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RESEARCH ARTICLE

Soil physical properties and hydrological indices to predict saturated hydraulic conductivity in agricultural terraces in the Mixteca region of Oaxaca, Mexico

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ABSTRACT

The saturated hydraulic conductivity (K_s) is a key parameter for understanding water movement in soil. This property is closely linked to the physical properties of the soil and affects crop management for better development and productivity. In the Mixteca region of Oaxaca, Mexico, pre-Hispanic agricultural terraces are built in the beds of intermittent streams, known as Lama-Bordo Systems (LBS). The LBS helps trap suspended sediments, creating agricultural surfaces. The objective of this study was to correlate soil physical properties and hydrological indices to create a predictive model for estimating K_s, which contributes to its determination in areas with similar sedimentary deposition conditions such as the LBS. Observed mean K_s was 4.26 cm ha^{-1}, ranged from 1.00 to 11.49 cm ha^{-1}, while for calculated K_s the mean was 4.50 cm ha^{-1} and ranged from 0.59 to 14.80 cm ha^{-1}. Finally, the clay fraction, bulk density, organic matter content, and stream power index (SPI) allowed for estimating K_s with an 82% reliability level. These findings highlight the relevance of soil physical properties in the capacity for water storage and flow, and consequently, in agricultural productivity.

Key words: Gully agriculture, sediment transport index, sediments, stream power index, topographic wetness index.

INTRODUCTION

Soil is the foundation of agriculture (Prashar and Shah, 2016). Its physical properties allow for the establishment of criteria for sustainable management. These properties include texture, internal drainage, aeration, structure, bulk density, erodibility, and aggregate stability (Haruna et al., 2020). Furthermore, soil texture, structure, and compaction influence water infiltration, available moisture, gas exchanges, root penetration, erosion susceptibility, and water and air movement, as well as solute transport (Rabor et al., 2018; Usowicz and Lipiec, 2021). Simultaneously, aggregate stability indicates organic matter content, biological activity, nutrient cycling, and erosion susceptibility (Haruna et al., 2020; Dong et al., 2021).

Consequently, soil physical properties significantly impact plant growth and crop management practices, such as irrigation, fertilization, drainage, and tillage. Over time, tillage increases bulk density, reducing available water capacity and hydraulic conductivity (Arnhold et al., 2015). As Arnáez et al. (2015) mentioned, terraces increase water infiltration and reduce surface runoff, decreasing sediment transport.

On the other hand, hydrological indices, such as the topographic wetness index (TWI), stream power index (SPI), and sediment transport index (STI), are key indicators for analyzing surface water movement in soil. These indices are associated with soil particle detachment and transport, sediment deposition, and water flow accumulation (Bannari et al., 2017).

In southern Mexico, the Mixteca region of Oaxaca is a mountainous area with rugged topography (Santiago-Mejía et al., 2024). In this area, the Lama-Bordo system (LBS), an agricultural terrace type, was constructed in streams or riverbeds. This system allows for the capture of sediments in alluvium, controls erosion in the channels, and improves water availability for dryland farming. Several studies report that this region faces serious soil erosion issues, linked to its geological origin (the bottom of ancient bodies of water) and exacerbated by primary activities on the slopes, such as deforestation, agriculture, and grazing (Palacio et al., 2016; Santiago-Mejía et al., 2018).

In the face of regional challenges such as soil degradation, high sediment transport, insufficient rainfall to satisfy the water requirements of maize, and the lack of permanent streams or springs (Santiago-Mejía et al, 2024), the Mixtec civilization developed the LBS. These systems were created to retain the most fertile soil, which is transported from the slopes, and conserve the gully's moisture, proving to be an effective alternative for agricultural production, and the effectiveness of these systems endures to this day (Palacio et al., 2016; Santiago-Mejía et al., 2024).

The LBS consists of stone or soil walls established perpendicular to the flow in natural channels to retain soil and store moisture, creating terraces designated for food production. These are considered agricultural terraces in intermittent channels (Pérez, 2016; Santiago-Mejía et al., 2024) and are common in mountainous regions (Arnáez et al., 2015). In these systems, the importance of alluvium is highlighted for its ecological functionality in recovering sediments to establish crops and capture moisture, particularly in areas where agricultural production conditions are unfavorable.

This study aimed to develop a predictive model to estimate the saturated hydraulic conductivity (K_s) of soils in the LBS of the Mixteca Alta of Oaxaca, based on the physical properties of alluvium and the hydrological indices in their microbasins, as a preliminary work to identify the behavior and correlation of these variables.

MATERIALS AND METHODS

Study area

The microbasins of the Lama-Bordo Systems (LBS) are situated in the Mixteca Alta region, Oaxaca, Mexico, between the coordinates 17°30'00"-17°36'00" N and 97°12'00"-97°17'00" W (Figure 1). These microbasins converge in the municipalities of Asunción Nochixtlán, Santa María Chachoápam, and San Juan Yucuita. According to Köppen's climate classification, modified by García (2004), there are two types of climates: Semi-arid temperate with an average annual temperature between 12 and 18 °C with summer rains (BS1kw), and temperate, subhumid, with an average annual temperature between 12 and 18 °C, with summer rains (C(wo)). The predominant soil types are Litosol and Feozem (INEGI, 2005).

Soil sampling

Using directed sampling, soil samples were collected from 21 sites within the LBS, each weighing 1 kg, and taken from the stratum of 0.0 to 30.0 cm depth, to analyze their physical properties. The samples were transported in properly labeled plastic bags. To estimate bulk density and saturated hydraulic conductivity, one sample for each property was taken using polyvinyl chloride (PVC) tubes with a diameter of 7.62 cm and a length of 10 cm, to ensure minimal disturbance to the soil.

Analysis of physical properties of alluvium

The laboratory analyses conducted on each soil sample were texture, bulk density (BD), saturated hydraulic conductivity (K_s), field capacity (FC), permanent wilting point (PWP), and organic matter (OM). Table 1 presents the methods used to determine the values of each property analyzed. The available water capacity (AWC) was calculated by subtracting the PWP from FC.

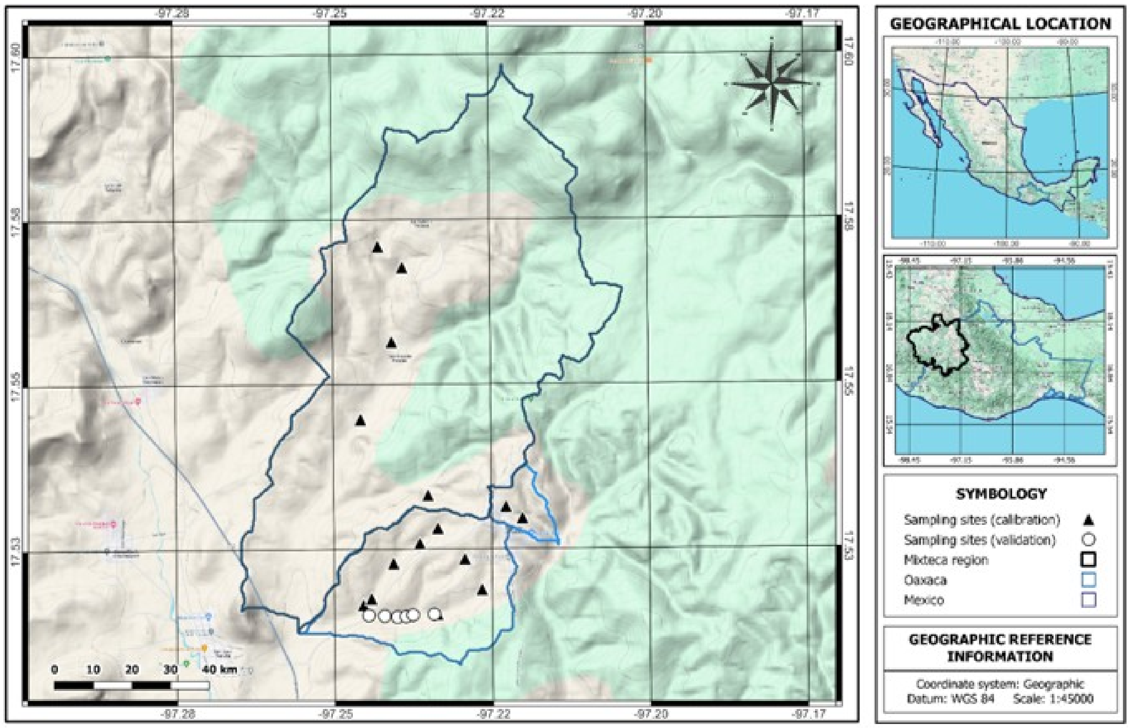

Figure 1. Location of soil sampling sites for the Lama-Bordo Systems.

Table 1. Methods used to determine the physical properties of Lama-Bordo Systems soils.

Property	Method
Texture, %	Bouyoucos method (Bouyoucos, 1962)
Bulk density, Mg m^{-3}	Modified cylinder method (PVC tubes)
Saturated hydraulic conductivity, cm h^{-1}	Constant head permeameter (Klute and Dirksen, 1986)
Field capacity, %	Pressure chamber (Klute, 1986)
Permanent wilting point, %	Pressure chamber-membrane (Klute, 1986)
Organic matter, %	Walkley and Black method (Walkley and Black, 1934)

Estimation of hydrological indices

Three hydrological indices were estimated for the microbasins that make up each sampling site: Topographic wetness index (TWI), stream power index (SPI), and sediment transport index (STI). To calculate these indices, the Mexican Elevation Continuum 3.0 was used (Instituto Nacional de Estadística y Geografía (INEGI), Aguascalientes, México), which underwent hydrological correction following the method proposed by Wang and Liu (2006). Subsequently, the slope matrix image in degrees and the specific catchment area, which allowed the estimation of hydrological indices through the WhiteboxTools v.2.0, tool, which is a complement for the QGIS program version 3.20.2. (QGIS, 2023), which uses the following equations.

Topographic wetness index (TWI), proposed by Beven and Kirkby (1979), quantifies the tendency of water distribution in the soil that is affected by topography (Equation 1):

$$\mathrm{TWI} = \mathrm{Ln}\left(\frac{A_s}{\tan(\beta)}\right) \qquad (1)$$

where A_s is the specific catchment area and β is the slope (°).

Stream power index (SPI), proposed by Moore et al. (1991), measures the erosive power of surface flow and is directly proportional to the stream power (Equation 2):

$$\mathrm{SPI} = {A_s}^{p} * \tan(\beta) \qquad (2)$$

where p is an exponent that controls the relationship between the contributing area and the discharge.

Sediment transport index (STI), proposed by Moore et al. (1991), predicts erosion at a specific point in the landscape and is a component of the Universal Soil Loss Equation (Equation 3):

$$\mathrm{STI} = (\mathrm{n} + 1) * \left(\frac{\mathrm{A_s}}{22.13}\right)^{\mathrm{n}} * \left(\frac{\mathrm{sen}(\beta)}{0.0896}\right)^{\mathrm{m}} \quad (3)$$

where n is 0.4 and m is 1.3.

Statistical analysis

The statistical analysis of data was conducted using RStudio, version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria), where descriptive statistics were calculated: Minimum, maximum, mean, standard deviation, and coefficient of variation. The assumptions of normality and homogeneity of variances were assessed using the Shapiro-Wilk and Levene tests, respectively. Normality was not met for three properties (silt, BD, and AWC), so an inverse transformation of the data was applied.

Simple linear regression models were evaluated to explain the relationship between the hydrological indices and individual physical properties. Furthermore, multiple linear regression models were executed to predict K_s. The backward stepwise method was employed, selecting the variables that best explain K_s. Initially, all analyzed soil properties were considered, and one variable at a time was eliminated based on the lowest statistical significance and the least contribution to R^2. The process ended when the remaining predictors produce a significant reduction in R^2. To validate the results, the assumptions of the final multiple linear regression model were checked. Normality was assessed using the Shapiro-Wilk test, heteroscedasticity with the Breusch-Pagan test, and multicollinearity with the variance inflation factor (VIF) test.

RESULTS AND DISCUSSION

Soil physical properties analysis

Five soil physical properties (texture, bulk density, saturated hydraulic conductivity, available water capacity, and organic matter) were analyzed, and three hydrological indices (sediment transport index, topographic wetness index, and stream power index) were calculated to evaluate their behavior along the Lama-Bordo Systems (LBS). Larger soil particles are anticipated to settle in the higher areas, resulting in higher saturated hydraulic conductivity (K_s) at the heads of the LBS. According to the coefficient of variation, bulk density (BD) did not show significant changes between the sampling points for the LBS. In contrast, K_s exhibited the greatest variation among all samples (Table 2).

Texture. The predominant soil texture classes in the LBS are clay loam (33%) and sandy clay loam (29%), and to a lesser extent, loamy, clayey, and silty clay loam soils are also found. Overall, clay loam soils predominate in the LBS. Given that the LBS is a set of agricultural terraces, Stavi et al. (2019) mention that loamy soil texture increases the risk of terraces' failure along with slope, terrace position, and vegetation cover.

Bulk density. The BD in the LBS ranged from 0.81 to 1.18 Mg m^{-3}, with a mean of 1.04 Mg m^{-3}. The LBS soils are very loose according to FAO classification, which considers BD and clay percentage. For agricultural terraces, reported values ranged from 1.02 to 1.38 Mg m^{-3} (Cucchiaro et al., 2021) and 1.29 to 1.65 Mg m^{-3} (Kercheva et al., 2017). These values are slightly higher than those found in the LBS studied. Consequently, the porosity percentage in the LBS was found to range from 55.33% to 69.57%.

Saturated hydraulic conductivity. The K_s in the LBS varied from 1.00 to 11.49 cm h^{-1} (slow to rapid rates). Pérez (2016) affirms that the formation of agricultural terraces enhances water infiltration, allowing the soil to remain moist for longer periods compared to soils with steeper slopes (Arnáez et al., 2015). Other studies on agricultural terraces report values from 2.6 to 3.3 cm h^{-1} (Kovář et al., 2016) and from 8.11 to 30.34 cm h^{-1} (Lamourou et al., 2021). A high variation between the ranges and greater statistical variability corresponds to the high coefficient of variation in the LBS. This is explained by considering K_s as an elusive property, as noted by Rienzner and Gandolfi (2014).

Table 2. Descriptive statistics of the physical properties of the soil in Lama-Bordo Systems in Nochixtlán, Oaxaca, Mexico. BD: Bulk density; K_s: saturated hydraulic conductivity; AWC: available water capacity; OM: organic matter; STI: sediment transport index; TWI: topographic wetness index; SPI: stream power index; K_{sp}: predicted saturated hydraulic conductivity.

Sites	Clay	Sand	Silt	BD	K_s	AWC	OM	STI	TWI	SPI	K_{sp}
	%	%	%	Mg m^{-3}	cm h^{-1}	%	%				
1	40.00	32.92	27.08	1.07	4.44	13.12	1.08	2.45	7.01	8.66	3.07
2	24.00	42.50	33.50	1.17	1.30	10.73	1.08	0.61	7.95	5.58	1.81
3	26.00	29.30	44.70	1.18	2.56	11.79	1.34	1.22	8.56	11.19	0.75
4	26.00	40.56	33.44	0.81	11.49	10.59	0.67	7.82	9.31	130.41	14.80
5	30.00	39.86	30.14	1.00	2.91	12.03	1.75	2.61	8.81	26.96	5.58
6	34.00	32.68	33.32	1.12	2.11	12.64	1.08	11.66	8.99	175.14	2.69
7	44.00	23.74	32.26	1.07	1.53	8.26	1.21	4.03	8.99	83.29	2.52
8	24.00	51.20	24.80	1.03	10.12	13.73	0.67	9.12	8.68	228.53	7.96
9	40.00	31.44	28.56	1.00	4.48	9.51	2.15	3.87	8.35	59.17	3.61
10	26.00	39.92	34.08	1.10	2.22	9.88	0.67	3.64	6.14	10.05	4.67
11	36.00	23.40	40.60	1.18	1.00	10.11	1.34	1.58	7.86	8.20	0.59
12	38.00	27.20	34.80	1.04	3.87	10.72	1.61	6.30	8.90	97.11	3.64
13	28.00	53.52	18.48	1.03	5.16	8.92	2.29	3.75	8.73	64.81	3.96
14	32.00	45.62	22.38	1.12	2.50	9.04	0.94	7.33	9.39	284.27	3.54
15	28.00	55.84	16.16	0.99	3.62	8.54	2.42	24.32	7.68	145.09	5.31
16	30.00	51.94	18.06	1.10	1.87	7.84	2.02	10.79	7.88	66.09	1.84
17	32.00	51.04	16.96	0.89	7.08	8.21	2.69	8.41	7.26	56.60	7.38
18	56.00	7.28	36.72	1.03	2.17	6.50	1.08	0.33	6.64	0.48	2.26
19	34.00	15.10	50.90	0.99	7.96	7.74	0.67	1.72	8.84	37.22	7.40
20	42.00	22.30	35.70	1.03	2.12	23.79	2.15	5.28	7.59	19.51	2.22
21	36.00	20.92	43.08	0.94	8.89	11.11	2.96	5.89	9.71	1442.97	8.90
Minimum	24.00	7.28	16.16	0.81	1.00	6.50	0.67	0.33	6.14	0.48	0.59
Maximum	56.00	55.84	50.90	1.18	11.49	23.79	2.96	24.32	9.71	1442.97	14.80
Mean	33.62	35.16	31.22	1.04	4.26	10.71	1.52	5.84	8.25	141.02	4.50
± SD	7.89	13.66	9.47	0.09	3.08	3.56	0.71	5.37	0.95	308.29	3.33
CV, %	23.47	38.86	30.34	8.94	72.25	33.21	46.81	91.85	11.48	218.62	74.01

Available water capacity. The mean available water capacity in the LBS varied from 6.50% to 23.79%. This variable regulates both the physical environment of plant roots and the chemical and biological conditions of the soil (Román Dobarco et al., 2019). Soil moisture plays a crucial role in productivity and C flow, governing organic matter decomposition, as Sierra et al. (2015) noted.

Organic matter. Organic matter (OM) in the LBS ranged from 0.67% to 2.96%, averaging 1.52%. Overall, the sampled soils are considered moderately poor in OM. Some similar agricultural terraces report values of 2.395%, where the age of the terraces influences the OM content (Santiago-Mejía et al., 2018).

Behavior of physical properties concerning hydrological indices

Simple linear regression analysis revealed that texture has the highest correlation with sediment transport index (STI), particularly sand and silt, as the proportion of sand increases alongside this index, while the proportion of silt decreases (Figure 2). Zhang et al. (2020) studied eroded sediments and found that sand and silt predominated, which is consistent with the results of the present study. The cohesion between soil particles can explain this relationship; sand with its smaller specific surface area, exhibits lower cohesion than silt and clay, which have a stronger attractive force between particles. Consequently, higher STI values often correspond with lower percentages of clay and silt in the soil. Additionally, the slope of the land also influences this relationship; increased slope heightens drag forces, which in turn increases shear stress in the channel bed.

The topographic wetness index (TWI) and K_s exhibited a positive linear relationship (Figure 3), supporting the findings of Yi et al. (2017). Higher TWI values suggest that the soil is more likely to become saturated; consequently, if the soil contains a high moisture content, K_s will reduce its infiltration volume, increasing runoff.

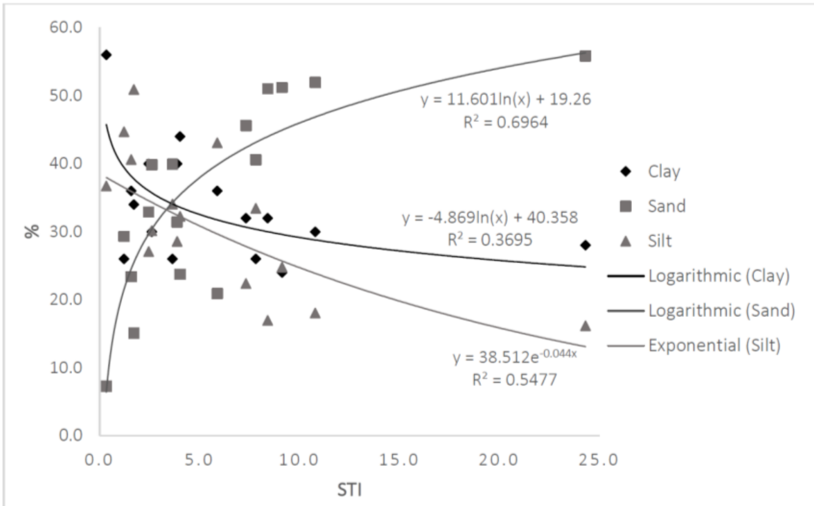

Figure 2. Relationship between clay, sand, and silt fractions and the sediment transport index (STI).

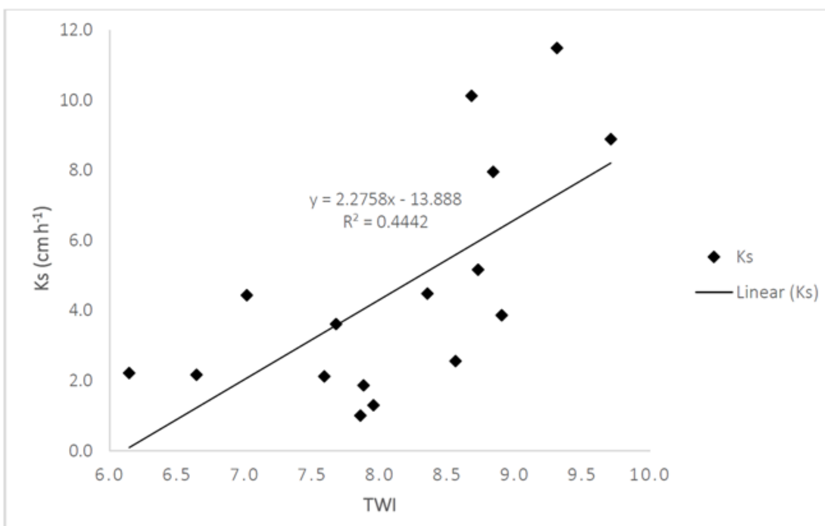

Figure 3. Relationship between saturated hydraulic conductivity (K_s) and the topographic wetness index (TWI).

Figure 4 illustrates the relationship between K_s and stream power index (SPI), indicating that as the risk of soil erosion and stream power (especially of finer particles) increase, the value of K_s also rises, as stated by Stewardson et al. (2016). The logarithmic trend line indicates that at lower SPI values, increases in K_s are significant, suggesting that the soil facilitates the passage of larger volumes of water and, as it becomes saturated and the SPI value rises, K_s tends to reach its maximum values.

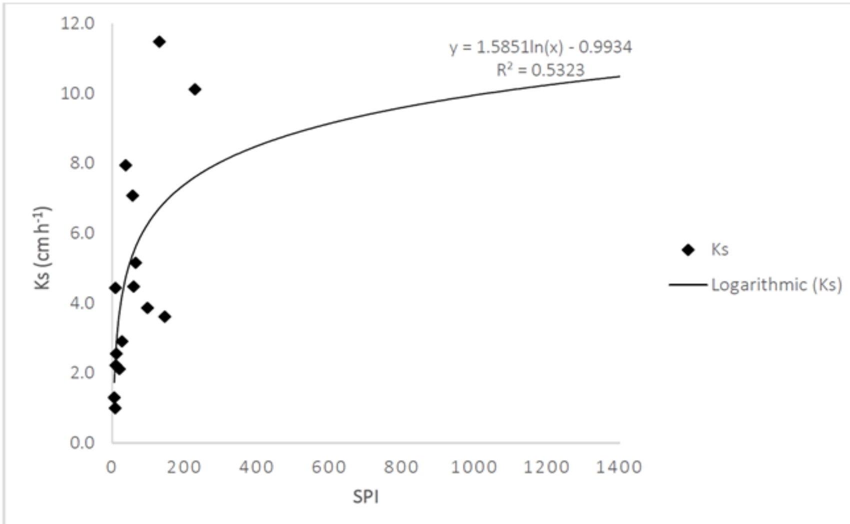

Figure 4. Relationship between saturated hydraulic conductivity (K_s) and the stream power index (SPI).

Model for estimating K_s: Calibration and validation

The predictive model for K_s was developed using data from sites 7-21 (Table 2). Initially, five physical properties and three hydrological indices were considered for estimating K_s. However, after performing multiple linear regression analysis with the "backward stepwise elimination method", the final model was established with four parameters: Clay, BD, OM, and SPI, as shown in Table 3.

Table 3. Multiple linear regression analysis of the physical parameters and hydrological indices of the Lama-Bordo Systems soil. SE: Standard error; BD: bulk density, OM: organic matter, SPI: stream power index. Significance level: *0.05, **0.01, ***0.001.

	Coefficient	SE	t	p >|t|
Intercept	46.363421	7.614801	6.089	0.000117***
Clay	-0.132816	0.046960	-2.828	0.017903*
BD	-33.674377	6.519672	-5.165	0.000422***
OM	-1.835473	0.626719	-2.929	0.015074*
SPI	0.003052	0.001193	2.558	0.028489*

The coefficients obtained from the multiple linear regression model enabled the construction of the final model to predict K_s in the LBS:

$$K_s = 43.363421 - 0.132816 \times \text{clay} - 33.674377 \times \text{BD} - 1.835473 \times \text{OM} + 0.003052 \times \text{SPI}$$

The values obtained for the parameters clay, BD, OM, and SPI explain 82% of the observed variability in the K_s of the LBS soil (R^2 = 0.8248 and adjusted R^2 = 0.7547). The p-value of 0.0008463 confirms the model's statistical significance, supporting its reliability for estimating this property in LBS soils.

The model was validated using data from sites 1-6 (Table 2). Table 4 presents a simple linear regression analysis comparing the observed and predicted K_s values, yielding a p-value of 0.004998. This result indicates that both variables are significant, thus validating the model for predicting K_s at the evaluated sites. In Table 2 it is observed that the predicted K_s (K_{sp}) has a mean of 4.50 cm ha^{-1} similar to the observed K_s of 4.26 cm ha^{-1}.

Table 4. Simple linear regression analysis for model validation. Significance level: *0.05, **0.01, ***0.001. SE: Standard error; K_s: saturated hydraulic conductivity.

	Coefficient	SE	t	p >|t|
Intercept	0.8685	0.8195	1.060	0.349
Observed K_s	0.6831	0.1220	5.598	0.005**

Figure 5 illustrates the linear regression with an $R^2 = 0.8868$ and the corresponding confidence interval. This value indicates a robust model fitting, suggesting a high reliability for estimating K_s in the LBS.

Previous studies have investigated the properties that contribute to predicting K_s. Some authors report the influence of BD, texture, land use, soil moisture, OM and organic C content, particle diameter, and soil horizon (Jorda et al., 2015; Stewardson et al., 2016). Among these factors, BD and texture have been the most frequently cited, aligning with the variables included in the predictive model developed in this study.

Considering that K_s is highly variable and challenging to predict (Jorda et al., 2015), it is recommended that the model developed in this study be applied under conditions similar to those reported to ensure its accuracy and reliability.

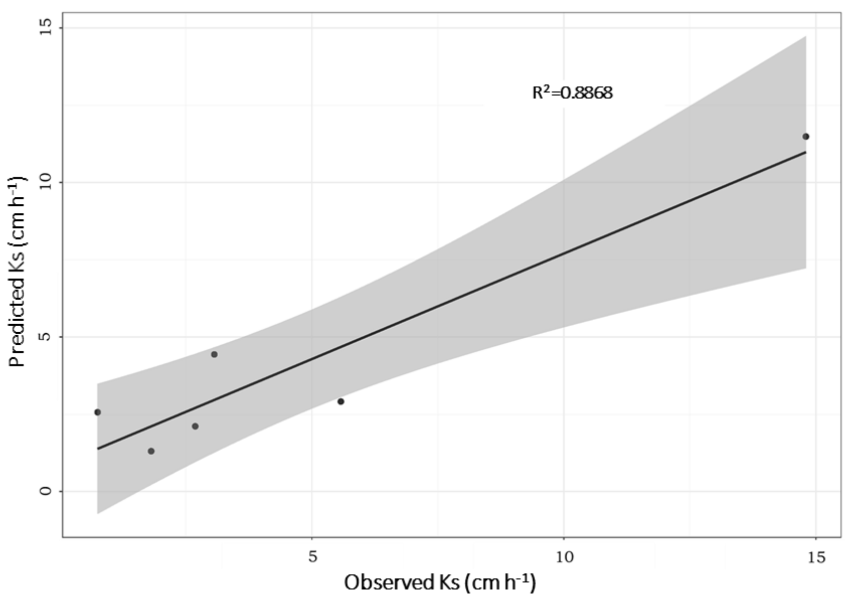

Figure 5. Linear regression of observed and predicted saturated hydraulic conductivity (K_s).

CONCLUSIONS

In the evaluated Lama-Bordo Systems (LBS), the soils exhibit clay loam and sandy clay loam textures, with an appropriate bulk density that does not restrict crop root development, providing high porosity and facilitating water movement in the soil. Although the saturated hydraulic conductivity varied significantly, it remained within an acceptable range for agricultural production. However, the low organic matter content in the soils suggests a limitation in nutrient availability for the crops.

The proposed model, which includes clay content, organic matter, bulk density, and stream power index, demonstrated a statistical reliability of 82% in predicting saturated hydraulic conductivity in soils with similar characteristics to those present in the LBS of the Mixteca. These findings highlight the importance of soil physical properties in water storage and flow capacity, which has a direct effect on water availability for crops and, consequently, on the agricultural productivity of LBS.

Author contribution

Conceptualization: B.E.S.M., D.S.F.R. Methodology: B.E.S.M., D.S.F.R., A.L.P. Software: B.E.S.M., A.L.P. Validation: B.E.S.M., D.S.F.R. Formal analysis: B.E.S.M., D.S.F.R., A.L.P. Investigation: B.E.S.M., D.S.F.R. Resources: B.E.S.M., D.S.F.R. Data curation: B.E.S.M. Writing-original draft: B.E.S.M., D.S.F.R. Writing-review & editing: B.E.S.M., D.S.F.R., A.L.P., M.A.B.G., J.P.V., J.U.A.R. Visualization: B.E.S.M., D.S.F.R., A.L.P., J.U.A.R. Supervision: D.S.F.R., M.A.B.G., J.P.V. Funding acquisition: B.E.S.M., D.S.F.R. All co-authors reviewed the final version and approved the manuscript before submission.

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References

Arnáez, J., Lana-Renault, N., Lasanta, T., Ruiz-Flaño, P., Castroviejo, J. 2015. Effects of farming terraces on hydrological and geomorphological processes. A review. Catena 128:122-134. doi:10.1016/j.catena.2015.01.021.

Arnhold, S., Otieno, D., Onyango, J., Kollner, T., Huwe, B., Tenhunen, J. 2015. Soil properties along a gradient from hillslopes to the savanna plains in the Lambwe Valley, Kenya. Soil and Tillage Research 154:75-83. doi:10.1016/j.still.2015.06.021.

Bannari, A., Ghadeer, A., El-Battay, A., Hameed, N.A., Rouai, M. 2017. Detection of areas associated with flash floods and erosion caused by rainfall storm using topographic attributes, hydrologic indices, and GIS p. 155-174. In Pirasteh, S., Li, J. (eds.) Global changes and natural disaster management: Geo-information technologies. Springer, Cham, Switzerland. doi:10.1007/978-3-319-51844-2_13.

Beven, K., Kirkby, M. 1979. A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Journal 24(1):43-69. doi:10.1080/02626667909491834.

Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analysis of soils. Agronomy Journal 54:464-465. doi:10.2134/agronj1962.00021962005400050028x.

Cucchiaro, S., Paliaga, G., Fallu, D.J., Pears, B.R., Walsh, K., Zhao, P., et al. 2021. Volume estimation of foil stored in agricultural terrace systems: A geomorphometric approach. Catena 207:105687. doi:10.1016/j.catena.2021.105687.

Dong, L., Zhang, W., Xiong, Y., Zou, J., Huang, Q., Xu, X., et al. 2021. Impact of short-term organic amendments incorporation on soil structure and hydrology in semiarid agricultural lands. International Soil and Water Conservation Research 10:457-469. doi:10.1016/j.iswcr.2021.10.003.

García, E. 2004. Modificaciones al sistema de clasificación climática de Köppen. Universidad Nacional Autónoma de México, Instituto de Geografía, México D.F. Available at http://www.publicaciones.igg.unam.mx/index.php/ig/catalog/view/83/82/251-1 (accessed March 2022).

Haruna, S., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S., et al. 2020. Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences & Environment 3:20105. doi:10.1002/agg2.20105.

INEGI. 2005. Conjunto de datos edafológicos (Shape). Serie I. Escala 1:1,000,000. Instituto Nacional de Estadística y Geografía (INEGI), Aguascalientes, Mexico. Available at https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825267636 (accessed January 2022).

Jorda, H., Bechtold, M., Jarvis, N., Koestel, J. 2015. Using boosted regression trees to explore key factors controlling saturated and near-saturated hydraulic conductivity. European Journal of Soil Science 66:744-756. doi:10.1111/ejss.12249.

Kercheva, M., Sokolowska, Z., Hajnos, M., Skic, K., Shiskov, T. 2017. Physical parameters of Fluvisols on flooded and non-flooded terraces. International Agrophysics 31:73-82. doi:10.1515/intag-2016-0026.

Klute, A. 1986. Water retention: Laboratory methods. p. 635-662. In Klute, A. (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. American Society of Agronomy (ASA), Crop Science Society of America (CSSA), and Soil Science Society of America (SSSA), Madison, Wisconsin, USA. doi:10.2136/sssabookser5.1.2ed.c26.

Klute, A., Dirksen, C. 1986. Hydraulic conductivity and diffusivity: laboratory methods. p. 687-734. In Klute, A. (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. American Society of Agronomy (ASA), Crop Science Society of America (CSSA), and Soil Science Society of America (SSSA), Madison, Wisconsin, USA. doi:10.2136/sssabookser5.1.2ed.c28.

Kovář, P., Bačinová, H., Loula, J., Fedorova, D. 2016. Use of terraces to mitigate the impacts of overland flow and erosion on a catchment. Plant, Soil and Environment 62(4):171-177. doi:10.17221/786/2015-PSE.

Lamourou, H., Karbout, N., Zriba, Z., Moussa, M. 2021. Soil organic matter rate inside the Jessours soil in the Matmata Mountainous Region. p. 1237-1242. In Kallel, A., Ksibi, M., Ben Dhia, H., Khélifi, Nabil (eds.) Recent advances in environmental science from the Euro-Mediterranean and Surrounding Regions. Environmental Science and Engineering. Springer, Cham, Switzerland. doi:10.1007/978-3-030-51210-1_196.

Moore, I., Grayson, R., Ladson, A. 1991. Digital terrain modelling: A review of hydrological, geomorphological, and biological applications. Hydrological Processes 5(1):3-30. doi:10.1002/hyp.3360050103.

Palacio, J.L., Rosado, E., Ramírez, X., Oropeza, O., Cram, S., Ortiz, M.A., et al. 2016. Erosion, culture and geoheritage; case of Santo Domingo Yanhuitlán, Oaxaca, México. Geoheritage 8:359-369. doi:10.1007/s12371-016-0175-2.

Pérez, V. 2016. Terrace agriculture in the Mixteca Alta Region, Oaxaca, Mexico: Ethnographic and archeological insights on terrace construction and labor organization. Culture, Agriculture, Food and Environment 38(1):18-27. doi:10.1111/cuag.12062.

Prashar, P., Shah, S. 2016. Impact of fertilizers and pesticides on soil microflora in agriculture. p. 331-361. In Lichtfouse, E. (ed.) Sustainable Agriculture Reviews, vol. 19. Springer, Cham, Switzerland. doi:10.1007/978-3-319-26777-7_8.

QGIS. 2023. QGIS Geographic Information System. QGIS Association, Grüt, Switzerland. Available at http://www.qgis.org.

Rabor, E., Wiesmeier, M., Schlüter, S., Vogel, H.J. 2018. Soil structure as an indicator of soil functions: A review. Geoderma 314:122-137. doi:10.1016/j.geoderma.2017.11.009.

Rienzner, M., Gandolfi, C. 2014. Investigation of spatial and temporal variability of saturated soil hydraulic conductivity at the field-scale. Soil & Tillage Research 135:28-40. doi:10.1016/j.still.2013.08.012.

Román Dobarco, M., Cousin, I., Le Bas, C., Martin, M. 2019. Pedotransfer functions for predicting available water capacity in French soil, their applicability domain and associated uncertainty. Geoderma 336:81-95. doi:10.1016/j.geoderma.2018.08.022.

Santiago-Mejía, B.E., Fernández-Reynoso, D.S., López-Pérez, A., Bolaños-González, M.A., Palerm-Viqueira, J., Macedo-Cruz, A. 2024. Predictive model for the estimation of sediment volume captured by lama-bordo systems in the Mixteca Alta of Oaxaca, Mexico. Revista Chapingo Serie Ciencias Forestales y del Ambiente 30:1-17. doi:10.5154/r.rchscfa.2022.12.086.

Santiago-Mejía, B.E., Martínez-Menez, M.R., Rubio-Granados, E., Vaquera-Huerta, H., Sánchez-Escudero, J. 2018. Spatial variability of physical and chemical soil properties in a lama-bordo system in the High Mixtec region of Oaxaca, México. Agricultura, Sociedad y Desarrollo 15:275-288. doi:10.22231/asyd.v15i2.796.

Sierra, C., Trumbore, S., Davidson, E., Vicca, S., Janssens, I. 2015. Sensitivity of decomposition rates of soil organic matter with respect to simultaneous changes in temperature and moisture. Journal of Advances in Modeling Earth Systems 7:335-356. doi:10.1002/2014MS000358.

Stavi, I., Gusarov, Y. Halbac, R. 2019. Collapse and failure of ancient agricultural stone terraces: On-site geomorphic processes, pedogenic mechanisms, and soil quality. Geoderma 344:144-152. doi:10.1016/j.geoderma.2019.03.007.

Stewardson, M.J., Datry, T., Lamouroux, N., Pella, H., Thommeret, N., Valette, L., et al. 2016. Variation in reach-scale hydraulic conductivity of streambeds. Geomorphology 259:70-80. doi:10.1016/j.geomorph.2016.02.001.

Usowicz, B., Lipiec, J. 2021. Spatial variability of saturated hydraulic conductivity and its links with other soil properties at the regional scale. Scientific Reports 11:8293. doi:10.1038/s41598-021-86862-3.

Walkley, A., Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science 37(1):29-38. doi:10.1097/00010694-193401000-00003.

Wang, L., Liu, H. 2006. An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modelling. International Journal of Geographical Information Science 20(2):193-213. doi:10.1080/13658810500433453.

Yi, L., Zhang, W., Yan, C. 2017. A modified topographic index that incorporates the hydraulic and physical properties of soil. Hydrology Research 48(2):370-383. doi:10.2166/nh.2016.119.

Zhang, P., Yao, W., Liu, G., Xiao, P., Sun, W. 2020. Experimental study of sediment transport processes and size selectivity of eroded sediment on steep Pisha sandstone slopes. Geomorphology 363:107211. doi:10.1016/j.geomorph.2020.107211.