CDR and DR of 0.44 and 0.25, respectively.

3.4 Socio-economic effects of gullies erosion in the study area

The study established both adverse and beneficial socio-economic impacts of gully erosion on the community (Fig. 3). Deaths and injuries of livestock from fatal falls into the gullies was reported by 56% of the respondents as a major negative socio-economic effect of gully erosion in the study area. Fatal falls into deep gullies also caused deaths and injuries to people as reported by 19% of the respondents (Fig. 3). This was corroborated by feedback from study participants in FGDs who indicated that gullies had caused loss of four people and over 100 cattle through fatal falls into the steep-sided deep gullies. Fatal injuries of cattle were noted to be a common occurrence in the area during the dry season. In addition, 15 and 12% of the respondents reported that severe gully erosion resulted into physical separation of neighbors and displacement of people, respectively. This occurred in areas with deep and elongated gullies which were evident within the farms. Development of severe gullies in the study area was believed to reduce economic value of land in the area by 50 – 60% according to one of the key informants. In addition, 44 and 32% of the respondents associated gully erosion with exposure of sand, rocks and minerals, respectively (Fig. 3). Building sand, gold and stones businesses in the area had led to emergence of new livelihoods in the area, which contributed directly to employment opportunities, especially to the youth.



3.5 Environmental effects of gully erosion in the study area

Figure 3: Socio-economic and environmental impact of gully erosion

About 38 % of the respondents associated deep gullies with emergence of new streams, which were being utilized as a source of water for both domestic and livestock during the dry seasons. However, 6 % of the respondents associated gully erosion with the drop in water table. One of the key informants noted that wells close to the deep gullies dry faster. Gully erosion had also caused destruction of infrastructures such as roads, bridges and buildings in the study area, as reported by 12% of the respondents. This had hampered efficient movement of people, goods and livestock in the area.

About 51 % of the respondents perceived gully erosion to have contributed to loss of top soil (Fig. 3). This corroborates field measurements obtained from the two catchments as shown in Table 2, where the land had lost close to 1.5 million Mg of soil due to gully erosion. The two

LIST OF TABLES

Table 1: Physico-chemical properties of the soils obtained in the study area.

Profile pit	Horizons	Bulk density	TOC (%)	(Clay+silt)/ sand ratio	Exchangeable sodium percentage (%)	Clay dispersion Ratio	Dispersion ratio	Soil type
001	A1	1.4	0.5	0.6	3.66	0.44	0.25	Cambisol with a sodic phase
	A2	1.7	0.3	0.3	6.45	0.39	0.77	
	B1	1.5	0.5	0.4	3.10	0.29	0.68	
	B2	1.7	0.24	0.2	15.82	0.47	0.41	
	B3	-	0.42	-	30.58			
002	A	1.4	1.12	0.3	1.91	0.89	0.76	Humic Lixisols
	Bt1	1.3	1.12	0.3	0.23	0.52	0.60	
	Bt2	1.4	0.34	0.4	0.09	0.52	0.61	
	B1	-	0.26	0.2	0.26	0.44	0.39	
	B2	-	0.32	0.4	6.07	0.50	0.58	
	C		0.86	0.4	1.62	0.68	0.68	
003	A	1.6	0.86	0.5	1.21	0.73	0.72	Salic Luvisols
	B	1.7	0.82	0.5	3.28	0.83	0.85	
	Bt	1.6	0.44	0.5	2.72	0.90	0.91	

Table 2: Gully morphometry in Chepareria Ward, West Pokot County

Sub catchments	Analysis	Exposure period (yrs)	Length (m)	Average width (m)	Average depth (m)	Total Volume (m^3)	Total soil mass (Mg)	Rate of soil loss (Mg ha^{-1} yr^{-1})	Gully growth rate (m yr^{-1})	Gully density (km km^{-2})
Sla	Minimum	21	374.0	4.9	3.1	9435.5	14,719.4	1298.6		
	Average	35	911.8	12.4	7.6	90,097.6	140,552.3	3795.5		
	Maximum	39	1500.0	16.6	11.2	152,088.3	237,257.7	8282.9		
	Total	39	5,471.0			540,565.5	843,282.3		140.3	0.6
Senetwo	Minimum	16	84.0	2.8	1.6	940.4	1467.0	1113.3		
	Average	33	470.8	7.8	4.5	25653.7	40019.7	2186.3		
	Maximum	45	1192.0	14.1	8.6	106456.6	166072.2	3870.8		
	Total	45	7,533			410,458.7	640,315.5		167.4	0.8

catchments had a total of 23 gullies of varying shapes and sizes which had caused substantial land fragmentation and destruction of vegetation (shrubs, grass and trees) as reported by 66 % and 27 % of the study respondents, respectively (Fig. 3). The shapes of gullies varied from dendritic, U to V-shape depending on soil types. Gullies that formed on Cambisols and Lixisols were U shaped while those on Luvisols were either dendritic or V-shaped. Gullies in the two catchments had a combined length of 13 km. Gullies in Senetwo sub-catchment were approximately 7,500 m long and on average 5 m deep, which was 2,100 m longer and 3 m shallower than those in Sla sub-catchment. However, despite the deeper gullies, the gully growth rate in Sla (140 m yr^{-1}) was slower than in Senetwo (167 m yr^{-1}) sub-catchment by 27 m yr^{-1}. Approximately 843,280 Mg of soil was lost due to gully erosion over a period of 39 years in Sla sub-catchment, translating to an annual soil loss of 21,600 Mg yr^{-1}. This was higher than the cumulative soil loss in Senetwo sub-catchment by 203,000 Mg, despite Senetwo sub-catchment having higher number of gullies and longer exposure period. Senetwo sub-catchment lost soil due to gully erosion at the rate of 16,000 Mg yr^{-1}. The two sub-catchments had lost an equivalent of 14 ha of land translating to soil loss at the rate of about 2,500 Mg ha^{-1} yr^{-1}. Gully density in Senetwo sub-catchment was 0.8 km km^{-2}, which was 0.2 km lesser than in Sla sub-catchment.

4. Discussion

4.1 Anthropogenic drivers of gully erosion

Deforestation, is the main driver of gully erosion in the study area. This collaborates with other findings in Waipaoa River Basin in New Zealand [35], Long Cane Ranger District of South Carolina [36], Taita Hills of Kenya [37, 38], Ziwuling region [39], Cantabrian Range in Peninsula [40], and Geba Catchment in Ethiopia [25] where deforesting steep and hilly landscape led to severe gully erosion. According to [28], forest area in West Pokot declined by 65,010 ha between 1980 and 2012. Besides trees, degradation of other vegetation cover such as grass as observed in our study could also contribute to the erodibility of soil. For example, in Iran, poor rangeland vegetation cover has been attributed to gully erosion [41]. Trees, shrubs and grass play key ecological functions that are critical in enhancing the resilience of an ecosystem. These functions include; stabilizing slopes, intercepting rain drops energy, conserving soil moisture and hence reducing hardsetting and crusting of the top layer, increasing infiltration and holding soil particles together [42-44]. Indirectly, they favor increased soil biodiversity, by providing suitable microclimate and organic matter that consequently increase infiltration rates.

Deforestation is stimulated by population increase without an equal increase in alternative livelihood opportunities [45, 46]. Thus, in our study, the limited livelihood options drive the communities to over utilize forest resources through charcoal making, selling firewood, producing timber, or clearance for human settlement and crop farming, which exacerbates the situation. Clearance of the vegetation exposes the soils to rain drop effect aggravating its vulnerability to erosion. Therefore, enhancing sustainable adoption of afforestation initiatives requires concurrent provision of alternative livelihoods to the community [47]. Depleting vegetation cover due to overgrazing and reduction of infiltration rates of soils are also consequences of overstocking, which contributes to gully formation [45, 48, 49].

Inappropriate drainage systems along the roads and poorly maintained water harvesting structures, was also witnessed in the study area, and may have contribute greatly to increased production of surface runoff which leads to development of gullies. Despite roads being classified as key contributor to gully erosion in West Pokot in early 2000s [3], no suitable measures have been taken to address this challenge. This has also been reported in other areas. For example, in Ethiopia, Kuliheni gully located in Geba Catchment is said to have developed after construction of Mekelle-Aladwa road [25]. In the same country, the Hadero Tunto-Durgi Road Project connecting Hadero Tunto and Tembaro regions is said to have led to development of severe gullies [50]. This confirms the role of roads in concentrating runoff and causing severe gullies where no suitable drainage channels are created to dissipate the surface runoff safely.

4.2 Natural drivers of gully erosion

Surface runoff was also an important driver of gully erosion. Farmers noted during FGDs that rains in the area are usually stormy and generate high runoff originating from the deforested steep slopes. Similar findings have been reported in other semi-arid regions of Bardenas Realas, Norva province of Spain [11]. In Bardenas Realas, intensive rainfall is said to occur at the beginning of autumn season, generating massive surface runoff responsible for the soil erosion reported during this time. Croplands without soil conservation structures receiving rainstorms generate massive surface runoff contributing to gully formation [23]. Besides rainstorms, low infiltration rates contribute significantly to surface ponding and eventual massive surface runoff. The low infiltration rates are caused by hardsetting of soils during the dry seasons [51, 52]. This is attributed to prolonged heating of bare soils leading to a compacted structureless mass of soil which greatly impairs infiltration rates.

Natural drainage channels were reported to contribute to gully erosion in the study area. In natural ecosystems, gullies form along bare natural drainage channels due to the erosivity of concentrated surface runoff [53]. This is amplified by human and natural calamities that reduce vegetation cover as well as increasing amount and velocity of surface runoff such as deforestation, overgrazing, drought, rainstorms, steep slopes and *El nino* events [21, 49]. Diverting surface runoff collecting along roads into natural drainage channels has also been attributed to gully formation in Kenya and Ethiopia [3, 23, 25, 54].

4.3. Physico-chemical properties predisposing soils to gully erosion

Erodibility of Cambisols could be attributed to its high exchangeable sodium percentage, dispersion ratio and sand content observed in our study. On the other hand, erodibility of Lixisols could be attributed to high dispersion ratio and sand content, while that of Luvisols due to the high clay dispersion ratio. High sand content, clay dispersion ratio and greater amounts of ESP leads to a weak aggregate on the soil making it more erodible [33, 45, 55, 56]. Occurrence of high ESP, DR, water dispersible clays in the sub-horizons, could partially explain the deeply incised U-shaped gullies found under both Lixisols and Cambisols. These findings concur with other studies which reported some soils such as Cambisols and Andosols to be more susceptible to soil erosion due to their inherent physico-chemical properties such as high ESP, soil compaction, high sand content, low organic matter, high water dispersible clays, high dispersion index and hardsetting [13, 33, 34,57-60].

4.4 Socio-economic and environmental effects of gully erosion

Death of human and livestock, conversion of arable land into badlands, and reduction of arable land have devastated the communities in the study site and has led to lose of livelihoods for numerous households, whose main economic activities are livestock and crop production. Similar outcomes have been reported in Ethiopia [5, 21, 23, 25], China [8], Britain [48] and Iran [41]. Gully erosion is thus significant in reducing the arable land besides causing loss of massive amounts of productive soil. Approximately 14 ha of arable land has been lost to gullies, with almost 1.5 million Mg of sediment being eroded. These results are approximately 3.7 ha more and four times higher loss of sediments to gully erosion than

what was reported in Genbo Wonze watershed in northwest Ethiopia [23]. In this region, Yazie *et al.* [23] reported about 340,000 Mg of sediment and 10 ha of land to have been lost to gully erosion. In another study by Belayneh *et al.* [22] in Gumara watershed in Northwestern Ethiopia, gully erosion had led to loss of about 11 ha of land and 273,000 Mg of sediments which was approximately 5.5 times less than what was reported in our study. The differences observed between Gumara watershed and our study area, could be attributed to differences in soil types where much sediments is lost with depth of the soil profile as compared to unit area, adoption of effective gully mitigation measures or natural gully stabilization. Another study in Ethiopia noted that there were no new gullies developing after 1995 due to increased adoption of gully mitigation measures such as stone bunds, check dams and more vegetation cover [25]. Over the 45 years since the first signs of gully incision, the region has been losing soil annually at a rate of 2,400 Mg ha^{-1} with an average gully growth rate of 154 m yr^{-1}. This is higher compared to what has been reported in other similar studies, which have reported rates lower than 100 Mg ha^{-1} [5, 22, 23, 25] and a growth rate of about 20 m yr^{-1} (16). Gully growth rate that is more than 10 m ha^{-1} is considered catastrophic [61]. On the other hand, gully density in the studied watersheds was high according to classification criteria by Golosov *et al.* [62] since it was in the range between 0.5 and 1.0 km km^{-2}. However, it was lower than the 1.4 and 1.87 km $km\text{-}^{2}$ reported by Hassen *et al.* [21] and Belayneh *et al.* [22] in similar semi-arid environments of Ethiopia.
Gully erosion directly significantly led to reduction in crop yield and pastures leading to persistent food and pasture insecurity as observed in other regions [9, 13, 25, 63]. This is through reduction of arable land and loss of top soil and essential plant nutrients. This could lead to conflict over resources in the future such as water and grazing fields as observed in other similar ASALs areas [64]. Thus, gully erosion poses a great threat to attainment of 8 Sustainable Development Goals (SDG) goals, that is; 1 (poverty reduction), 2 (attaining food and nutritional security), 3 (healthy lives and well-being), 8 (attaining sustainable inclusive economic growth), 10 (reduction in inequality), 13 (combating climate change), 15 (protecting, restoring and promoting sustainable use of terrestrial ecosystems, and 16 (promoting peaceful and inclusive societies for sustainable development [65].
Nevertheless, this study has also elucidated positive outcomes of gullies, such as exposure of sand and other valuable minerals such as gold, as well as emergence of springs. In Namibia, gullies were reported to provide linear oasis during the dry seasons, thus providing water for domestic use and livestock [24]. Upon proper rehabilitation, gullies have also been found to have important ecological functions such as creation of biodiversity 'hotspots' responsible for regeneration of key ecosystem services [26]. However, these perceived positive impacts may be short-lived since the minerals are non-renewable resource. On the other hands, the streams and springs may not flow for extended periods, due to the fact that the recharge of water table could be negatively affected by irregular precipitation driven by climate change.
To manage this menace, timely, integrated mitigation and rehabilitation of gullies is critical to mitigate an increase in aridification and desertification processes in the area. Thus, suitable measures of mitigating and rehabilitating existing gullies need to be implemented and up-scaled in an integrated and community-led approach. The measures ought to target reduction of surface runoff, increased vegetation cover, regrading walls of existing gullies, erecting enclosures to manage movement of livestock during grazing, physical barriers for interception of eroded sediment, among others. Some of these methods include; terracing, stone bunds, check dams, sand dams, afforestation, seeding water ways, regrading gully walls, and cut off drains [10, 13, 66].

5.0 Conclusion

Gully erosion is a major economic problem in the semi-arid environments of West Pokot. This study elucidated the factors contributing to gully erosion in the area as well as its socio-economic and environmental impacts. The findings showed that gully erosion in the area was mainly contributed by deforestation, population increase without an equal increase in sustainable alternative livelihoods, deforested steep slopes, livestock paths, surface runoff, overstocking in addition to the highly erodible soils. Lixisols and Cambisols, which were characterized by U-shaped gullies, were highly erodible due to high clay dispersion ratio (CDR) and dispersion ratio (DR) in either the surface or sub-surface horizons. Rate of soil loss due to gully erosion varied from 3,796 and 2,186 Mg ha^{-1} yr^{-1} depending on the catchment. Cumulatively, the study area had lost about 14 ha of arable land to gully erosion. Although gullies in the study area contributed to lowering of water table, in some parts they acted as source of streams. In addition, gullies were source of sand, exposed rocks and minerals which were of economic value to some of the residents. However, these perceived positive impacts may be short-lived since the minerals are non-renewable resource, while the streams may not flow for extended periods, due to the climate change. Thus, there is urgent need for adopting effective integrated gully mitigation and rehabilitation measures in the study area. For effective mitigation of gully erosion, it is important to upscale integrated measures that reduce surface runoff while increasing vegetation cover such as terracing, cut-off drains, enclosures, afforestation and growing effective cover crops. In order to prevent death of more people and livestock while putting the badlands into economical use, gully rehabilitation engineered on the basis of regrading the gully walls and re-greening them, must be prioritized urgently.

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