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Reducing Associated Resource Constraints in Erosion Risk Evaluation in Nigeria

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ABSTRACT

Erosion risk determination is time-consuming, cumbersome, and costly. To ensure food security, methods of estimating erosion risk that substantially reduces associated constrains are needed; therefore, this study determined the soil properties central to providing structural stability and using same to build empirical models to forecast possible response of soil structural framework to the shattering effects of raindrops (D). Five core and auger surface soil samples from five locations were collected across Central Nigeria. A chemical and physico-structural soil properties correlation matrix was produced; 'D' was then fitted to a linear multivariate model. Models with the highest coefficient of determination (R^2) and minimal standard error with interpretations applicable to real situations were selected for validation on 10 other test soils. Results indicate that the Ca content of soils and soil porosity were the single most important soil chemical and physical property respectively, determining 'D', whereas Na (-0.49) and bulk density (-0.73) where the most negatively correlated chemical and physical property to 'D'. Models 2, 11 and 12 best predicted 'D' with 'r' values between measured and predicted 'D' as 0.97, 0.94 and 0.95, and Model 2 predicted 'D' in 80 % of the test soils, whereas Models 11 and 12 did so in 70 % of test soils. However, the cost associated with model 2 was six and four folds higher compared to model 11 and 12 respectively. Based on the related cost, model 11 is the choice, whereas in terms of versatility model 2 is. All models developed were cheap and high in predictive accuracy for 'D'. The models (2, 11 and 12) with few entries (soil properties) are simpler than existing models.

Nijerya'da Erozyon Riski Değerlendirmesinde İlişkili Kaynak Kısıtlamalarının Azaltılması

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ÖZ

Erozyon riskinin belirlenmesi zaman alıcı, zahmetli ve maliyetlidir. Gıda güvenliğini sağlamak için, ilgili kısıtlamaları önemli ölçüde azaltan erozyon riskini tahmin etme yöntemlerine ihtiyaç duyulmaktadır; bu nedenle, bu çalışmada, yapısal istikrarı sağlayan temel toprak

Anahtar Kelimeler:
Erozyon risk değerlendirmesi
Gine Savanı
Toprak yapısı
Toprak kimyasal özellikleri
Toprak fiziksel özellikleri
Nijerya

özelliklerini belirlemiş ve aynı özellikleri kullanarak, toprak yapısal çerçevesinin yağmur damlalarının parçalanma etkilerine olası tepkisini tahmin etmek için ampirik modeller oluşturmuştur (D). Orta Nijerya'da beş farklı konumdan beş adet karot ve burgu yüzey toprak örneği alınmıştır. Kimyasal ve fiziko-yapısal toprak özellikleri korelasyon matrisi oluşturulmuş; daha sonra 'D' doğrusal çok değişkenli bir modele uyarlanmıştır. En yüksek belirleme katsayısına (R2) ve en düşük standart hataya sahip, gerçek durumlara uygulanabilir yorumlara sahip modeller, 10 farklı test toprağı üzerinde doğrulama için seçilmiştir. Sonuçlar, toprakların Ca içeriğinin ve toprak gözenekliliğinin sırasıyla 'D'yi belirleyen en önemli toprak kimyasal ve fiziksel özelliği olduğunu, Na (-0,49) ve kütle yoğunluğunun (-0,73) ise 'D' ile en negatif korelasyon gösteren kimyasal ve fiziksel özellik olduğunu göstermektedir. Modeller 2, 11 ve 12, ölçülen ve tahmin edilen 'D' değerleri arasındaki 'r' değerleri sırasıyla 0,97, 0,94 ve 0,95 ile 'D' değerini en iyi şekilde tahmin etmiştir. Model 2, test edilen toprakların %80'inde 'D' değerini tahmin ederken, Modeller 11 ve 12 test edilen toprakların %70'inde bunu başarmıştır. Bununla birlikte, Model 2'nin maliyeti, Model 11 ve 12'ye kıyasla sırasıyla altı ve dört kat daha yüksektir. İlgili maliyete göre Model 11 tercih edilirken, çok yönlülük açısından Model 2 tercih edilmektedir. Geliştirilen tüm modeller ucuz ve 'D' için yüksek tahmin doğruluğuna sahiptir. Az sayıda girdiye (toprak özellikleri) sahip modeller (2, 11 ve 12), mevcut modellere göre daha basittir.

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Introduction

Soil is one of the important natural resources and a significant factor in global food production. More than 99% of human food comes from the land (Pimentel and Pimentel, 2000). Soil also supports plants and acts as a reservoir of water and nutrients, but not all soils suit these purposes. According to Buringh and Dudal (1987) the world's total land area is 14.9 billion hectares, 29% of the earth surface, the remaining 71% is covered with water. A part of the land, about 1.4 billion, is permanently covered with ice, and the remaining 13.4 billion is used for Agricultural purposes, which include grazing and forests. According to FAO (2013), a small fraction about 1.5 billion hectares is suitable for growing crops, yet about 10 million hectares of cropland are lost every year to accelerated erosion from the action of water and wind, which causes undesirable changes in soil structure leaving the soil degraded (Pimemtel, 2006).

Erosion was reported by Lal (1994) to be the most serious type of soil degradation undermining the long term viability of arable soils across the globe. Oldeman *et al*. (1991) estimated that erosion accounts for 84 % of total global area of degraded soils. United Nation (UN) Convention to Combat Land Degradation (CCD) opines that soil erosion leads to loss of chemical, biological, and economic productivity of terrestrial ecosystem diversity (Telles *et al*., 2011). Some researchers also argued that a significant area of cultivated land may be rendered biologically and/or economically unproductive if erosion continues unabated (Brown and Wolf, 1984; Lal, 1994; Pimental et al.1995; Eaton, 1996).

The process of soil erosion by water is initiated when the constituent particles of the aggregates are detached by the shearing force of raindrops incident on the soil surface. For an aggregate to be destroyed, the intrinsic force of resistance of soil aggregates must be overcome by the shearing force of raindrops. Therefore the extent of soil erosion depends on the binding forces that sustain the integrity of the structural units, enabling resistance to the shattering forces of raindrops (Meyer et al., 1975). Torri et al. (1987) reported that an aggregate detachment index (D) can be determined by the ratio of the raindrop detaching force (Fd) to the force of soil resistance (Fr), thus,

$$D = Fd / Fr = \Psi d\ Ad / \Psi s\ A_s$$

Where Ψd is the total shear stress of the average raindrop, Ψs, the soil cohesive force, Ad, the area over which Ψd acts and A_s, the area of soil aggregate over which Ψs acts.

From current reports, raindrop diameter, raindrop velocity of impact, surface tension, contact angle, duration and orientation of raindrops are the most important factors which affects 'Fd' (Nearing and Bradford, 1986; Nearing and Bradford, 1987; Truman et al., 1990; Barry et al., 1991; Kinnell, 2005; Wuddivira et al., 2009). Similarly, the force of resistance (Fr) refers to the ability of soil aggregates to withstand breakdown. The force of resistance (Fr) is influenced by the initial water content of the aggregate at impact (Cruse and Larson, 1977), the soil cropping history, with stability declining with continuous tillage (Ahamefule and Peter, 2013) compared to adjacent forest soils (Beare et al., 1994), and the nature and concentrations of microbial synthesized aggregate-stabilizing substances like resins and gums (Harris et al.,1966; Lynch and Bragg, 1985). Harris et al. (1966), Hamblin and Davies, (1977); Oades, (1984) and Lynch and Bragg, (1985) revealed that the significant properties of the soil which influence its stability can be grouped into invariant (intrinsic) and dynamic; and that the exhibition of their influence is related to type of soil, season and climate. Since water content is dynamic, by holding 'Fd' constant, a raindrop kinetic energy-based index of soil detachment (D) can be determined for correlating 'Fd' to some factors which affect 'Fr'. By doing this, a simple model of relating 'D' to some more-easily determined soil properties can be developed. Several studies have adopted the raindrop technique to compare soil's structural stability and erodibility of soils (McCalla, 1944; Low, 1954; Imeson and Vis, 1984; Ramos et al., 2003; Canton et al., 2009). It is generally known that no single determined soil property can completely stand for the bulk response that makes up soil erodibility (Lal, 1990); however, Bruce-Okine and Lal (1975) proposed the adoption of the multiplicative inverse of the total number of water drops needed to shatter an aggregate as an erodibility marker for tropical soils. De Vleeschauwer et al. (1978) and Mbagwu, (1986) reported highly correlated inverse relationships between the total kinetic energy of raindrops required to destroy aggregates and the quantity of soil lost from simulated rainfall.

A major setback to the adoption of 'D' for routine characterization of soil structural stability is the difficulty related to its determination. The apparatus for raindrop simulation must be arranged in such a way that the characteristics of raindrops are uniform while the investigation lasts. This is not readily achievable. A high coefficient of variation in 'D' which ranged from 38 to 47% was reported by Mbagwu (1986, 1989).

The need therefore arises for studies in which more-easily determined soil properties are related to 'D'; Wustamidin and Douglas (1985) made such attempt, in which they put forward a model for estimating 'D', the model had 15 independent variables (co-variants included). This model is complex, time-consuming, and probably expensive, and its affordability with the present unfavourable economic realities may not permit its use, particularly in developing countries.

Therefore, the objectives of this study were to:

(a) Evaluate and characterize the invariant properties of the soil that influence soil aggregate stability, and

(b) Develop and validate simple empirical models for estimating the resistance of soil aggregates in the study areas and similar environments to water-drop impacts 'D' from soil properties that are more easily determined.

Material and Methods

The Study Area

Kwara state is located in a tropical region with a bi-modal rainfall pattern and a tropical wet and dry seasonal climate lasting about six months (Olanrewaju, 2009). Temperature is between 25^{o}C and 30^{o}C throughout the rainy season except in July – August when the is a rise in the temperature due to the formation of cloud in the sky, which prevents direct insolation (heatstroke) while in the dry season it ranges between 33^o C to 34^{o}C. It is sunny and the sun shines brightly for 6.5 to 7.7 hours daily from November to May (Oyegun,1982).

Soil Sampling

Soil samples were collected from five locations evenly spread across Kwara state. The locations were Irepodun (Kwara West), Ifelodun (Kwara South), Moro (Kwara North), Baruten (Kwara East) and Ilorin, which is situated in the centre of the state, as shown in Fig1. Cylindrical metal cores and augers were used for collection of samples from the five locations shown in Table 1. The auger samples were collected at 10 m regular intervals, bulked and a composite taken, giving a total of 25 composite samples. Three samples from each location (fifteen in total) were used to develop the models. In comparison, the remaining two from each location (ten samples in total) were used to validate the developed models. The soil samples were air dried, sieved using a 2 mm sieve and used for soil analyses.

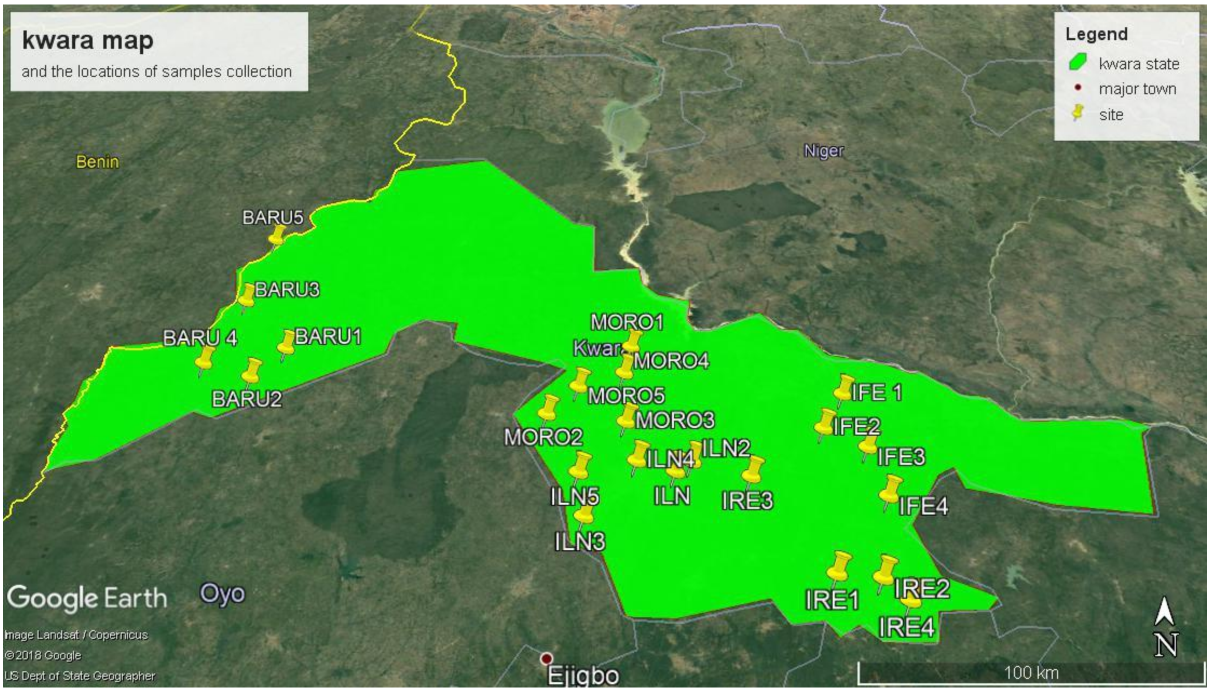

Figure 1. Map of Kwara State showing sampled locations

Table 1. Coordinates of sampled locations

Serial number	Name of location	Cardinal point of location
1	Ifelodun1	9° 1'13.77" N, 4° 59'13.27" E
2	Ifelodun2	8° 57'57.87" N, 5° 2'22.45" E
3	Ifelodun3	8° 53'7.08" N, 5° 7'18.01" E
4	Ifelodun4	8° 50'46.56" N, 5° 2'55.05" E
5	Ifelodun5	8° 57'17.07" N, 4° 54'14.70"E
6	Moro1	8° 36 '25" N, 4° 32'40" E
7	Moro2	8° 37 '18" N, 4° 31'58" E
8	Moro3	8° 39 '33" N, 4° 31'20" E
9	Moro4	8° 40'15" N, 4° 31'13" E
10	Moro5	8°42'49" N, 4° 27'57" E
11	Irepodun1	8° 7'51.17" N, 5° 6'9.06" E
12	Irepodun2	8° 7'9.65" N, 5° 7'45.20" E
13	Irepodun3	8° 15'0.22" N, 4° 55'0.20" E
14	Irepodun4	8° 4'17" N, 5° 5'36." E
15	Irepodun5	8° 3 '19" N, 5° 6'6." E
16	Baruten1	8° 53'43.80" N, 3° 23'21.98" E
17	Baruten 2	8° 53'43.80" N 3° 11'48.98" E
18	Baruten3	9° 0'57.12" N 3° 32'12.79" E
19	Baruten 4	9° 12'36.96" N 3° 27'29.44" E
20	Baruten 5	9° 4'31.41" N, 3° 15'46.80" E
21	Ilorin1	8° 34'44" N, 4° 42 '55" E
22	Ilorin 2	8° 27'28" N, 4° 43 '5" E
23	Ilorin 3	8° 34'1" N, 4° 34 '2" E
24	Ilorin 4	8° 29'48" N, 4° 32 '32" E
25	Ilorin 5	8° 29'48" N, 4° 35 '35" E

Laboratory Analyses

The Following Laboratory Analyses Were Conducted:

Soil Physical Properties

A constant head permeameter was used for the determination of saturated hydraulic conductivity (Ksat) according to Bouwer (1986), then applying the transposed Darcy's equation for vertical flows of liquid, thus:

$$K_{sat} = \frac{Q}{AT} \times \frac{L}{\Delta H}$$

Where Q is the stead state volume of flow (cm^3)

A is the cross-sectional area of the a core sample (cm^2)

T is the elapsed time (hr)

L is the length of the core sample (cm)

ΔH is the change in hydraulic head (cm)

The core method was used to determine of soil bulk density (Blake and Hartge, 1986). Total porosity was determined using the formula:

$$TP = \left(1 - \frac{Pd}{BD}\right) \times 100$$

Where TP is the total porosity

Bd is the bulk density

Pd is the particle density (2.65 g cm^{-3})

The wet –sieving method of Kemper and Rosenau (1986) was used to determine mean weight diameter (MWD) of water-stable aggregates. Particle size analysis (% sand, silt and clay) was determined by Bouyoucos (1932) hydrometer methods. Aggregated silt and clay (ASC) was determined according to the technique of Middleton (1930) as silt and clay in calgon-dispersed samples minus silt and clay in water-dispersed samples.

The clay dispersion index (CDI) was determined following the procedure of Dong *et al*. (1983), as clay in water-dispersed samples / clay in calgon-dispersed samples.

Moisture content at saturation was determined by saturating soil samples collected in a cylindrical metal core for 24 h and then weighing them. The soil samples were oven-dried for 24 h and weighed. Moisture content at saturation (MC) was then calculated thus:

$$MC = \frac{Mass\ of\ water\ at\ saturation}{mass\ of\ dried\ soil} \times 100$$

Soil structural index (SSI) was determined using the formula: $\frac{1.724 \times OC}{Si + Cl} \times 100$

Where OC = % soil organic carbon

Si = % silt

C = % clay

Moisture content at wilting point (-1.5megapascals) was determined by the use of pressure plate equipment.

Assessment of The Detachment Energy of A Water Drop (D)

Wustamidin et al. (1983) and Imeson and Vis, (1984) procedure was used to determine the detachment energy of a water drop (D). The 2 – 4 mm air-dried aggregates were weighed, and composite samples used to determine the residual gravimetric moisture content (θm) on oven-dry mass basis. The device for water drops simulation was consisted of a burette with an overflow device to maintain a constant pressure head. A silicon tube was fitted to the burette nozzle to deliver water drops of known mass and diameter at regular intervals. One gram of the dried aggregates (Wi) was placed on a fiberglass gauze of 1 mm aperture attached to a glass funnel. The aggregates of the samples were subjected to a maximum of 100 water-drops impacting from a 1 m height at a drop / s through a 15 cm diameter plexiglass tube. The frequency of water-drops completely destroyed an aggregate and was recorded, and total kinetic energy derived from the terminal velocity according to Laws (1941). The water-drop detachment energy 'D' defined as the kinetic energy required to break down and pass 1 g of aggregates through a 1 mm sieve aperture was calculated thus:

$$\text{'D'} = [\Sigma ni = 1(0.5MV2)] / (\text{M}i - \text{M}b)$$

Where 'D' is in J / kg

M is the water drop mass (kg),

V is the water-drop velocity at impact (m / s),

n is the number of applied drops of water,

Mi is the initial mass of aggregates used (kg),

Mb is the leftover mass of aggregates on the sieve (kg) and

J is joule.

Twenty replicate determinations were made on each sample. The mass of the water drop was 0.03 g with a size of 1.5 mm, and the kinetic energy = 2×10^{-4}J per drop

Determination of Soil Erodibility Factor

The Wischmeier and Smith (1971) nomograph was used to estimate the soil erodibility factor.

Analyses of Chemical Properties of the Soil

Duplicate determinations were made for soil pH in both distilled water and in 0.1N KCl solution, using 5g of soil to water in the ratio 1:2.5 and stirred after 30 minutes, Beckman zeromatic pH meter was used to read off the pH values (Peech, 1965). The micro-Kjeldhal distillation method of Bremner (1996) was used to determine total nitrogen (N). The Ammonia evolved was distilled with 45 % NaOH into 2.5 % boric acid and determined by titrating with 0.05 N KCl. Available Phosphorus (P) was determined by the Bray II method, a procedure described by Bray and Kurtz (1945). The available phosphorous was read off from the standard curve after obtaining the optical density from the colorimeter. Organic matter was determined by the procedure of Walkley and Black using the dichromate wet oxidation method (Nelson and Sommers, 1982). Exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+} , Na^{+}) were extracted by leaching the soil with 1 N ammonium acetate solution. Exchangeable K^{+} and Na^{+} in the extract were determined using a flame photometer whereas an atomic absorption spectrophotometer was used to determine Calcium and Magnesium (Anderson and Ingram, 1993).

Data Analyses and Model Development

A matrix of correlation among each of the chemical, physical and structural data subsets was derived to determine soil properties that are auto correlated-'D' was subsequently transposed into a linear multivariate model of the form:

$$D = B_o + X_1B_1 + X_2B +_2 \ldots \ldots\ldots\ldots + B_n X_n + e$$

Where e is random error; X_1 to X_n, the independent variables in each data set, and B_o to B_n, the empirical constants using the IBM SPSS Statistic 21 package. Models with the highest coefficient of determination (r^2), the lowest standard error (SE) and having relevant physical interpretations over the range of determined values were validated with independent data from 10 other test-soils. The choice of regression model was predicated on the ease of determining the independent variables.

Results and Discussion

Characterization of Soils Used for Model Development

The characteristics of the soils used to develop the models are presented in Table 2. The results indicate that the study soils collected from different locations across Kwara State are predominantly sandy clay loam and sandy loam in texture, with exceptions in Baruten2 and Ilorin1 where a loamy sand and sandy clay texture were observed respectively. Soil pH varied from slightly alkaline to strongly alkaline across the state. Irepodun soil had the highest pH (mean pH = 8.5) while Baruten had the lowest (mean pH = 7.7). Organic matter (OM) content also varied across the state, with soils of Moro recording the lowest organic matter (mean OM = 0.55%) while Ilorin had the highest (OM = 2.99%).

The detachment energy (D) values staggered across the state. Ilorin had the widest 'D' range (0.05 – 0.52 $JKg^{-1} \times 10^{-3}$) and the highest mean value of 'D' (0.21 $JKg^{-1} \times 10^{-3}$), Irepodun had the lowest mean (0.07$JKg^{-1} \times 10^{-3}$) whereas Moro soils had the narrowest range of 0.07 – 0.1 $JKg^{-1} \times 10^{-3}$.

Relationship Between Selected Soil Chemical Properties with 'D'

The correlation of selected soil chemical properties with 'D' is shown in Table 3. The result indicates that only Ca (r = 0.8) was correlated ($P \leq 0.01$) with 'D' whereas sodium (r = -49) and pH (r = -0.46) were negatively correlated.

Table 2. Selected physico-chemical properties of soils of Kwara State used for model development

Local	Clay (%)	Silt (%)	Sand (%)	Txt Class	O.M (%)	pH	D (JKg^{-1} × 10^{-3})
Ife1	20.25	11.25	68.50	SCL	0.38	8.00	0.11
Ife 2	13.75	6.36	79.89	SL	0.95	8.20	0.22
Ife 3	21.68	18..07	60.25	SCL	0.91	8.30	0.11
Mor1	22.66	17.89	59.46	SCL	0.69	8.20	0.07
Mor 2	33.71	6.74	59.55	SCL	0.50	8.40	0.10
Mor 3	34.50	11.50	54.00	SCL	0.47	8.10	0.07
Ire1	23.04	18.44	58.52	SCL	1.53	8.20	0.10
Ire 2	25.69	17.84	56.48	SCL	1.07	9.00	0.05
Ire 3	14.57	19.77	65.66	SL	1.16	8.30	0.06
Bar 1	32.91	2.67	64.42	SCL	1.79	7.60	0.33
Bar 2	5.47	6.07	88.46	LS	2.29	8.10	0.07
Bar 3	20.34	16.95	6271	SCL	3.05	7.50	0.03
Iln 1	40.13	9.69	5019	SC	3.62	8.10	0.52
Iln 2	15.66	15.82	68.52	SL	3.05	8.10	0.07
Iln 3	26.10	14.72	59.18	SCL	2.29	8.30	0.05

D= Detachment energy of water drop, TXT CLASS = Textural class O. M = Organic matter, SCL = Sandy clay loam, SL = Sandy loam, SC = Sandy clay, Ire = Irepodun, Ife = Ifelodun, Bar = Baruten and ILN = Ilorin

Table 3. Correlation between selected chemical properties and water-drop detachment energy (D)

Soil Properties	Range	Correlation (r) With D
O.M (%)	0.38 – 3.65	0.45
A.P (%)	2.79 – 5.25	0.20
EA (cmol Kg^{-1})	0.28 – 0.76	0.15
EB (cmol Kg^{-1})	25.75 – 95.93	0.04
CEC (cmol Kg^{-1})	26.11 – 95.21	0.05
N (%)	0.35 – 0.99	0.36
Ca (cmol Kg^{-1})	0.09 – 62.98	0.80^{**}
K (cmol Kg^{-1})	0.09 – 1.33	0.38
Na (cmol Kg^{-1})	19.28 – 34.94	– 0.49
Mg (cmol Kg^{-1})	3.21 – 10.31	0.29
pH	7.6 – 9.0	– 0.46

OM = organic matter; CEC = cation exchangeable capacity; EA = exchangeable acidity; EB = exchangeable basicity; OC = organic carbon, AP = available phosphorus ** significant at P ≤ 0.01

There was non–significant ($P < 0.05$) positive correlation between OM and 'D'and moderate correlation of K^+ (r = 0.38) and Mg^{2+} (r = 0.29) with 'D'. Soil CEC was weakly correlated with 'D'.

Models Relating Selected Soil Chemical Properties With 'D'

Table 4 shows that Ca^{2+} increased the predictive ability of regression models that relate 'D' to soil chemical properties. Models with Ca^{2+} accounted for 67 – 80% (R^2 values) variability in 'D'. Based on the use of soil chemical properties for the prediction of 'D', model 2 is the best, considering that it had the highest predictive ability (80%) in the study soils. The standardized coefficient- beta (B) index (column 4 in Table 4) measures the effect of individual soil properties on ‘D’. The index reaffirms that Ca^{2+} had the highest influence on ‘D’ (predicted detachment energy) compared to other constituent soil properties of model 2.

Table 4. The regression models relating Detachment energy index (D) in $JKg^{-1}\times10^{-3}$ to chemical properties of soil

Model number	Equation	Coefficient of determination (R^2)	Standardized Coefficient (B)	Associated cost per sample (NGN)
1	$D = 0.0093(Ca) - 0.00034(Ca)^2 + 0.000005(Ca)^3 + 004$	0.71	Ca = 2.59 Ca^2 = 2.41 Ca^3 = 1.11	150
2	$D = 0.005(Ca) + 0.0001(Na^2) + 0.023(OM) - 0.064$	0.80	Na = 0.1 Ca = 0.71 OM = 0.11	1300
3	$D = 0.003(Ca) + 0.013(OM) - 0.00001(Na)^2 + 0.032$	0.74	Ca = 0.75 OM = 0.19 Na^2 = 0.036	1300
4	$D = 0.108(N) + 0.045(P) - 0.012(Mg) - 0.001(Ca) - 0.135$	0.73	N = 0.162 P = 0.3 Mg = 0.15 Ca = 0.82	2800
5	$D = 0.133(N) + 0.011(Mg) + 0.001(Ca) - 0.003(CEC) - 0.01$	0.72	N = 0.2 Mg = 0.14 Ca = 0.87 CEC = – 0.44	2800

CEC = Cation exchangeable capacity, NGN = Nigeria Naira (money)

Table 4. cont.: The regression models relating Detachment energy index (D) in $JKg^{-1} \times 10^{-3}$ to chemical properties of soil

Model number	Equation	Coefficient of Determination(R^2)	Standardized Coefficient (B)	Associated cost per sample (NGN)
6	D = 0.135(N)+ 0.032 (P) + 0.096 (K) – 0.154	0.22	K = 0.269 P = 0.213 N = 0.202	2650
7	D = 0.007(Ca) + 0.014 (OM) – 0.0350(P) – 0.026 (K) – 0.114	0.71	K = –0.074 P = 0.23 Ca = 0.81 OM = 0.11	2800
8	D = 0.05 (Acidity) – 0.15 (pH) + 0.012 (Mg) – 0.049 (OM) + 0.11	0.41	EA = 0.007 pH = 0.414 Mg = 0.17 OM = 0.049	2250
9	D = – 0.007 (Na) + 0.006 (Ca) – 0.009 (Mg) – 0.033(K) – 0.0303	0.67	Na = – 0.25 Ca = 0.77 Mg = – 0.11 K = – 0.093	600
10	D = 0.45 + 0.002(CEC) – 0.057(0M)	0.21	CEC = 0.014 OM = 0.45	2500

CEC = Cation exchangeable capacity, NGN = Nigeria Naira (money)

Relationship Between Selected Soil Physico-Structural Properties With 'D'

The result in Table 5 showed that the correlation between sand and 'D' (r = – 0.19) was negative and weak whereas a moderately positive correlation existed between clay and 'D' (r = 0.51). There was moderately positive relationship between silt and 'D'.

Porosity gave a significant positive linear relationship with 'D' (r = 0.733) whereas bulk density gave the reverse (r = – 0.729).

Moisture content at saturation and wilting point related positively with ‘D’ with ‘r’ values of 0.634 and 0.534 respectively. Table 5 further shows that MWD has strong correlation with ‘D’ (r = 0.71). Aggregate silt and clay (ASC) and clay dispersion index (CDI) were not significantly correlated with ‘D’. No significant correlation was established between saturated hydraulic conductivity and ‘D’ of the soil. There was negative (inverse) correlation (r = – 0.47) between ‘D’ and the erodibility factor (K) of Wischmeier *et al.* (1971).

Table 5. Correlation between some soil physico-structural properties with water-drop detachment energy (D)

Soil Properties	Range	Correlation (r) With D
Sand (%)	50.19 – 88.46	– 0.19
Clay (%)	5.47 – 40.13	0.51*
Silt (%)	2.67 – 19.77	0.51*
Porosity (%)	31.32 – 59.25	0.73*
Bulk Density (g cm^{-3})	1.29 – 1.82	– 0.73**
MWD (mm)	0.65 – 3.09	0.71**
ASC (%)	3.95 – 11.56	0.17
CDI (g/g)	0.65 – 1.24	– 0.36
K_{sat} (cmh^{-1})	6.44 – 102.50	0.32
MCS (%)	19.53 – 60.58	0.64*
WP (%)	7.90 – 22.6	0.53*
SSI (%)	1.01 – 19.87	0.03
Erodibility (t h MJ^{-1} mm^{-1})	0.03 – 0.21	– 0.47

BD = Bulk density, MC = Moisture content at saturation, K_{sat} = Saturated hydraulic conductivity, MWD_w = Mean weight diameter of wet soil aggregates, WP = Wilting point, CDI = Clay dispersion index, ASC = Aggregate silt and clay, SSI = Soil structural index. MCS = Moisture content at saturation * significant at $p \leq 0.05$ ** significant at $p \leq 0.01$

Models Relating Selected Soil Physical Properties With ‘D’

Models that relate ‘D’ to physical properties are shown in Table 6. Only model 11 and 12 best predicted ‘D’ with the models accounting for 91 % and 94 % variability in ‘D’ respectively. The standardized coefficient beta (B) indicate that among three physical properties water content at wilting point (WP) had the highest positive effect on ‘D’ (B = 7.72) in model 11, meaning that a unit increase in WP will increase ‘D’ by 7.72. Bulk density (BD) had negative influence (B = -8.43) on the strength of predicting ‘D’ by model 11. An increase in BD will cause a reduction in the value of ‘D’ by a factor of 8.43. In model 12, BD^2 had positive effect on ‘D’ indicated by a high B value of 8.54. While the effect of BD on ‘D’ was negative squaring its value gave a positive effect.

Models Relating Selected Soil Structural Properties With ‘D’

The models that relate ‘D’ to soil structural properties are presented in Table 7. Model 19 showed the highest predictive accuracy among other models developed from soil structural properties. This model is solely based on mean weight diameter (MWD) which is one out of four soils structural properties (ASC, CDI and SSI) determined. A strong correlation between MWD and ‘D’(r = 0.71) had earlier been shown. The ‘B’ values in Table 7 shows that MWD^2 had multiplier effect on ‘D’ whereas MWD^3 had negative effect on ‘D’ in model 19. Therefore increasing MWD^3 by 1 will cause reduction in the value of ‘D’ by 12.56.

Table 6. Regression models relating Detachment energy index (D) ($J/Kg \times 10^{-3}$) to physical properties of the soils

MODEL NUMBER	Regression equation	Coefficient of Determination (R^2)	Standardized Coefficient (B)	Associated cost per sample (NGN)
11	$D = 0.000011(WP)^2 + 1.88(BD)^2 - 0.001(WP) - 5.99(BD) + 4.84$	0.91	$WP^2 = 7.72$ $BD^2 = 0.1$ $WP = -0.18$ BD = – 8,43	200
12	$D = 7.49 - 7.44(BD) - 0.019(P) - 0.004(MC) + 2.08(BD)^2$	0.94	$BD = -10.46$ $P = -1.008$ $MC = -2.68$ BD^2 = 8,54	300
13	$D = 0.091(SC)^3 - 0.5(SC) - 0.04(SC)^3 + 0.83$	0.48	$SC = -13.78$ $SC^2 = 45.27$ $SC^3 = -32.08$	150
14	$D = 0.003(C) + 0.194(P) + 6.87(BD) - 18.63$	0.59	$C = 0.20$ $P = 10.27$ $BD = 9.67$	300
15	$D = 0.0002(C) + 0.0002(Ksat) - 0.47(BD) + 0.824$	0.54	$BD = -0.66$ $C = 0.07$ $Ksat = 0.086$	350
16	$D = 8.3(BD) + 0.001(K_{sat}) + 0.23(P) - 22.44$	0.50	$BD = 11.67$ $Ksat = 0.24$ $P = 12.33$	350
17	$D = 6.43(BD) + 0.18(P) + 0.005(WP) + 0.02(MC) - 17.45$	0.54	$BD = 9.04$ $P = 9.55$ $WP = 0.16$ $MC = 0.15$	400
18	$D = 0.009(WP) + 0.0003(K_{sat}) - 0.07(MC)$	0.45	$MC = 0.51$ $WP = 0.25$ $Ksat = 0.045$	350

WP = Water content at wilting point, BD = Bulk density, MC = Moisture content, Ksat = Saturated hydraulic conductivity, SC = Sand/ clay, P = Porosity, C = Clay, NGN = Nigeria Naira (money)

Table 7. The regression models relating Detachment energy index (D) in $JKg^{-1} \times 10^{-3}$ to structural properties of soil

Model number	Regression equation	Coefficient of determination (R^2)	Standardized coefficient (B)	Associated cost per sample (NGN)
19	$D = -0.21(MWD)^3 + 1.06(MWD)^2 + 1.33(MWD) + 0.54$	0.82	$MWD = 7.12$ $MWD^2 = 19.99$ $MWD^3 = -12.56$	200
20	$D = 0.031(MWD^2) - 0.005(ASC) - 0.11(CDI) + 0.20$	0.43	ASC = 0.11 CDI = 0.2 MWD = 0.59	350
21	$D = 0.07(CDI) + 0.031(MWD^2) - 0.001(SSI) + 0.13$	0.42	CDI = 0.126 $MWD^2 = 0.59$ SSI = – 0.019	350
22	$D = 0.32(WP) - 0.072(CDI) - 0.003(SSI) - 0.009(ASC) - 0.1$	0.53	CDI = – 0.13 SSI = – 0.12 ASC = – 0.19 MWD = 0.73	350
23	$D = 0.15(MWD) - 0.003(SSI) - 0.005(ASC) + 0.012$	0.52	SSI = – 0.13 ASC = – 0.122 MWD = 0.73	350

MWD = Mean weight diameter, ASC = Aggregate silt and clay, CDI = Clay dispersion index SSI = Soil structural index, NGN = Nigeria Naira (money)

Models Relating The Most Influential Soil Properties With 'D'

Models developed from the most influential physico-chemico-structural soil properties are shown in Table 8. Model 24 developed from water content at wilting point and mean weight diameter accounted for about 87 % ($R^2 = 0.865$) of the effect of variables on which 'D' was dependent (predictive accuracy). The model was most influenced by MWD^2 (B = 1.06), followed by WP (B = 0.61) whereas MWD^3 exerted a negative influence (B = – 0.47) on 'D'. Model 25 - developed from Ca, MWD and BD (chemico-physico-structural properties) indicated 91 % ($R^2 = 0.905$) predictive accuracy for 'D'. The effect of MWD (B = 0.49) was of the most positive influence of the three soil properties used to develop the model.

Criterion for Model Validation, Characterization of the Soils and Model Validation

Validation was performed on models with R^2 values ≥ 80% with data generated from 10 other soil samples as shown in Table 9. Table 10 shows that Model 2 predicted 'D' in 80 % of the other soil samples used as test soils with 97 % correlation between the predicted and measured 'D', model 11 and model 12 predicted 'D' in 70 %, Models 19 and 24 predicted 'D' in 60 % and 50 % of the test soils respectively while model 25 had the least prediction of 10 % for 'D'. Predicted 'D' for Models 2, 11 and 12 had a very strong correlation with measured 'D'(r = 0.97, 0.94 and 0.95 respectively), models 19 and 24 strongly correlated with measured 'D'(r = 0.76 and 0.65 respectively). In contrast, model 25 predicted 'D' weakly with 23 % correlation between the predicted and measured 'D'. The correlation between the predicted D (PD) and measured D (MD) for the respective models developed was not proportional to their coefficient of determination (R^2). Model 2 which predicted 'D' in the highest number of soils (80 %), had the lowest coefficient of determination ($r^2 = 0.80$) while model 25, with the least prediction of 'D' (10%) in the test soils, had a very high coefficient of determination ($R^2 = 0.91$). As R^2 values approach 1.0, it indicates that most of the soil properties on which 'D' is dependent have been captured in the model; this determines the predictive reliability of models. Model 2 predicted 'D' in soils of Irepodun, Moro and Ilorin with a precision of 100 % whereas it predicted 'D' with 50 % precision in soils of Ifelodun and Baruten. Model 11 predicted 'D' with 100 % precision in soils of Moro and Baruten and 50 % in soils of Ifelodun, Irepodun and Ilorin. Model 12 predicted 'D' with100 % precision in soils of Ifelodun, Moro, and Baruten and 50% in soils of Ilorin but failed to predict 'D' in soils of Irepodun. Model 19 predicted 'D' in 100 % of soils in Moro and Irepodun, 50 % in soils of Ifelodun and Ilorin, but failed to predict 'D' in soils of Baruten. Model 24 predicted 'D' in

100 % of soils in Ilorin, 50 % of soils in Ifelodun, Moro, and Irepodun and failed to predict 'D' in soils of Baruten. Model 25 only predicted 'D' in 50 % of soils from Moro. All the models predicted 'D' in at least 50 % of the soils from Moro.

Generally, the results in Table 10 show that the model based on physico-chemical properties (model 25) is a poor predictor of 'D' in the test soils, model based on physico-structural (model 24) and structural (model 19) properties are fair predictors of 'D', models based on physical properties (models 11 and 12) and chemical properties (model 2) were the best predictors of 'D'. However, between the models that best predicted 'D', the cost associated with model 2 was more than six times and four times higher than that of model 11 and 12 respectively. Therefore, based on associated cost, model 11 should be the choice model whereas based on versatility, it should be model 2.

Table 8. Models that relate the most influential soil properties to detachment energy (D)

Model number	Soil properties	Regression equation	Coefficient of determination (R^2)	Standardized Coefficient (B)	Associated cost per sample (NGN)
24	Physical and structural	$D = -0.034(MWD)^3 + 0.001(WP)^2 + 0,14 (MWD)^2 + 0.13$	0.87	$MWD^3 = -0.47$ $MWD^2 = 1.059$ $WP = 0.606$	300
25	Chemical, physical and structural	$D = 0.02(Ca) + 0.03(MWD^2) -0.07(BD^2) + 0.164$	0.91	$MWD^2 = 0.49$ $Ca = 0.325$ $BD^2 = -0.494$	450

MWD = mean weight diameter WP = wilting point, NGN = Nigeria Naira (money)

Table 9. Selected physico-chemical properties of soils of Kwara state used for model validation

Sample	Sand (%)	Silt (%)	Clay (%)	Texture	OM (%)	CEC (Cmol/Kg	pH
Ife 4	67.95	15.41	16.64	SL	0.81	68.75	8.6
Ife 5	68.18	17.76	14.063	SL	3.42	51.28	9.0
Moro4	75.14	12.95	11.91	SL	0.76	41.51	8.0
Moro5	70.71	13.31	15.98	SL	1.16	37.54	8.2
Ire4	85.31	6.30	8.39	LS	0.91	47.58	8.1
Ire 5	86.13	6.67	7.20	LS	1.03	54.52	8.3
Baru4	49.68	26.21	24.11	SCL	1.82	54.65	8.0
Baru5	60.50	17.96	21.55	SCL	1.38	45.49	8.3
ILN4	57.56	17.40	25.045	SCL	3.62	46.09	8.7
ILN5	86.72	7.41	5.87	LS	1.41	39.41	8.2

CEC= cation exchangeable capacity, OM= organic matter SL = sandy loam, LS = loamy sand, SCL = sandy clay loam Ire = irepodun, Ife = Ifelodun, Baru = Baruten and ILN = Ilorin

Table 10. Comparison between measured (md) and predicted (pd) aggregate detachment energy (d)

Sample Number		Model predicted 'D' (PD)					
	MD	Model 2	Model 11	Model 12	Model 19	Model 24	Model 25
Ife 4	0.13	0.19	0.09*	0.09*	0.15*	0.04	0.51
Ife 5	0.05	0.06*	0.09	0.05*	0.23	0.08*	0.33
Moro4	0.13	0.17*	0.17*	0.18*	0.11*	0.06	010*
Moro5	0.07	0.06*	0.07*	0.06*	0.04*	0.04*	0.01
Ire4	0.13	0.13*	0.07	0.05	0.12*	0.31	0.43
Ire 5	0.54	0.54*	0.68*	0.76	0.54*	0.58*	0.40
Baru4	0.08	0.14	0.07*	0.06*	0.67	0.29	0.46
Baru5	0.09	0.08*	0.09*	0.1*	0.21	0.04	0.27
ILN4	0.19	0.14*	0.06	0.04	2.56	0.17*	1.16
ILN5	0.07	0.06*	0.11*	0.04*	0.04*	0.04*	0.13
PSP (%)		80	70	70	60	50	10
C		0.97	0.94	0.95	0.76	0.65	0.23

MD = Measured detachment energy; PSP = Per cent of soils predicted; C (MD & PD) = Correlation(r) between measured and predicted D

Discussion

Variation in the soil properties used to develop models may be attributable to differences in agricultural land-use practices (Ameyan and Ogidiolu, 1989). Ahamefule et al., (2020) also reported differences in water transmission characteristics of the experimental soils due to parent materials (basement complex and sandstone) and land-use.

The relatively low 'D' values observed for Irepodun soils suggest they will be the most vulnerable to water erosion. Moro soils with the narrowest range of 'D' indicate less variability suggesting similar agricultural practices and soil-forming processes across the community.

The strong positive correlation between Ca and 'D' is attributable to the reported bridging role played by Calcium in the soil (Chan and Heenan, 1999). Similarly, Wuddivira and Camps- Roach (2007) reported that increase in soil structural stability following liming of soils results from strong bonds formed from Ca^{2+} bridges. Calcium also inhibits clay dispersion and soil aggregate breakdown by substituting primarily Na^{+} and sometimes Mg^{2+} in clay aggregate (Wuddivira and Camps- Roach, 2006). Hanke and Dick, (2017) reported that all soil flocculating (Mg, K and Ca) and binding agents (OM) were positively related to 'D'. However, according to Wuddivira and Camps-Roach (2006), high calcium content in the soil (calcareous soils), with low organic matter, could cause soil degradation (hard, dense surface crust), in which Ca^{2+} could displace acidic cations (Al^{3+} and Fe^{2+}) whose loss contributes to soil disaggregation. In soils with high pH, the concentration of acidic cations is usually low (Idowu, 2003). This was the reason for this study's negative correlation between soil pH and 'D'. Acidic cations (Al^{3+} and Fe^{2+}) are known as soil stabilizing agents. Romken et al, (1977) reported that iron stabilized soil aggregates in the temperate region and suggested that it should be included in models for the prediction of potential erodibility of soils.

The negative influence of Na^{+} on the soil is due to its ability to disperse soil aggregates and accelerate their breakdown by impacting raindrops. Warrence et al, (2002) reported that Na^{+} caused soil dispersion, clay platelets, and aggregate swelling by disrupting the force that binds clay particles together when they come in- between clay particles and bring about separation that leads to swelling of clay particles and soil dispersion. Thus, sodium in the soil leads to soil aggregates breaking down.

The positive correlation between OM and 'D' corroborates the report of Mbagwu and Bazzoffi, (1998) and Idowu, (2003) that organic matter relates positively with 'D'. The organic carbon pool of the soil is unarguably the most significant component of the soil influencing soil structure (Bullock, 2005) by binding the soil particles into bigger and stable aggregates (Picolo and Mbagwu, 1999). However, the non-significant positive correlation between OM and 'D' could be attributable to the low content of the soil organic matter. For organic matter to significantly affect soil structure, it should make up about10 % of the overall soil (DeBoodt, 1985). The organic matter content in the studied soils ranges between 0.38 to 3.65% and, therefore, is not expected to significantly correlate with 'D'. In addition, the binding potential of organic matter could be suppressed by the high pH recorded in the study soils (7.6 - 9.0).

Soil with high pH has low concentration of $Fe^{2+}$and Al^{3+} which reduces the effect of organic carbon pool on soil structural stability. Mbagwu and Bazzoffi (1998) submitted that in soils where the concentration of Fe^{2+} and Al^{3+} is low, the effect of organic matter in such soils is usually suppressed. Organic matter comprises two components responsible for soil aggregation: polysaccharides and humic substances. The polysaccharides cement soil particles by acting as glue in-between soil particles (Cheshire and Hayes, 1990). In contrast, humic substances interact with metallic ions, oxides (Iron and Aluminum), and hydroxyl to form water stable aggregates (Oades, 1989).

Moderate correlation of K^+ and Mg^{2+} with 'D' is due to their ability to reinforce soil aggregates by inducing clay flocculation (Levy and Torrento, 1995), in addition, Mg^{2+} also neutralizes the phenolic acids and clay-dispersing polycarboxyls produced during the decomposition of organic substances in the soil (Oades, 1990; Emerson, 1983). Weak correlation between CEC and 'D' might be due to hydration of the cations. Nweke and Ijeh (2017) observed that CEC had less influence on wet than dry aggregate stability.

The correlation between sand and clay with 'D' corroborates the results of Bruce-Okine and Lal (1975) and Mbagwu and Bazzoffi (1998) that soil erodibility varied directly with sand but inversely with clay. Schoonover and Crim (2015) suggested that particles of sand are relatively easy to detach due to a lack of cohesiveness, while clay particles are difficult to detach since they readily bond together. On the other hand, there has been discordant reports on the relationship between silt and 'D', Igwe et al, (1995) are among the authors that reported a positive correlation which is consistent with the findings of this study; nevertheless, it was reported that certain amount of clay, silt and very fine sand are needed for the formation of good soil aggregate (Norhayati and Verloo, 1984).

The observation that porosity was positively ($r = 0.73$) correlated to 'D' whereas bulk density was negatively (-0.73) correlated indicates that as porosity increases, particularly with increasing organic matter content, soil particles become less prone to detachment and transportation by runoff as more water sinks. However, the case is reversed when the soil bulk density increases. Idowu (2003) gave possible reasons for an inverse relationship between bulk density and 'D'. He posited that continuous soil tillage results in soil compaction (which increases bulk density) and low organic matter content, leading to low soil aggregate stability. Mbagwu and Bazzoffi (1998) however, reported a contrary finding in which aggregate stability correlated positively with bulk density and negatively with porosity.

The positive correlation of water content at wilting point with 'D' was similarly reported by Mbagwu and Bazzoffi (1998), the authors surmised that this may be attributable to the impact of clay in the soil. Muawia (2013) established that increasing clay content will increase the soil moisture content due to its affinity for water. These last two authors held that the impact of clay is more pronounced in dry soils than in moist soils. In addition, Idowu (2003) reported that due to its high affinity for water, organic matter also contributes to moisture content determination, especially air-dry moisture content. This background, therefore, reaffirms that high moisture content in the soil suggests high organic matter and/or clay content.

The strong positive correlation of MWD to ‘D’ is the leverage in their interchangeable use for estimating of soil aggregate stability. The non-significant correlation of ASC and CDI with ‘D’ is premised on the fact that for CDI and ASC to show a significant effect on ‘D’, maximal dispersion of soil is required; this may, however, not have been achieved due to the dominant impact of calcium (an anti-dispersant) in the study soils.

The inverse relationship observed between ‘K’ and ‘D’ had earlier been reported by De Vleeschauwer et al., (1978) and Mbagwu, (1993), the authors had reported that ‘D’ could be used to evaluate soil susceptibility to erosion. Soil erodibility (K) explains the intrinsic susceptibility of a soil to breakdown by erosive raindrops and runoff, and it is the inverse of ‘D’.

The presence of bulk density in most models (particularly model 11 and 12) relating soil physical properties to ‘D’ highlights the importance of bulk density in the predicting aggregate stability. Some reports indicate that an increase in the bulk density of the soil result in the sealing of the soil’s surface which give rise to low infiltration leading to surface runoff and soil loss (Towhid, 2013).

Models with R^2 values ≥ 80 % were chosen for validation to ensure high precision in the models that would be subsequently recommended. However, Mbagwu and Bazzoffi (1998) had earlier chosen models with R^2 values ≥ 75 % for validation.

The fairly wide variation in the soil properties that was used for the development (Table 2) and validation (Table 9) of models 2, 11 and 12 and their good prediction of ‘D’ suggest: (1) that they may find applicability in similar soils where similar data is available and (2) that they may also be applied in a wide variety of other soils with similar intrinsic properties. In the same vein, the high multiple of soil properties associated with past models for predicting ‘D’, which made such models cumbersome, has been drastically reduced in the models derived in this study. This feat reduces time and financial inputs/resources needed, making these models deployable during economic booms and lean (post COVID-19). Be that as it may, these models will need re-validation across a range of other soils since the models were developed from a correlation and regression approach. These approaches adopted for this study may not guarantee similar levels of prediction in other soils when the values obtained for their properties do not fall within the range used for the models here-in developed.

Conclusions

This study concludes that: (1) the detachment energy of the soils of Kwara state, Nigeria (a typical Guinea Savanna soil) is low which predisposes soils of this area to erosion. (2) The Ca content of the study soils is the most critical soil property which determines 'D' (3) Based on associated cost, model 11 should be the model of choice, suitable for the predominantly peasant and resource poor farming population in the study area. In contrast, based on versatility, it should be model 2, which gives comparatively better prediction across all the study locations (4) All the models (beyond 2, 11 and 12) tested were at least fairly suitable for predicting 'D' in soils of Moro (5) The most important physico-structural soil properties relating to the prediction of 'D' mean weight diameter and bulk density, and (6) The models developed can also be used to determine potential erosion risk of other similar soils, particularly those in the southern Guinea agro-ecological zone of Nigeria.

Conflict of Interest Statement

Authors declare no conflict of interest

Authors Contribution

The authors contributed equally

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