Int.J.Curr.Res.Aca.Rev.2021; 9(11): 50-64

International Journal of Current Research and Academic Review

ISSN: 2347-3215 (Online) Volume 9 Number 11 (November-2021)

Journal homepage: http://www.ijcrar.com

doi: https://doi.org/10.20546/ijcrar.2021.911.007

Effectiveness of Gully Rehabilitation Materials Integrated with Locally Available Vegetative Measures under Natural Environment of Mitike Watershed, Northwestern Ethiopia

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Abstract

Gully erosion is a very severe problem in Northern Ethiopia where continuous cultivation was a common production system. These different methods of gully reclamation measures were undertaken where not all rehabilitation measures were not effective. Therefore, this research was designed to select appropriate rehabilitation measures in the humid lowland of north western Ethiopia. The result of the research indicates that integration of check dam integrated with vegetation measures and area closure reduced gully depth, slope gradient, gully volume, and soil loss. Slope of gully bed was reduced by 72%, 60.3% and 68% due to check dams; bamboo net check dam, sand bag check dam, and brushwood check dam, respectively. Similarly, gully depth reduced by 91%, 80% and 55% while gully volume was reduced by $32m^3$, $7m^3$, and $4m^3$ due to check dams as in the same order of slope change. The ratio of width-depth was higher under gullies treated with bamboo net check dam (56.69) followed by sand bag check dam (37) where they are integrated with locally available vegetative material and area closure. The rate of soil loss reduction due to bamboo net check dam was 5 times effective relative to the initial soil loss due to gully while sand bag check dam was 1.54 times effective. The amount of soil deposition due to rehabilitation measures was also affected by check dams as bamboo net check dam trap 303 ton/ha followed by sand bag check dam which trap 37 ton/ha. Thus, rehabilitation of gully with bamboo net check dam is 45% effective over the control treatment as it reduced 80% of the soil lost at the initial year. Compared with the control, soil water storage was increased by 18% due to bamboo net check dam integrated with vegetative measures and area closure. Therefore, bamboo net check dam filled with soil from the surrounding gully side integrated with plantation of vegetation measures like lowland bamboo in the gully bed, and area closure was effective to rehabilitate gully erosion around Pawe area, humid low land area.

Article Info

Accepted: 15 October 2021
Available Online: 20 November 2021

Keywords

Land degradation, fuel wood, soil piping, geo-environmental problems.

Introduction

Land degradation due to soil erosion which is caused by the hydrodynamics of geo-environmental problems in countries of semi-humid and semi-arid Mediterranean (Tsimi *et al.*, 2012; Frankl *et al.*, 2012). As it contributes to a significant soil loss, it is a major concern in these countries (Taddese, 2001; Tebebu *et al.*, 2016). In Northern Ethiopia, land degradation due to gullying was sever (Frankl, Poesen, Haile, *et al.*, 2013) about 50% to

80% of the overall sediment production was contributed by gully erosion (Poesen *et al.,* 2002), which is also specifically ranged from 28% in semi-arid Tigray (Nyssen *et al.,* 2008) and to 90% in sub-humid highlands in Amhara (Tibebu *et al.,* 2010). This leads to 100 to 1350 tons/acre annual soil from watersheds with valley bottom gullies (Tibebu *et al.,* 2010). Thus, gully erosion is severe threat of production where soil losses due to gully was 17.6 $tonh^{-1}yr^{-1}$ over the period of 1963/1965 – 1994 (Frankel *et al.,* 2013b). In the highlands of Amhara region about 3000 km^2 of land has been destroyed due to gullies (Desta *et al.,* 2012).

The gullies resulting from an accumulation of severe rainfall events that occurred between November and December 2016 led to a channel overflowing that was built to protect farmland from the hillslope drainage(Frankl *et al.,* 2014). Deforestation or clearing of vegetation cover, overgrazing, removal of crop residue and animal dung for fuelwood, poor construction of culverts, soil and water conservation measures and drain, and poor farming systems are main causes of human induced gully erosion (Addis *et al.,* 2015).

Gullies could also be created due to soil piping, which cannot be controlled by soil and water conservation measures like check dams (Frankl *et al.,* 2014). Besides the climatically and land use induced increased in discharge, degradation of valley-floor also causes a widespread and rapid gully formation (Prosser & Slade, 1994).

In the proximity of gully agricultural production decreased especially at the end of the cropping season where crops are wilt around the gully due to depressed water table (Frankl *et al.,* 2014). Gully formation significantly affects the livelihood of the rural families by destroying the productive lands used for crop production and livestock feed, and increasing the walking distances between villages and markets (Kidane and Alemu, 2015; Mitiku *et al.,* 2006; Worku and Tripathi, 2015).

Gully rehabilitation through community participation is effective in reducing river sediment concentration, support to increase livestock and crop production, and extend the life expectancy of reservoirs (Ayele *et al.,* 2014). As gabion and loose rock check dams are cost and difficult to implement by the smallholder farmers, it is effective to implement low cost gully rehabilitation measures in controlling gully erosion and associated sediment losses (Addisie *et al.,* 2015). Gully head controlling can enclosed the head and makes the land profitable as it is used for growing fodder to fatten the cattle (Addisie *et al.,* 2018). Soil loss through gullies significantly reduced due to appropriate physical gully rehabilitation measures integrated with vegetation measure which further stabilize the gullies from further enlargement (Addis *et al.,* 2015).

In Semen Gonder area, the most successful gully control measures were the integration of different technologies, i.e., awareness creation, area closure or closing the gully from cattle through fencing, vegetative measures, and physical measures (Addis *et al.,* 2015).Treating gully head is very important in reducing gully enlargement where regarding the gully head and treating with stone riprap is effective control measure while growing grasses in fenced-in areas are very economical to farmers (Addisie *et al.,* 2018).

Despite the benefit of rehabilitating gullies with gully rehabilitation measures, various gully rehabilitation measures such as construction of check dams across the gully bed integrated with planting trees could be unsuccessful where banks store more water and high ground water weaken the soil strength (Tibebu *et al.,* 2010; Addisie *et al.,* 2017) while tree roots below 3m depth couldn't be dense to anchor the soil and stabilize the banks, therefore not effective (Zegeye *et al.,* 2018).

Gully rehabilitation measure has economic implications that directly constructed on the gully floor need certain costs for material purchase. Even though adoption of gully rehabilitation measures like loos rock and gabion check dam is crucial in the highland of Ethiopia, considering their technical and financial capacities, it is difficult and costy to be managed by the smallholder farmers(Addisie *et al.,* 2015). Thus, the subsistence farmers, who often earn less a dollar per day, cannot afford to construct these structures (Yitbarek *et al.,* 2012).

Selecting appropriate gully rehabilitation measures with locally available materials integrating with vegetative measures has significant importance in areas with subsistence farmers where gully erosion is very severed.

Therefore, the objective of this research was to identify and assess best check dam constructed by locally available materials on rehabilitating gullies, to identify best gully rehabilitation measures on reducing soil erosion and to best check dam technologies and to understand the effect of check dam on gully morphology.

Materials and Methods

Location

The study was conducted at Pawe, Metkel Zone of Benishagul Gumuz National Regional State of Ethiopia. It is situated at Mitike watershed, which is part of Beles sub-basin. Pawe district is located 565km from the capital city of the country, Addis Ababa in Northwestern direction. It is geographically located between11^{0}18'40''N to 11^{0}19'29''N latitude and 36^{0}24'26''E to 36^{0}25'27''E longitude. The altitude is the range of 1100 –1200m above sea level with the humid-hot climate. The mean annual total rainfall is 1609mm and mean maximum and minimum temperature are 32.6^{0}C and16.7^{0}C, respectively. The rainy season for the area starts in May and extends to the end of October. Nitosols is the dominant soil type for specific study area

80% of Metekel zone is characterized by having sub-humid and humid tropical climate. The topography of the zone presents undulating hills which is slightly sloping down to low land Plateaus having an altitude ranged from 600-2800 meter above sea level. The dominant vegetation cover of the study area is characterized by different types of woodland which include broad-leaved deciduous woodland, Acacia species woodland, riparian woodland along the major rivers, *Borassus aethiopum* woodland and bamboo thicket (UNDP/ECA, 1998).

Treatment set up

Rehabilitation of gully with an integrated novel practice is effective than using check dams solely (Addisie & Wassie, 2021). The treatment was selected to rehabilitate gully erosion in the study area using locally available materials to minimize the cost and difficulty of sophisticated work integrated plantation of vegetative measures i.e., lowland bamboo and area closure to avoid cattle and revegetate the bared area due to gullied. Therefore, the research was undertaken on three check dam types and one control to compare their potential to trap the eroded sediment within a unit catchment area. These selected treatments are:

Sand bag check dam

Double brush wooden check dam

Soil filled bamboo net check dam

Control

Data collection and analysis

The gully sites were selected together with the communities, development agents' researchers, agricultural development experts and other stakeholders. Primarily, the study area was selected purposively on the basis of the availability of gullied land severity, its potentials and significance and community participate.

The gullies were treated with double post brush wooden check dams, sand bag check dams and soil filled with bamboo net from mid-2017 to early 2019 at Mitike watershed, Beles sub-basin. Locally available vegetative measures are incorporated uniformly within all treatments where lowland bamboo was planted within the gully bed.

Gully morphology i.e., gully longitudinal profile of volume, top and bottom width, slope, vertical and horizontal distance, ground length, depth and catchment area parameters were taken by ground surveying before gullied land treated from the gully systems. These measurements were averaged to get an estimation of the volume using equation 1.

$$V = L \times A \quad \text{.....(1)}$$

Where V, volume gullied land L, is the length of the gully in meters and A is the cross-sectional area of the gully in m^{2}as shown in equation 2.

$$A = \left(\frac{b_1 + b_2}{2}\right) \times d \quad \text{.......(2)}$$

Where: A = cross sectional area (m^2); b_1 = top width of gully (m); b_2 = bottom width of gully (m); and d = gully depth (m)

The numbers of check dams constructed within the gully bed were determined by measuring the average gully channel gradient, horizontal distance and vertical distance of the number of check dams (FAO, 1986) for each portion of the calculated main gully channel as shown in equation 3.

$$NOCC = \frac{a - b}{h} \quad \text{.....(3)}$$

Where;

NOCC: Number of check dams constructed

a: The total vertical distance is calculated according to the average gully channel gradient and the horizontal distance between the first and last check dam in that portion of the gully bed.

b: The total vertical distance is calculated according to the compensation gradient and horizontal distance between the first and last check dam in that portion of the gully bed (compensation gradient.

h: The average effective height of the check dams, excluding foundation, to be constructed in that portion of the gully bed.

The spacing of check-dams was determined by using an empirical formula (FAO, 1986) as shown in equation 4.

$$s = \frac{1.2H}{G} \quad \text{……(4)}$$

Where; S it the spacing in meters; H is the effective height of the check-dam (spillway height in m); G is the gully gradient in decimal. Samples was taken in the gully beds by using a cylindrical core sampler with a volume of 100 cm^3. The samples were taken throughout the area of the gullies and only the main occurring soils were sampled randomly at upper, middle and lower part of the gully taken. The results were processed and the outcomes were used to analyze the physicochemical properties of soil due to the constructed gully rehabilitation measures. Dry bulk density is indispensable to calculate the sediment yield of the gullies. The dry bulk density (ρd) in g cm^{-3} will be expressed as shown in equation 5:

$$\rho = \frac{M}{V_t} \quad \text{…….(5)}$$

Where: ρ= The dry bulk density (gcm^{-3})

M: is the mass of the dry sample (g)

Vt: is the total volume (volume of the wet sample) (cm^3).

Soil erosion and deposition

Soil erosion through gully erosion was calculated by measuring the gully morphology of the gullied area as a volume of gully multiplied by the bulk density of the gully bed. Similarly, gully deposition was estimated by subtracting the final volume of gully from the initial gully volume, which was multiplied by the bulk density as shown in equation 6.

$$S_y = (V_1 - V_2) \times \rho \quad \text{……(6)}$$

Where

Sy: sediment yield in tone; V_2: is the current volume of the gully in m^3; V_1: is the initial volume of gully at the start of the study period; and ρ = The dry bulk density (gcm^{-3})

Finally, the collected data were analyzed and compared using Microsoft excel. The percent of deviation through time and between treatments were calculated by dividing the final value or interested treatment with the initial or control treatment value and subtract one and the result was multiplied by 100 as shown in equation 7 and 8.

$$PD = \frac{(Targeted\ treatment - control\ treatment)}{Control\ Treatment} \times 100 \quad \text{….(7)}$$

$$PD = \frac{(Current\ reading - initial\ reading)}{Initial\ record} \times 100 \quad \text{….(8)}$$

Results and Discussion

Slope gradient of gully bed

As shown in figure 1, the slope of gully bottom was generally decreased due to rehabilitation measures. In 2018 the slope of gully was reduced due to construction of check dams i.e., bamboo net check dam, brushwood check dam, and sand bag check dam, which was integrated by locally available vegetative measures like lowland bamboo and also due to sole rehabilitation of gullies by locally available vegetative measures i.e., lowland bamboo. But in 2019 the slope of gully bottom under bamboo net and sand bag check was increased compared with 2018 observation. This is due to termite problem, durability of materials, hot climate during winter and spring season.

The lowest percentage reduction of slope was observed from brushwood check dam while the highest percentage change in slope were under sand bag check dam followed by bamboo net check dam (Figure 2). These in 2018 rainy season the slope of gully due to rehabilitation using check dam were reduced by 71.2%, 47.1%, and 73% due to bamboo net check dam, brushwood check dam, and sand bag check dam. Whereas, in 2019 the slope of gully bed was reduced by 72%, 68%, and 60.3% in the same order as 2018. Similarly, gullies without physical rehabilitation measures sole plantation of lowland bamboo and closing the gullies from animals also reduce slope of gully bottom by 21.5% in 2018 and 47.4% in 2019, while it reduced by 33% in 2019 compared with 2018 due to vegetation cover increased through time leads to trap eroded sediment that fills the lower part of gully. But it increased from 2018 to 2019 by 47% under sand bag check dam. This is due to durability of construction materials, absence of maintenance, higher rainfall amount, and greater maximum and minimum temperature which leads more sediment transport along with higher runoff amount. Proper attention to engineering design, time of intervention, and long-term maintenance are essential for sustaining the structures and minimize failure(Addisie *et al.*, 2016).

Depth of gully

The depth of gullies was greatly reduced due to implemented rehabilitation measures as time goes on relative to the initial year (Figure 3). Therefore, rehabilitating gullies with check dams integrated with locally available vegetative materials like lowland bamboo supported by closing the site to regenerate the vegetation cover, leads the deposition of sediment by reducing the runoff velocity and increasing gully bottom roughness where the sediment to be trapped by the structure as well as the vegetation. In 2018 season, the lowest depth was measured from bamboo net check dam integrated with vegetative measures and area closure while the lowest depth was from brush wood check dam. This is due to the space created by the amassment of woody materials allows more runoff flow along with sediment while the bamboo net check dam and sand bag check dam block runoff water and allow the sediment to settle which further reduce the depth of gully.

As indicated in Figure 4, Compared with initial depth of gullies, the percentage change of gully depth reduction was higher under bamboo net check dam (71%) followed by sand bag check dam (56%), and the lowest were measured from brushwood check dam (40%) followed by gully without physical rehabilitation measures (53%) in 2018. Whereas, the lowest depth in 2019 was measured from gully where no check dams were implemented (53%) while the highest was from bamboo net check dam (91%) followed by sand bag check dam (80%). Similarly, relative to gully depths measured in 2018, the highest percentage reduction of gully depth was observed from bamboo net check dam (70%), followed by sand bag check dams (55%) where no depth change was observed on gully rehabilitated with only locally available vegetative measures like lowland bamboo with area closure. This is because, the sand bag as well as the bamboo net were filled with soils from reshaping the side wall of the gully which leads to plug any space, allow to store the runoff water, and settle the sediment.

Gully width

Width of gully which indicates the activity of gully also changes through time due to the implementation of check dam (Table 1). The top width of gully profile was increased by 179.2% (from 2.4m to 6.7m) at the end of the experimental period followed by the control treatment which increases top width by 110.8%. Whereas, the highest bottom width was also recorded from sand bag check dam treated gully which increases by 275%, followed by bamboo net check dam (65.5%). The increase in gully width indicates that the erosion and sedimentation on the gully bed was through gully bank erosion.

The highest width-depth ratio was recorded from gullies treated with bamboo net check dam (56.69) followed by sand bag check dam (37) and brushwood check dam (8.47). Thus, the highest WDR indicates the greater sedimentation within the gully bed while more erosion was from the gully bank as the width of the treated gully increases while its` depth reduced as time goes on from Jun-2017 to December 2019. Similarly, a one season record at January 2018 also indicates that the higher WDR was recorded from bamboo net check dam treated gully. Thus, sediment aggradation within the gully bed was higher under gullies treated with bamboo net check dam and sand bag check dams where they are integrated with vegetation (plantation of lowland bamboo) and area closure to avoid the effect of animals.

Gully volume and soil erosion

The volume of gully was decreased from time to time as compared with the initial year of implementing the rehabilitation measures (Figure 5). Compared with the initial gully volume, construction of check dam across the gully bed reduced the volume of gully was reduced by $32m^3$, $7m^3$, and $4m^3$ on December 2019; under bamboo net check dam, sand bag check dam and brushwood check dam, respectively. At the end of 2017 (Jan 2018), gully volume was reduced by $27m^3$, $4m^3$ and $2m^3$ in the same order of 2019. This indicates the implemented gully rehabilitation measures i.e., physical measures integrated with locally available vegetative measures and sole plantation of lowland bamboo where the area was closed to enhance revegetation of the catchment area as well as the gully profile, were effective in trapping the eroded sediment from the catchment area of the respective gully. Thus, the loss of soil from the gully profile is the replica of gully volume. The highest soil loss was observed from the gully where bamboo net check dam (45 ton) was implemented before implementation while the lowest was from gullies where brushwood check dam (11.42 ton) were planned to be implemented. But in the last year (Dec 2019) the lowest soil loss was measured from gullies which was under bamboo net (7.9 ton) and brushwood check dam (7.8 ton) type gully rehabilitation measures integrated with biological methods while the highest was from gullies without physical rehabilitation measures (13.9 ton) where the bamboo net which was filled with soil and compacted can retain the runoff and gives time to settle the sediment. Thus, the rate of soil loss reduction due to bamboo net check dam was 3 times (2018) and 5 times (2019) effective from the initial year while sand bag check dam was 1.3 times (in 2018) and 1.54 times (in 2019) effective.

Therefore, the amount of soil deposited due to rehabilitation measures were increased from time to time which was the reverse of gully volume and/or soil loss (Figure 6). The highest soil was deposited due to bamboo net check dam (30 ton in 2018 and 36 ton in 2019) where it allows more time to settle the sediment, while the lost soil deposition was measured from gullies rehabilitated using locally available vegetative measures (lowland bamboo; 2 ton in 2018 and 4 ton in 2019) followed by brushwood check dam integrated with vegetative measures (4 ton in 2018 and 5 ton in 2019). Similarly, the amount of soil deposition per a unit catchment area was highest due to bamboo net check dam (255 ton/ha in 2018 and 303 ton /ha in 2019 followed by sand bag check dam integrated with locally available vegetative measures (22 ton/ha in 2018 and 37 ton/ha in 2019). Thus, rehabilitation of gullies by closing the areas to avoid any contact with human and animals with construction of check dams like bamboo net check dam and sand bag check dam integrated with locally available vegetative measures were effective around Nitisol of Pawe area.

Check dams are effective gully rehabilitation measures as they reduce sediment lost by the gullied. The effectiveness of check dams under experimentation was ranged from 21% to 80% and 18% to 46% compared with initial year and the control treatment, respectively (Figure 7). Compared with the initial year of the experiment, Bamboo net check dam (80%) was highly effective in reducing sediment loss at the end of the experimental year followed by sand bag check dam (35%) and brushwood check dam (32%). Similarly, bamboo net check dam shows 46% reduction of soil loss relative to the control treatment while brushwood check dam and sand bag check dam shows 41% and 18% reduction of soil loss, respectively. This is due to their ability to allow sediment deposition just upstream of the structure and the revegetation of the gully area.

Soil water storage

The amount of water stored in one meter soil layer due to gully rehabilitation measures was higher compared with the control treatment (Figure 8). Thus, the highest soil water storage was recorded from gullies rehabilitated by bamboo net check dam integrated with locally available vegetative measures (503.83 mm) followed by brushwood check dam integrated with local available vegetative materials while the lowest was from control where only rehabilitated by locally available vegetative materials (428 mm).

Compared with the control, the percentage increment of soil water storage relative to the control treatment was also similarly highest due to bamboo net check dam integrated with locally available materials (18%) followed by brushwood check dam integrated with locally available vegetative measures (2%). This indicates that, the soil under control was relatively compacted as the bulk density was highest (1.23 g/cm3) while bamboo net and sand bag check dam leads to lower the compaction of soil layer by allowing more organic matter accumulation which makes the soil spongier and allows more water to store even though the compaction of soils from all treatments were good as the result was below $1.3g/cm^3$.

Table.1 The effect of check dams on width of gully and with-depth ratio through time

Gully control measures	Year	bottom width (m)	top width (m)	PD bottom width (m)	PD top width (m)	Av. Width (m)	Width-depth ratio (WDR)
Bamboo net	Jun-17	2.26	4.03			3.15	3.30
	Jan-18	2.36	5.6	4.42	38.96	3.98	14.44
	Dec-19	3.74	5.58	65.49	38.46	4.66	56.69
Average		2.79	5.07	34.96	38.71	3.93	24.81
Brushwood	Jun-17	1.12	2.2			1.66	2.47
	Jan-18	1.55	2.94	38.39	33.64	2.25	5.60
	Dec-19	1.99	3.1	77.68	40.91	2.55	8.47
Average		2.26	4.07	58.04	37.28	3.17	16.54
Control	Jun-17	1.9	2.04			1.97	2.33
	Jan-18	2.88	5.07	51.58	148.53	3.98	9.99
	Dec-19	1.89	4.3	-0.53	110.78	3.10	7.78
Average		2.25	4	25.53	129.66	3.13	13.86
Sand bag	Jun-17	1.2	2.4			1.80	2.35
	Jan-18	2.78	3.73	131.67	55.42	3.26	9.67
	Dec-19	4.5	6.7	275.00	179.17	5.60	37.00
Average		2.36	4.06	203.34	117.3	3.21	14.35

Fig.1 Effect of check dams on slope gradient of gully bed

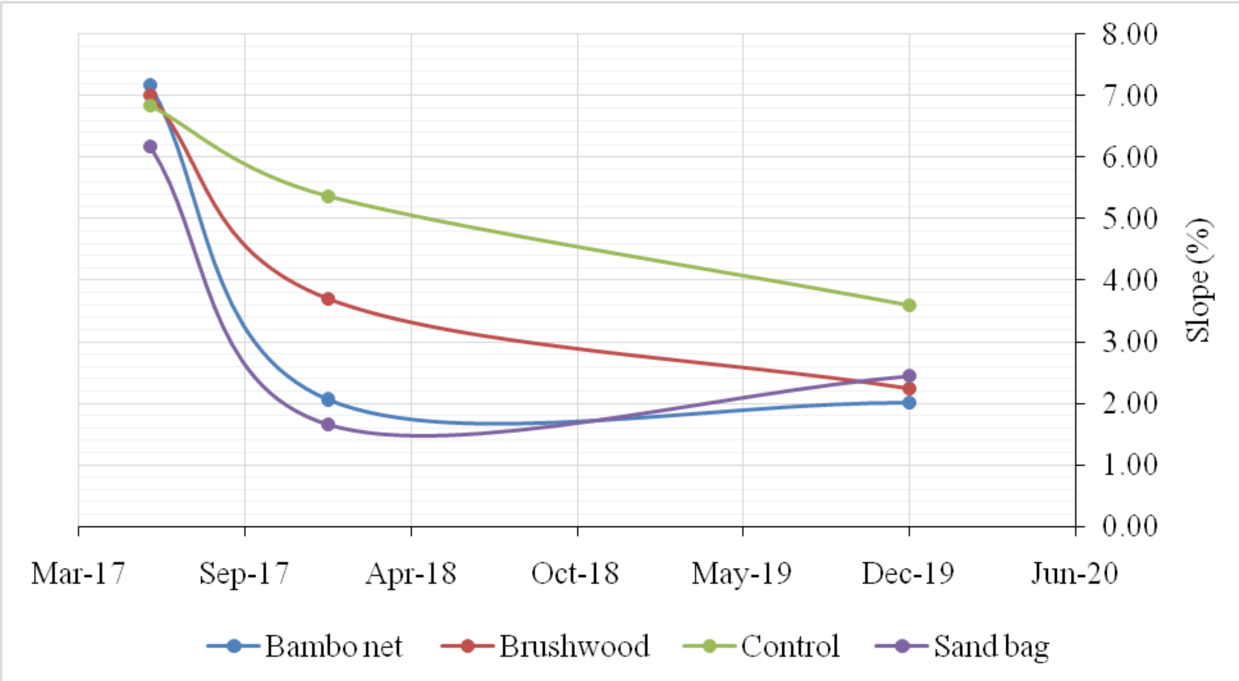


Fig.2 Percentage change of gully bed slope due to check dams

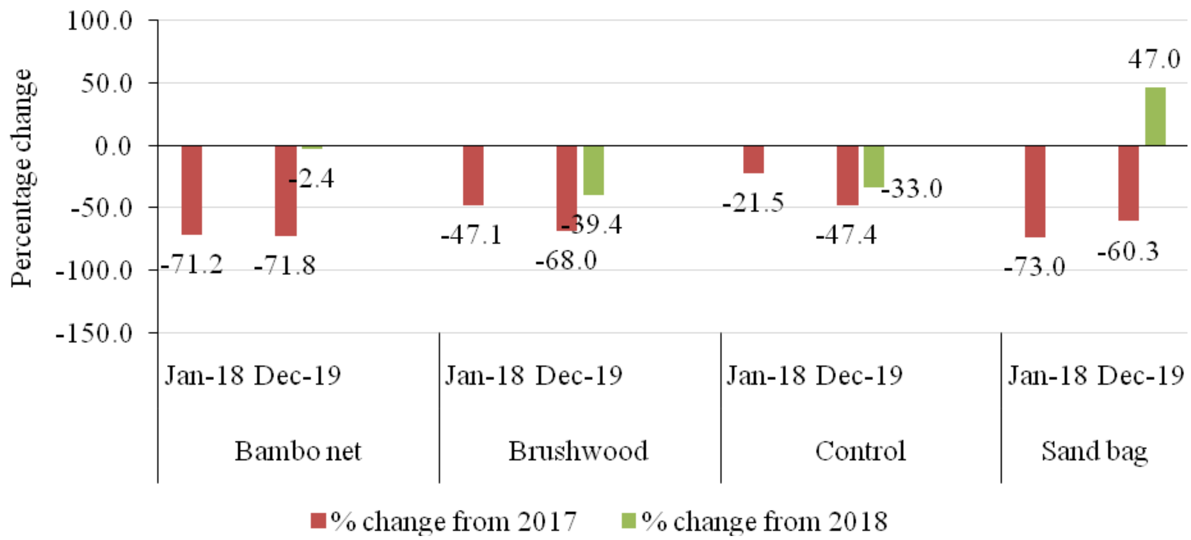


Fig.3 Effect of check dams on gully depth

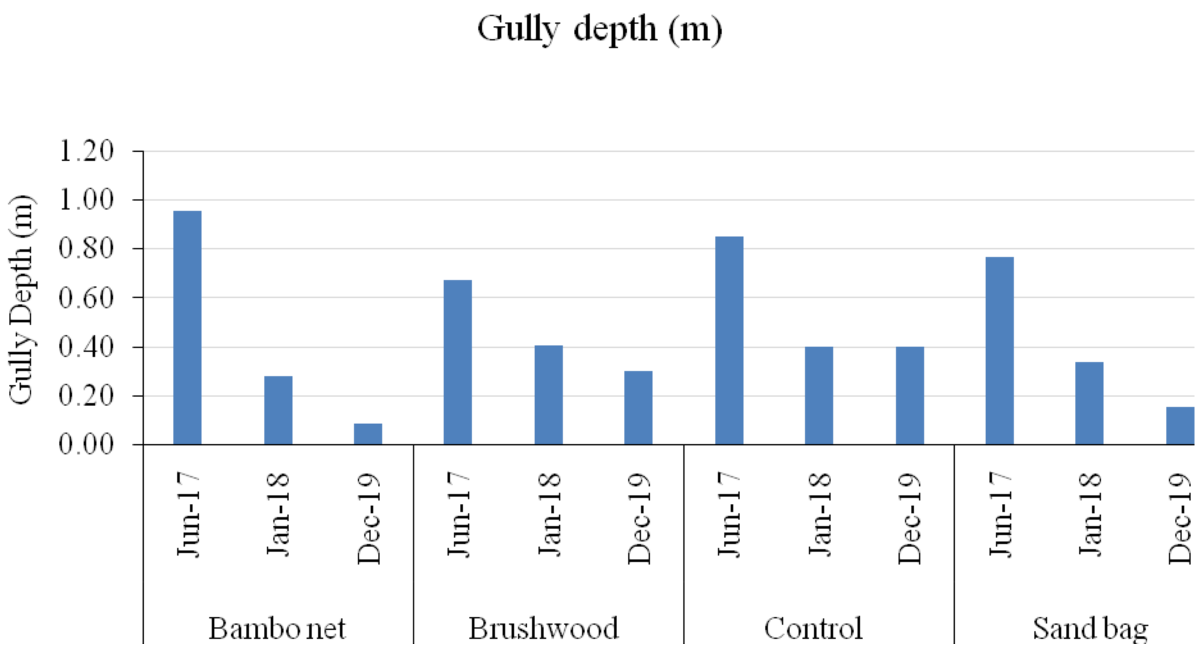


Fig.4 Percentage reduction of gully depth due to check dams

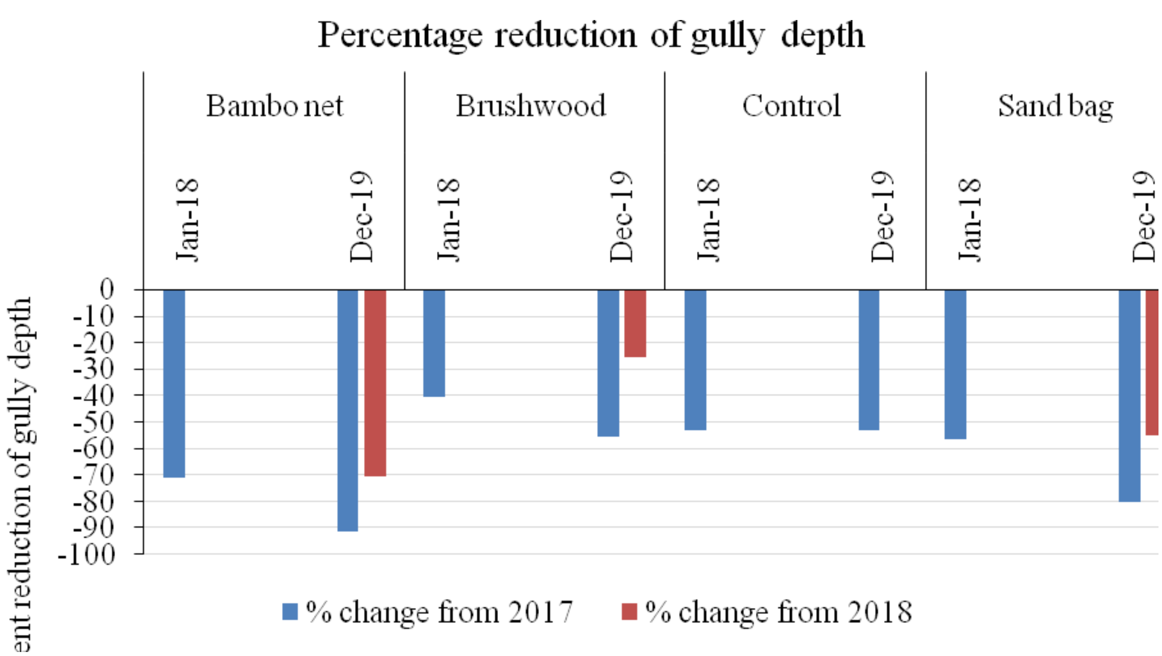


Fig.5 Effect of check dam on gully volume and soil loss

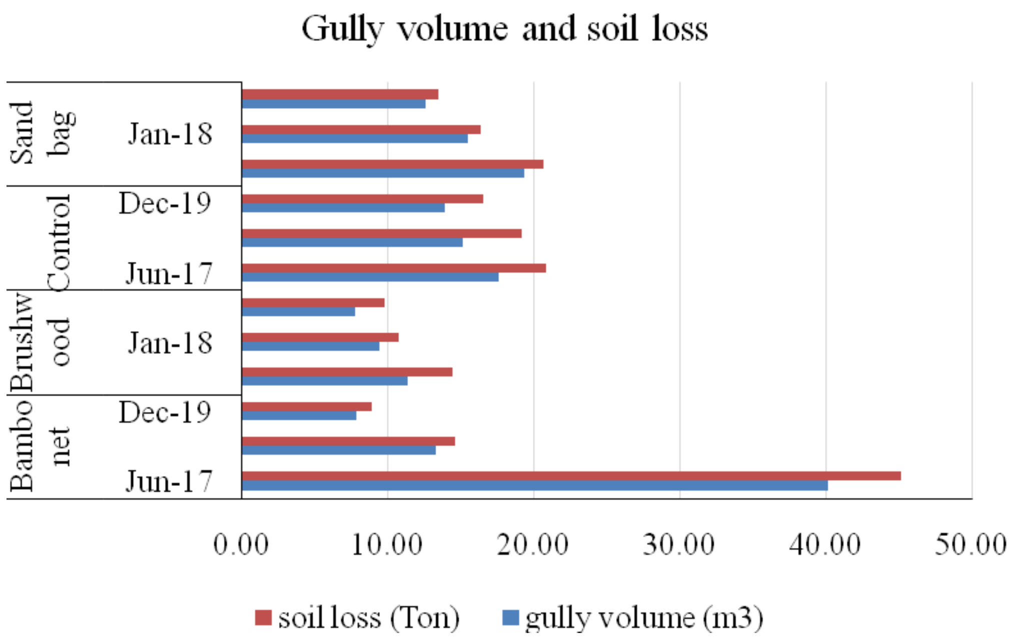


Fig.6 Effect of check dam on soil deposition within the gully bed

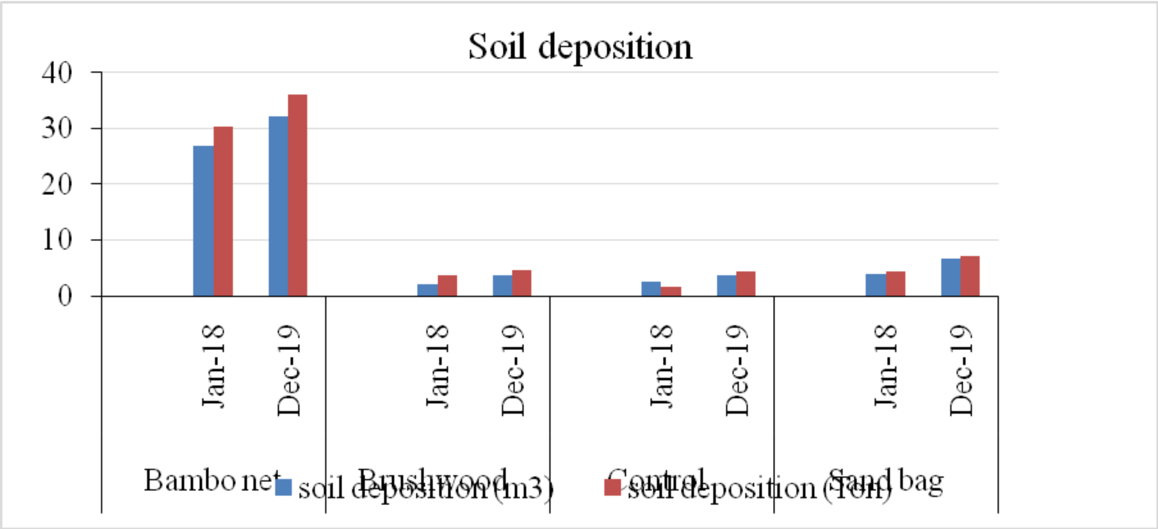


Fig.7 Percent reduction of soil loss due to gully rehabilitation measure

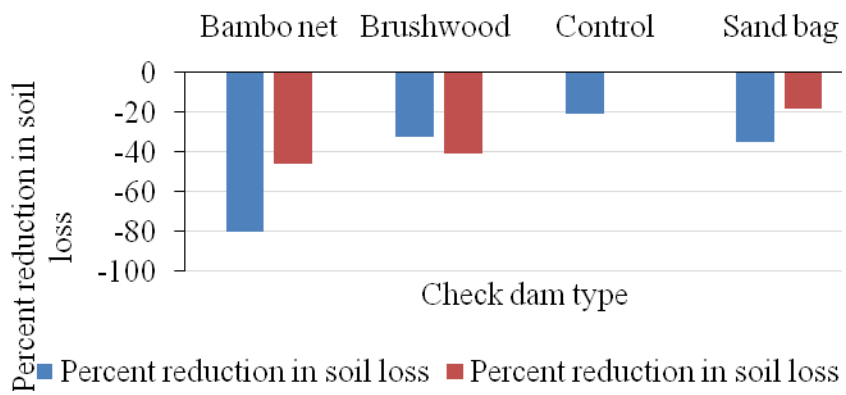
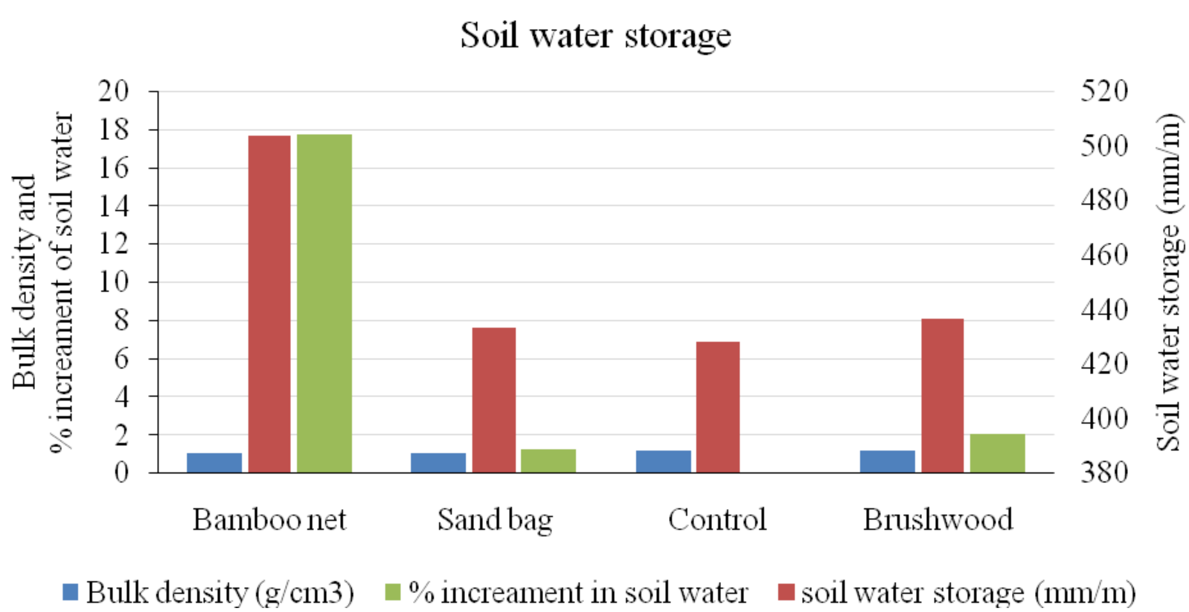
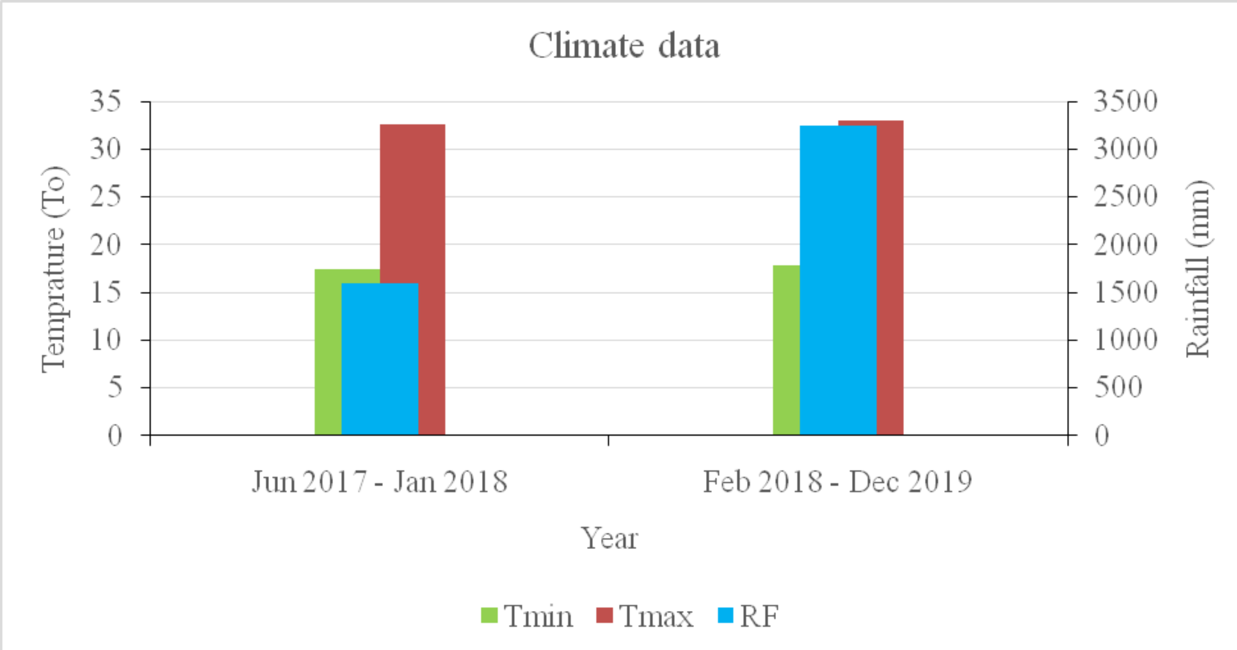


Fig.8 Effect of check dams on soil water storage and bulk density



Annex.I Climate of the experimental site



Implementing integrated vegetative measures (grass like vetiver, elephant grass, and green gold) with physical measures, which are temporal structures constructed across the gully lines like check dams were significantly reduce soil erosion and surface runoff, while improving production of forage and fuel wood whereas soil fertility improved (Addis *et al.,* 2015). Implementation of check dams are effective in reducing sediment loss ranged from 25% to 90% (Wright, 2010). Check dams interrupts the velocity of surface runoff and allows more water to infiltrate rather than eroding the gully channels (Agoramoorthy, 2008). In Northern Ethiopia, sand bag check dam reinforced by brushwood check dam, stone check dam, bamboo check dam, and gabion check dam was the most prominent type of gully control measures (Addis *et al.,* 2015).

Check dams constructed with in the gully bed reduces the original gully gradient and finally reduces the eroding power of runoff (Addis *et al.,* 2015).

The runoff which loss its power is susceptible to settle the sediments and leads aggradation of gully bed and finally leads to change the slope of gully bed. Similarly, slope of gully bed is related with width and depth. Thus, as the ratio of top width to depth of gully increased, the slope of the local slope gradient also decreased (Frankl, Poesen, Scholiers, *et al.,* 2013). Meanwhile, sedimentation in the gully due to the implemented check dams leads to decrease the longitudinal gradient of the streams (Addisie & Wassie, 2021).

The relationships between gully morphologies could be varied due to the activities of gully where if the gully is treated the increase in top width may not indicate the increase in depth. Gully under rehabilitation measures could allowed sedimentation in the upper part of check dams which reduces gully depth while the sediment could be from gully bank and these increase top width (Addisie & Wassie, 2021). But, if the gully is active and untreated, the increase in top width of gully leads the increase in gully depth (Frankl, Poesen, Scholiers, *et al.*, 2013). Compared with untreated gullies, the depth of gullies was reduced by one-third due to the implementation of gully control measure like check dams. Depth of gully at the middle of its` length is positively and strongly correlated with length of gully similarly the lower width is also (Addis *et al.*, 2015). Thus, all gully morphologies are positively correlated to each other (Addis *et al.,* 2015).

Gully volume is directly affected by gully length and gully cross sectional area. Therefore, gully morphologies could affect the volume of gully and the volume of soil lost due to gully formation. Gully volume is predicted by the catchment area and length of gullies (Frankl, Poesen, Scholiers, *et al.*, 2013) which is the volume of soil lost by gully erosion. Thus, the higher the catchment area of the gully and length of gully leads the higher gully volume keeping other factors constant. Slope gradient and catchment area affects the vulnerability of soil loss by gully (Frankl, Poesen, Haile, *et al.*, 2013). Therefore, gully reclamation with plantation of vegetation within the gully is effective in trapping the sediment where almost 5cm soil layer was deposited within the gully due to construction check dams where 20 ton of soil was lost from untreated gully(Addisie *et al.*, 2016). Soil loss by volume and weight due to gully erosion is highly correlated with gully length where the presence of colluvium (loose and/or heterogenous) layer in gully increases the gully dimension (Martins *et al.,* 2019).

Similarly, the increase in gully length leads the increment in soil loss in the highlands of Ethiopia (Frankl, Poesen, Scholiers, *et al.*, 2013). Soil loss by volume and weight due to gully erosion is highly correlated with gully length where the presence of colluvium (loose and/or heterogenous) layer in gully increases the gully dimension (Martins *et al.,* 2019). Similarly, the increase in gully length leads the increment in soil loss in the highlands of Ethiopia (Frankl, Poesen, Scholiers, *et al.*, 2013). Thus, in Northwestern Ethiopian highlands of Birr watershed, gully control measures significantly reduce soil erosion by 87% which reduce from 7.5t/ha/yr. to 0.96t/ha/yr. (Addisie *et al.,* 2016). This is due to the decrease in the average depth of the gully due to sedimentation on the upstream of check dams where it reduces the gully gradient and store more water temporarily(Addisie & Wassie, 2021). Thus, the porous the check dam, the lower water to be stored on the surface and within the soil profile as well.

Generally, rehabilitation of gully with check dams leads morphological changes with an increase in width to depth ratio, gully bank erosion and sediment aggradation in the gully bed (Addisie & Wassie, 2021). This indicates that, the ratio of width-depth is an indicator of gully activity.

Gully erosion is a very devastating problem causing the land degradation by leading the land out of production. Therefore, rehabilitating gullies could allow the area to reduce its in-site and off-site production constraints. A three-year experiment was undertaken to select best rehabilitation measures from 2017 to 2019 at Nito sol of Pawe area, Benshangul Gumuz regional state.

From the experiment, brushwood check dam shows the lowest percentage reduction of slope while the highest percentage change in slope were under sand bag check dam followed by bamboo net check dam. Similarly, the highest width-depth ratio was recorded from gullies treated with bamboo net check dam (56.69) followed by sand bag check dam. Thus, the highest WDR indicates the greater sedimentation within the gully bed while more erosion was from the gully bank as the width of the treated gully increases while its` depth reduced as time goes on from Jun-2017 to December 2019.

Check dams are effective gully rehabilitation measures as they reduce sediment lost by the gullied. The effectiveness of check dams under experimentation was ranged from 21% to 80% and 18% to 46% compared with initial year and the control treatment, respectively. Thus, bamboo net and sand bag check dams integrated with locally available vegetative materials and area closure are effective in reducing soil loss by as they allow to stored more runoff water on the upper side of the check dams which gives more time to settle the sediment and more water to be infiltrated. Similarly, bamboo net check dam integrated with locally available vegetative measures is effective to store more water in the root zone.

Generally, rehabilitation of gullies by closing the areas to avoid any contact with human and animals with construction of check dams like bamboo net check dam and sand bag check dam integrated with locally available vegetative measures were effective around Nitisol of Pawe area. Therefore, it is better to extend bamboo net and sand bag check dams integrated with area closure and locally available vegetative materials with the extension system to effectively rehabilitate gullies with shorter period of time.

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How to cite this article:

Getnet Asfawesen, Zeleke Melese and Yenesew Assaye. 2021. Effectiveness of Gully Rehabilitation Materials Integrated with Locally Available Vegetative Measures Under Natural Environment of Mitike Watershed, Northwestern Ethiopia. *Int.J.Curr.Res.Aca.Rev.* 9(11), 50-64. doi: https://doi.org/10.20546/ijcrar.2021.911.007