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Research article

Efficiency of Modeled Empirical Equations in Predicting Soil Loss from Ephemeral Gully Erosion in Mubi, Northeast Nigeria

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ABSTRACT

A field study was carried out in Mubi area to assess soil loss from ephemeral gully (EG) erosion at 6 different locations (Digil, Vimtim, Muvur, Gella, Lamorde and Madanya) between April, 2008 and October, 2009. Each location consisted of three watershed sites from where data were collected during the study period. Land use and conservation practices were noted, while EG channel parameters (length, width, depth and shape) were measured at each site. Physico-chemical properties of the soils were determined in field and laboratory using prescribed procedures. Soil loss was measured and empirically predicted. Results showed that the soils were heterogeneous and lying on flat to hilly topography with few grasses, shrubs and trees. Soils were mainly sandy with considerable silt and clay contents. The exchangeable K, Ca, Na and Mg contents were low to high. The empirical soil loss was generally related with the measured soil loss and its prediction was widely reliable at all sites, regardless of season. The measured and empirical soil loss were better related in terms of VSL (r^2 = 0.9330) and MSL (r^2 = 0.9171), than for ASL (r^2 = 0.2673) predictions on aggregate basis. The empirical estimates of VSL and MSL were consistently higher at Muvur (less vegetation) and lower at Madanya and Gella (denser vegetations) in both years. The maximum efficiency (M_{se}) of the empirical equation in predicting ASL in the sites was between 1.4100 (Digil) and 89.0678 (Lamorde), while the M_{se} was higher at Madanya (2.5577) and lowest at Vimtim (15.6635) in terms of VSL prediction efficiency. The model's efficiency (M_{se}) also ranged from 1.8359 (Madanya) to 15.7443 (Vimtim) in respect of MSL predictions. Recommending that soil conservationists, farmers, private and/or government agencies, should use the empirical model for erosion studies in Mubi area.

Keywords: Empirical model, Soil Loss, Prediction efficiency, Ephemeral Gully Erosion, Mubi, Northeast Nigeria

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INTRODUCTION

Several water erosion prediction models such as the universal soil loss equation (USLE) and its revised version (RUSLE) (Wischmeier and Smith, 1978), as well as the modified universal soil loss equation (MUSLE) (Williams, 1982) have been widely used to estimate soil erosion and to select conservation and management practices for erosion control. However, USLE technology does not estimate ephemeral gully (EG) erosion. Other empirical models which patterned after the USLE such as the soil loss estimation model for South Africa (SLEMSA) (Elwell, 1977; Elwell and Stocking, 1982), areal non-point source watershed environment response simulator (ANSWERS) (Beasley *et al.*, 1980), chemical, runoff, and erosion from agricultural management systems (CREAMS) (Knisel, 1980), and kinematic runoff and erosion model (KINEROS) (Woolhiser *et al.*, 1990), among other empirical models, were not capable of estimating soil erosion occurring in concentrated flow channels, where EG erosion occurs. EG erosion is a recently recognized class of water erosion (Foster, 1986), which causes irreversible and colossal losses of fertile agricultural land resources (Lal, 2001). It is a significant factor in soil erosion by water, whose visible damage is usually obliterated by farming operations. The magnitude of EG erosion is largely influenced by climate, topography and vegetation (Poesen *et al.*, 2003; Capra and Scicolone, 2002; Oygarden, 2003).

In nature, selection of good conservation method remains difficult, unless the type and magnitude of erosion processes are correctly assessed. There have been no formulated or tested indigenous model for studying soil loss from such ephemeral gullies or concentrated flow channels in the northeastern part of Nigeria. Most of the existing empirical erosion models are adapted, hence the persistent problem of adopting statistical data on soil erosion from other regions as being questionable and non-compatible due to wide range of methods of data collection and extrapolation (Lal, 2001). The desire to provide information on EG erosion is imminent in this part of the World, and therefore the need to test the reliability and efficiency of such locally modeled soil loss prediction tools (Tekwa *et al.*, 2013) that may be suitable in the drive to curb erosion problems in Mubi and its environs.

The Study area

The selected sites are located in Mubi North (Digil, Vimtim, and Muvur) and Mubi South (Gella, Lamorde and Madanya) local government areas of Adamawa state in northeast Nigeria (Fig. 1). The sites were selected based on their land use, topography, vegetation cover and soil type. The climate of the area was a typical wet and dry seasons. The dry season spans from November to April, while the wet season runs from May to October. The average annual rainfall amount is between 700 mm and 1,050 mm (Udo, 1970; Adebayo, 2004). The average minimum temperature is 15.2 ^oC in December and January, while the maximum temperature occurs in April (Adebayo and Tukur, 1999) or March, being the driest months. The dominant vegetations are grasslands with scattered trees typical of a savannah region (Adebayo and Tukur; 1999; Adebayo, 2004; Tekwa and Usman, 2006). Land use types in the area are mixed farming comprising cattle rearing and arable farming systems confronted by erosion hazards each year.

METHODOLOGY

Soil sampling and analysis

Representative composite soil samples were collected during the 2 growing seasons. A soil sample was collected from each of the 3 EG selected at each of the 6 sites studied. Soil samples were collected using a bucket auger at top soil surfaces (0 - 15 cm depths) in a transverse direction, when the soils were relatively moist and then bulked. Each composite soil sample was stored in a labeled plastic bag. The samples were air-dried, crushed and sieved through a 2 mm sieve, before laboratory determination of selected physical and chemical properties that relates to water erosion.

Determination of soil physical properties

The particles size distribution was determined using the Bouyocous hydrometer method (Trout et al., 1987). while the water holding capacity was measured by gravimetric water content of a given quantity of soil fully saturated with water (Trout et al., 1987). The bulk density was determined by the clod method (Wolf, 2003),

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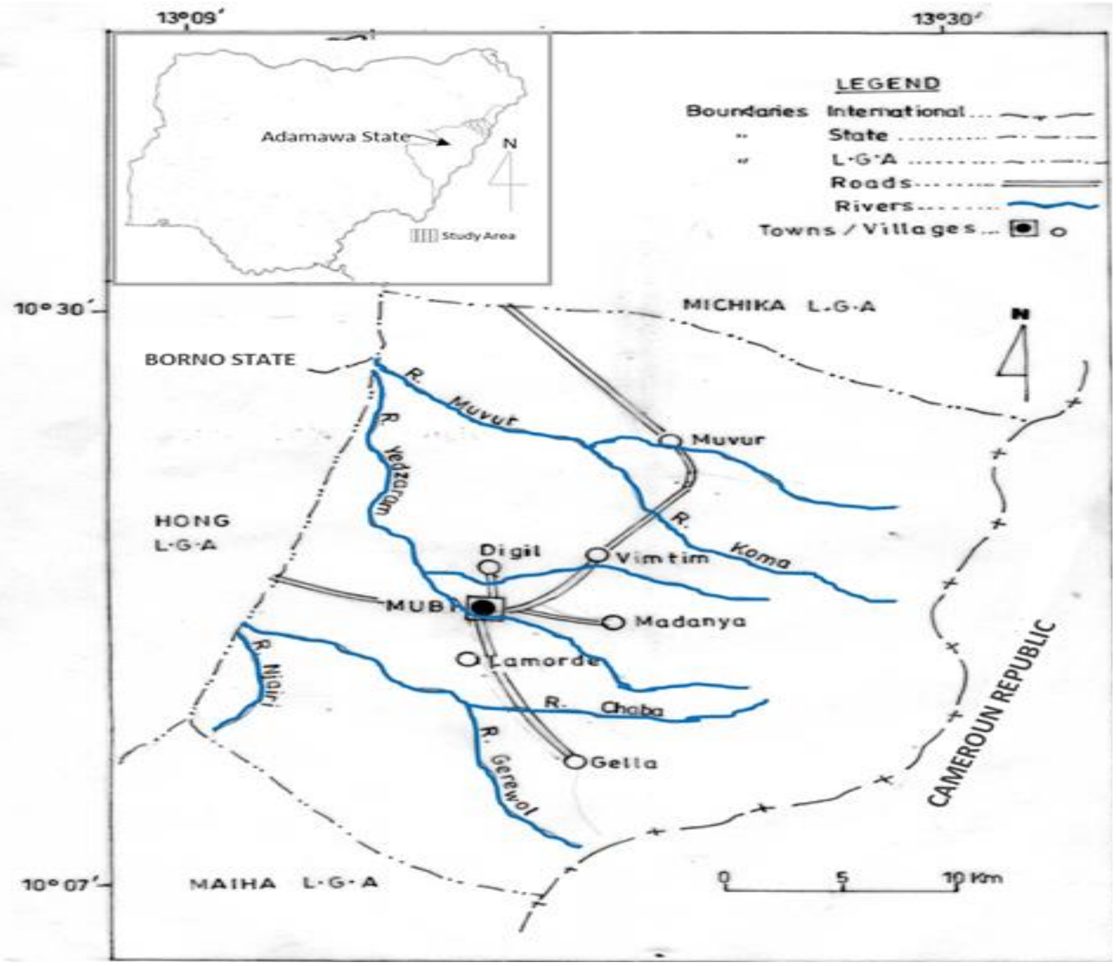

Figure 1: Map of the study area showing farm sites Adapted from Tekwa *et al.* (2014).

Determination of soil chemical properties

The soil organic carbon (OC) content was determined using the potassium dichromate wet-oxidation method of Walkley and Black (1934). The O.C content was converted into organic matter (OM) content by multiplying with a factor of 1.724 (Wolf, 2003). The exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}) were extracted using Ammonium Acetate (1 N; pH 7.0). The exchangeable Ca^{2+} and Mg^{2+} were later measured by titrimetric method, while the exchangeable K^{+} and Na^{+} were measured using flame photometry (Jackson, 1965). The total exchangeable base (TEB) was computed as a summation of the exchangeable bases. The chemical properties were rated in accordance with the reports of Aduayi *et al.* (2002).

Determination of measured soil loss in the study area

The measured (actual) soil loss was determined using mathematical expressions as presented below:

i) Area of soil loss (ASL)

The area of EG cylindrical shaped = $2\pi rl_2 - 2\pi rl_1$

where: r = radius of a cylindrical EG shape

l = length of EG feature

π = constant of proportion

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The area of EG cone shaped = $\pi r^2 h_2 - \pi r^2 h_1$
where: r = radius of an EG head-cut area
h = perpendicular height of EG head from an imaginary axis (5 m adopted)
Total ASL = Net area of EG cylinder shaped + Net area of EG cone shaped

ii) Volume of soil loss (VSL)
Volume of soil loss (VSL_2-VSL_1) of EG cone shaped = $\frac{1}{3}\pi r^2 h_2 - \frac{1}{3}\pi r^2 h_1$
where: h = perpendicular height of gully head (cone shaped)
r = radius of an EG head-cut (Cone shaped)
Volume of soil loss along EG cylinder shaped = $\frac{1}{2}\pi R^2 l_2 - \frac{1}{2}\pi R^2 l_1$
where: R = radius of gully basin (cylinder-shaped)
l = length of gully basin
h = EG incision depth (cylinder shaped)
Total VSL (T_{vl}) = Net VSL (EG cone shaped) + Net VSL (EG cylinder shaped)

iii) Mass of soil loss (MSL) = VSL × soil bulk density (δ_b)

Determination of empirical soil loss in the study area

The empirical model adapted is a linear equation formulated using quantitative field data and a multiple regression analysis (equation 1) earlier reported by Tekwa *et al.* (2013). The regression equation is presented in equations 2 - 4.

$$Y_{ASL} = 3166.40 - 2087.82 (\delta_b) - 7.20977 (clay) + 419.453 (SEI) + 13.2948 (PL) - 133.601 (OM) - 7109.39 (\tau c) + 2.90245 (SR) + 480.420 (Run\text{-}off);\ r^2 = 0.3997 \qquad \text{-- - - -- (2)}$$

$$Y_{VSL} = 2170.98 - 1556.63 (\delta_b) - 4.8032 (clay) + 868.765 (SEI) + 13.0510 (PL) - 102.693 (OM) - 5322.86 (\tau c) + 4.75836 (SR) + 199.491 (Run\text{-}off);\ r^2 = 0.9515 \qquad \text{- - - - - (3)}$$

$$Y_{MSL} = 2666.99 - 1899.59 (\delta_b) - 6.93032 (clay) + 1124.52 (SEI) + 17.2004 (PL) - 136.544 (OM) - 7011.92 (\tau c) + 6.60113 (SR) + 284.778 (Run\text{-}off);\ r^2 = 0.9388 \qquad \text{- - - - - (4)}$$

where, Y_{ASL} = predicted area of soil loss,
Y_{VSL} = predicted volume of soil loss,
Y_{MSL} = predicted mass of soil loss,
δ_b = bulk density,
Clay = clay content,
SEI = erodibility index,
PL = plasticity index,
OM = organic matter content,
τc = shear strength,
SR = site slope rate,
Run-off = volume of run-off water,
r^2 = coefficient of determination

Data Analysis

The data collected was analyzed using the generalized linear model in a randomized complete block design for the ANOVA (Statistix 9.0, version 2012). The standard polynomial curves (2^{nd} order) were also used to validate the relationships between the measured and empirical erosion. In addition, analysis of errors in predicting the empirical soil loss was determined using the standardized mean error (M_{es}) and root mean square error (M_{se}) as described by Capra *et al.*, (2004), and expressed as:

$M_{es} = 1/n \sum((Z_i - Z_i^*) / S)^2$, and -- -- -- -- -- -- -- (1)

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$M_{se} = [1/n \sum(Z_i - Z_i^*)^2]^{0.5}$, -- -- -- -- -- -- -- (2)

where S = standard deviation of the measured soil loss,
n = number of observations
Z_i = empirical soil loss estimate, and
Z_i^* = measured soil loss estimate.

RESULTS AND DISCUSSION

Erosion site characteristics

Characteristics of the erosion sites are heterogeneous in nature with EG channels having "V" and "U" shapes due to seasonal channel incisions by run-off water on mostly rolling terrains (Tekwa *et al.*, 2013). There are fewer grasses and trees at Vimtim and Digil, than at Gella and Lamorde, which influences agricultural tillage activities. Some conservation practices such as vegetative barriers, terraces, and tied - ridges and rough tillage are used as erosion controls (Ekwue and Tashiwa, 1992; Tekwa *et al*., 2014). The soils are generally sandy clay loamed, except Gella with sandy loam texture (Tekwa *et al*., 2014).

Chemical properties such as organic matter are low and inadequate to reduce erosion losses in the study area. The basic cations (K, Ca, Mg, and Na) known for abating erosion (Lal, 2001), significantly ($P<0.05$) differ in the study sites (Tekwa et al., 2010, 2013, 2014). The exchangeable K are consistently very high, while Ca and Na contents are moderate to high, and to very high in terms of Mg saturation, especially at Lamorde and Madanya sites (Tekwa *et al*., 2013). This perhaps explains why soil loss was minimal at Madanya site with comparably higher estimates of OM, Ca, Mg and TEB as earlier reported by Tekwa *et al*. (2013; 2014).

Relationship between measured and empirical soil loss estimates

Results in respect of the empirical ASL, VSL, and MSL in the various study sites expressed a low to high relationships (Table 1). The measured and empirical ASL estimates had up to 100, 98.28, 94.38, and 66.53% at Muvur, Gella, Lamorde and Madanya, and could not adequately predict ASL at Vimtim and Digil sites. The high relationship observed between measured and empirical ASL at Muvur was perhaps due to efficiency of the erosion variables in determining actual erosion at the sites. A similar relationship of 91% was also observed between measured and empirical soil loss parameters in the Mediterranean environment (Nachtergaele *et al.*, 2001b).

The measured and empirical VSL were 99.71, 99.06, 97.92, 97.61 and 98.15% related at Gella, Vimtim, Lamorde, Madanya and Muvur, compared to their poor relationship at Digil (33.05%). The relationship between empirical and measured VSL was generally high in this study. In other words, the empirical equation sufficiently predicted the extents of VSL in the various sites, except at Digil with sparse vegetation. This good ability of empirical model agrees with the report of Laflen *et al.* (2004), that good vegetation cover condition is an essential variable that reduces soil erosion on most watersheds. Similar work by Capra *et al.* (2004), however, found a good relationship ($r^2 = 0.64$) between EG length and volume, when studying EG erosion.

On the other hand, the estimates were related by 99.52, 98.74, 98.40, 97.06, 87.01 and 38.28%, respectively at Lamorde, Gella, Madanya, Vimtim, Muvur and Digil. The relationship widely expressed high associations between measured and empirical erosion. The results suggest that the empirical equation was well related with measured MSL estimates at all sites, except at Digil, as it was in the case of VSL prediction. This outcome was perhaps due to the spurious correlation between measured and empirical variables. The widely observed high rates of prediction efficiency compares higher than those reported (91%) by Nachtergaele *et al.*, (2001b), which further explains the relevance of the erosion predictors in this work.

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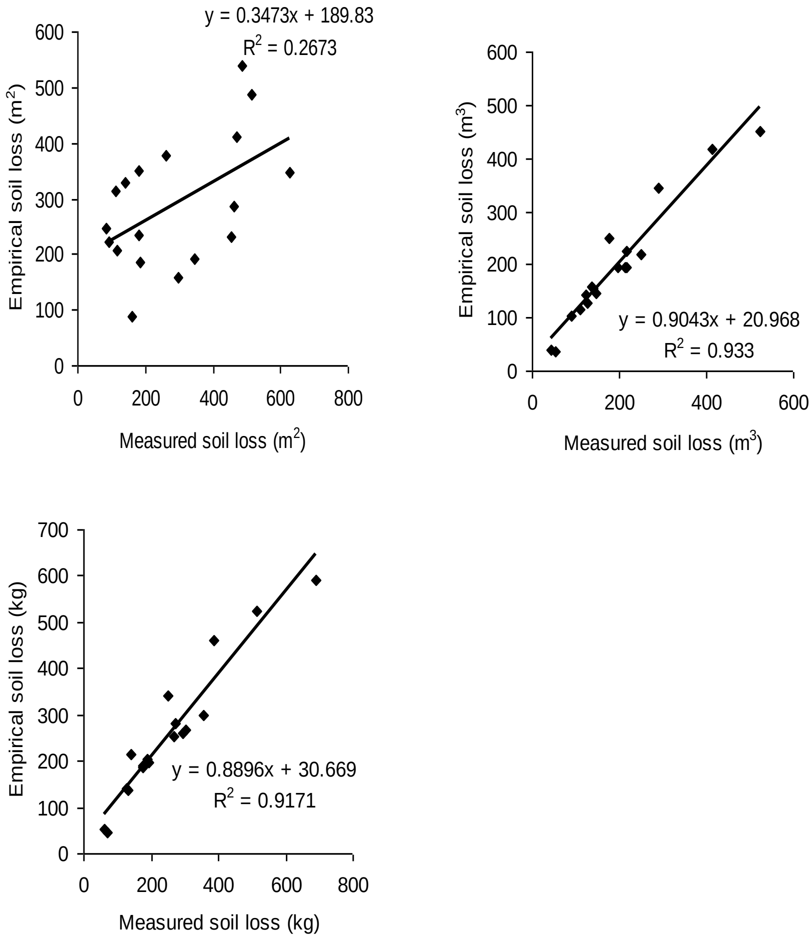

a). b). c).

Figure 2: Relationships between measured and empirical aggregate estimates of: a). ASL, b). VSL and c). MSL across sites

On the aggregate, the results showed that the measured and empirical ASL, VSL, and MSL were related by 26.73, 93.30, and 91.71% across the sites. The relationship between the aggregate estimates of measured and empirical, and as well as between measured and EGEM model in predicting soil erosion (ASL, VSL and MSL) in the study area expressed very low to high prediction relationships. But the empirical model could not adequately predict the extents of ASL in this study. However, the empirical equation was able to predict both VSL (r^2 = 0.9330) and MSL (r^2 = 0.9171) with higher precisions. The relative efficiency of empirical over physically based models (e.g. EGEM) model has since been reported by Nachtergaele *et al*. (2001 a & b) and Capra *et al.* (2004).

Efficiency of the modeled empirical erosion in the study sites

The results showed that the empirical ASL prediction was reliable at Vimtim, Madanya, Gella, and Digil with a standardized mean error (M_{es}) of 0.0008, 0.0504, 0.0734, and 0.0702 respectively, while it was comparably less efficient at Muvur and Lamorde with a respective M_{es} of 7.4940 and 2.6630.

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Table 1: Prediction efficiency (reliability) of aggregate soil loss estimates in the study sites

Study Location	Area of soil loss (m^2)		Error analysis		
	Measured	Empirical	R^2	M_{es}	M_{se}
			Area of soil loss (ASL) prediction accuracy		
Digil	240.22	294.05	0.2884	0.0702	1.4100
Vimtim	315.99	325.20	0.3103	0.0008	5.3174
Muvur	470.28	394.15	1.0000	7.4940	43.9537
Gella	401.44	280.01	0.9828	0.0734	70.1076
Lamorde	119.48	273.75	0.9438	2.6630	89.0678
Madanya	175.33	170.11	0.6653	0.0504	3.0138
			Volume of soil loss (VSL) prediction accuracy		
Digil	172.80	196.21	0.3305	0.0863	13.5158
Vimtim	303.36	276.23	0.9906	0.0061	15.6635
Muvur	305.48	319.66	0.8915	0.0064	8.1868
Gella	133.29	125.27	0.9971	0.0040	4.6303
Lamorde	162.00	170.11	0.9792	0.0091	4.6823
Madanya	81.74	86.17	0.9761	0.0053	2.5577
			Mass of soil loss (MSL) prediction accuracy		
Digil	243.00	265.95	0.3828	0.0425	13.2502
Vimtim	395.41	368.14	0.9706	0.0032	15.7443
Muvur	399.04	415.42	0.8701	0.0076	9.4569
Gella	177.44	165.10	0.9874	0.0052	7.1245
Lamorde	212.44	224.23	0.9952	0.0181	6.8069
Madanya	106.62	109.80	0.9840	0.0020	1.8359

Key: R^2 = coefficient of determination
M_{es} = standard mean error;
M_{se} = root mean square error

Conversely, the maximum efficiency (M_{se}) of the empirical equation in the sites was in the order: Digil (1.4100) ≥ Madanya (3.0138) ≥ Vimtim (5.3174) > Muvur (43.9537) > Gella (70.1076) ≥ Lamorde (89.0678). The empirical equation prediction was observed as efficient at Vimtim, Madanya, Digil, and Gella, compared to Lamorde and Muvur. Even though, there was high association between these estimates with the measured ones at most of the sites. Also, the corresponding M_{se} fairly correlated with the observed M_{es}, depicting the models' accuracy as adequate in some of the sites. The high association was likely due to the empirical nature of the modeled equation in relation to the measured ASL. This agrees with the report of Capra *et al.* (2004), that performance of empirical models was no worse than the better tested EGEM output in the Mediterranean environments.

The results showed that the empirical VSL prediction was generally efficient at all sites. The M_{es} in the sites was in the order: Gella (0.0040) ≥ Madanya (0.0053) ≥ Vimtim (0.0061) ≥ Muvur (0.0064) ≥ Lamorde (0.0091) ≥ Digil (0.0863). In addition, the M_{se} of the empirical equation corresponded well with the observed M_{es} values. The M_{se} was best at Madanya (2.5577) compared to Vimtim (15.6635), being the less reliable among the sites. The prediction efficiency of the empirical equation was however, observed to be fair in its prediction efficiency in this study. Nachtergaele *et al.* (2001a) and Capra *et al.* (2004) similarly observed that empirical studies gave more accurate estimates of eroded volume, when compared with those of EGEM at the Mediterranean Loess belt. The M_{es} and M_{se} indices due to these models were observed to be fairer than the range of 0.7 - 4.5 and 14.8 - 96.4 from eroded volume earlier reported by Capra *et al.* (2004) from a similar work in Sicily, Italy.

The results revealed that the empirical MSL prediction was generally efficient at all sites, as it was in the case of VSL predictions. On the other hand, the M_{se} of the empirical equation in the sites was in the order: Madanya (1.8359) > Lamorde (6.8069) ≥ Gella (7.1245) ≥ Muvur (9.4569) > Digil (13.2502) > Vimtim (15.7443). The result

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of empirical prediction was also widely efficient in predicting MSL across the sites, as it were the case of VSL predictions. Both the M_{es} and M_{se} indices observed in this work appear fairer than those earlier reported by Capra *et al.* (2004). This trend is still likely due the individuated prediction ability of empirical equation as earlier emphasized by Nachtergaele *et al.* (2001a), Capra *et al.* (2004), and Nasri *et al.* (2008).

CONCLUSION

The empirical model prediction efficiency was largely found as reliable at all sites, regardless of season. However, the accuracy of the empirical model was better in terms of VSL (r^2 = 0.9330) and MSL (r^2 = 0.9171), than ASL (r^2 = 0.2673) prediction on aggregate basis. The empirical estimates of VSL and MSL were consistently higher at Muvur (less vegetation) and lower at Madanya and Gella (denser vegetations) in both years. It suffices to conclude that the model could serve as a suitable alternative to the rigorous field measurement method for EG erosion studies in the area.

RECOMMENDATIONS

The modeled equations are strongly recommended for implementation among farmers, soil conservationists, environmental protectionists, and other private and/or governmental agencies in their policy issues regarding erosion studies in Mubi area. Incorporation of erosion variables such as channel parameters (length, width, and depth), TEB content as additional variables in the empirical model is recommended for possible improvement in ASL prediction efficiency.

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