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Conversion of soil water infiltration rates between vegetated and non-vegetated land covers by using the Kostiakov-Lewis model

Conversão de taxa de infiltração de água em solo com e sem cobertura vegetal usando o modelo de Kostiakov-Lewis

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ABSTRACT

Soil water infiltration rates are essential for hydrological studies, planning and design of irrigation and drainage systems, among other applications. Various studies have been carried out in plots with and without vegetation cover, aiming to identify the influence of the cover on the water infiltration process in soil. However, a few works have addressed the relationship between infiltration rates of a plot with and without vegetation cover. Here we investigated the ability to iterate between infiltration rates with and without vegetation cover, seeking to identify potential correlations. We propose an innovative and easy-to-use empirical model that allows the conversion of infiltration rates in systems with vegetation cover into infiltration rates without coverage and vice versa. Altogether, we used a dataset comprising 142 rainfall simulation experiments under plots with and without cover, including 6 different types of soil and 18 types of land cover and management. The proposed model was based on the Kostiakov-Lewis model, presenting performance similar to other infiltration models, which is effective in a variety of planting and vegetation cover systems.

Keywords: Infiltration model; Infiltration rate; Rainfall simulator.

RESUMO

O conhecimento da taxa de infiltração de água no solo é fundamental para estudos hidrológicos, planejamento e projeto de sistemas de irrigação e drenagem, entre outras aplicações. Diversos trabalhos têm sido realizados em parcelas com e sem cobertura vegetal, objetivando identificar a influência da cobertura no processo de infiltração de água no solo. Porém, poucos trabalhos tem abordado a relação entre as taxas de infiltração com e sem cobertura vegetal. Avaliamos, neste trabalho, a capacidade de iteração entre as taxas de infiltração com e sem cobertura vegetal, buscando identificar potenciais correlações. O objetivo principal deste trabalho foi de propor um modelo empírico inovador, de fácil utilização, que permita a conversão de taxas de infiltração em sistemas com cobertura vegetal em taxas de infiltração sem cobertura e vice versa. A base de dados foi composta por 142 testes, sendo 71 testes com cobertura e 71 testes sem cobertura vegetal, compreendendo 6 diferentes tipos de solo e 18 tipos de coberturas e manejo. O modelo proposto tomou como base o modelo Kostiakov-Lewis, apresentando desempenho semelhante a outros modelos de infiltração, sendo eficaz em qualquer sistema de plantio e cobertura vegetal.

Palavras-chave: Modelo de infiltração; Taxa de infiltração; Simulador de chuva.

INTRODUCTION

Soil water infiltration rates are essential for hydrological studies, planning and design of irrigation and drainage systems, among other applications. Several studies have been carried out over the last decades to understand the influence of soil and plant management on the water infiltration process in soil (Rahman & Islam, 1989; Logsdon et al., 1993; Thierfelder et al., 2005; Castellini et al., 2019).

Water infiltration in soil can be measured in the field or estimated by empirical and/or theoretical mathematical models. Empirical models have the advantage of relating model parameters to soil characteristics, without requiring that they have physical significance, which in general leads to factors that are difficult to consider in theoretical models (Mirzaee et al., 2014). Several models have been developed in order to describe the water infiltration process in soil, among which we can mention the models proposed by Kostiakov (1932), Lewis (1937), Horton (1933), Philip (1957), Green & Ampt (1911).

After using the Kostiakov-Lewis, Horton and Philip models, Santos et al. (2016) observed that the Horton model was the most adequate to represent the behavior of water infiltration rates in Entisols (Fluvents) in Brazil. However, after evaluating the application of eight infiltration models, including the Kostiakov, Horton, Modified Kostiakov and Revised Modified Kostiakov models (RMK) in soils with different textural classes, Mirzaee et al. (2014) observed that the RMK and Kostiakov models showed better performance to predict the infiltration rate and accumulated infiltration rate, respectively. Thus, a model like Kostiakov-Lewis can be applied to a wide variety of soils.

After evaluating the Kostiakov-Lewis, Horton and Philip models, Almeida et al. (2018) concluded that the Horton model showed better efficiency, although it did not present the same performance in soils without vegetation cover, a situation better estimated by the Philip model. The authors also commented that the three models are acceptable. We must consider that the Kostiakov-Lewis model offers the advantage of being semiempirical, considering the final infiltration rate, whereas the Philip model is mathematical, not considering physical attributes. In addition, the Kostiakov-Lewis model is simpler than the Horton model (which depends on two physical attributes).

Comparative studies of the efficiency among infiltration models indicated the Kostiakov-Lewis model as one of the best to estimate the infiltration of water in soils (Araghi et al., 2010; Oliveira et al., 2018; Suryoputro et al., 2018). According to Oliveira et al. (2018), the model that stood out the most among 6 researched methods (Kostiakov, Horton, Philip, Kostiakov-Lewis, SCS e Swartzendruber) was the Kostiakov-Lewis, which presented an R^2 of 99.8% and a mean square error of 1.84%.

Suryoputro et al. (2018) concluded that in short periods of time the model that presented the best performance was the Kostiakov, followed by the Kostiakov - Lewis and Horton models, respectively. However, taking into account the disadvantage of the Kostiakov model, which showed a tendency for the infiltration rate to approach zero over long periods of time, the authors recommend using the Kostiakov model - Lewis or Horton, which adds the final infiltration rate parameter.

According to Almeida et al. (2018), in pasture plots, the Kostiakov-Lewis model showed a better fit. The Kostiakov-Lewis empirical model is used mainly in irrigation management and the equation is normally used to estimate the accumulated infiltration. According to Mirzaee et al. (2014), this model demonstrated good efficiency for both clayey and silty soils.

Various studies have been carried out in plots with and without vegetation cover, aiming to identify the influence of the soil cover in the process of water infiltration in the soil (Santos et al., 2016; Almeida et al., 2018). However, to the best of our knowledge, a few works have addressed the relationship between infiltration rates with and without vegetation cover. The possibility of iteration between the infiltration rates for the conditions with and without vegetation cover, opens up a gap to estimate water infiltration in soil after deforestation or burning. It would also be easier to predict the potential for runoff and erosion that can occur with vegetation removal. Not mentioning the fact that the model can be used with past data that the field plot no longer exists, obtaining new data from these plots. Furthermore, the gain in terms of increased infiltration with the recovery of degraded areas could also be easily estimated. In this sense, the proposed model can be used in forecastings and hindcastings studies related to soil water infiltration.

In this work, we evaluated the ability to iterate between infiltration rates with and without vegetation cover, aiming to identify the potential for correlation. The main objective was to propose an easy-to-use innovative empirical model, which allows the conversion of infiltration rates in land use and management systems with vegetation cover into infiltration rates without coverage and vice versa. To apply the proposed model, we must take an existing empirical model and determine the final infiltration rate, which can be obtained by simple field tests, such as the double ring infiltrometer test.

MATERIAL AND METHODS

Water infiltration tests in soil were carried out using a portable rainfall simulator, developed by Alves Sobrinho et al. (2008), in plots with and without vegetation cover, aiming to provide an iterative analysis between the results. The iteration between the data was based on the Kostiakov-Lewis model, chosen as the base model.

Criteria used for developing the model: (i) We look for factors that, when added to the base model, can convert results from the infiltration tests performed with vegetation cover, to values corresponding to conditions without vegetation and vice versa. (ii) We aim to identify the factors that give results closer to those obtained in the field tests. (iii) The verification of the capacity of investigated factors in estimating the infiltration rates was made by the graphical comparison between the infiltration curves obtained by the field tests and the results from the investigation. (iv) Statistical metrics were used to verify the efficiency of the factors in the tested models.

Field testing procedures

To obtain the water infiltration rates in the soil needed for developing and calibrating the proposed model, the locations of the field tests were properly characterized according to the type of soil management and cultivation adopted (Table 1). The simulator tests were carried out in the municipality of Campo Grande, state of Mato Grosso do Sul (MS) and in the municipality of Sinop, state of Mato Grosso (MT) (Figure 1a). The predominant soil classes along the study sites were Oxisols and Entisols, which are commonly found in Brazil; the plots were deployed in the field following the terrain slope, which varied between 1.8% and 4.1%.

In Sinop, the tests were carried out on a crop-livestock integration system in the Caiabi River microbasin, a contributor to the Teles Pires River. In the municipality of Campo Grande, tests were carried out in four locations. At the Embrapa Beef Cattle (20 ° 24 '59" S and 54 ° 42 '34" W), where several management systems and soil cultivation were implemented: a rotational grazing system with *Panicum*; continuous grazing system of *Braquiária Decumbense*; continuous soybean crop system; integrated crop-livestock-forest production system. In the Guariroba Basin, the tests were carried out on pastures recovered with *Brachiaria Brizantha cv. Piatã* and *Stylosanthes ssp. vc.* and in traditional pasture with *Braquiária Decumbense*. The tests were also carried out in the urban area of the city of Campo Grande in permeable areas with vegetation cover that are close to buildings and urban roads; and in the Ribeirão Salobra Hydrographic Basin, tributary of the Aquidauana River, located about 50 km away from Campo Grande, characterized by a pasture area.

The rainfall simulator used operates with two parallel Veejet 80,150 nozzles that, positioned at 2.30 m in relation to the ground level and under service pressure of 35.6 kPa, produces drops with an average volumetric diameter of 2.0 mm (Figure 1b-1d). The test plot that receives the simulator's rainfall is delimited by galvanized steel sheets with a useful area of 0.70 m^2 (0.70 m wide by 1.0 m long). The tests were carried out initially with the vegetation cover. Afterwards, the vegetation was carefully removed using gardening scissors to avoid changes in the soil surface conditions, and avoiding the removal of the plant roots. A new infiltration test was then carried out on the plot without vegetation cover. This methodology, after a few changes, has been adopted in several previous studies (Almeida et al., 2018; Sone et al., 2019).

The field trial with the simulator lasted up to 60 minutes. The collection time for each runoff sample was 1 minute, performed at 2 minutes intervals after the runoff started. The equilibrium infiltration rate was obtained after observing the stabilization of the surface runoff, which usually occurs after 30 minutes after the beginning of the runoff.

Database construction

We used a database of infiltration tests in plots with and without vegetation cover, resulting from several field campaigns to validate the models (Table 1 and Figure 1a). Altogether, there were 142 tests, 71 tests with vegetation cover (WVC) and 71 tests without vegetation cover (WOVC), comprising 6 different soil classes and 18 types of land cover and management. The tests resulted

Table 1. Field tests used to develop and validate the proposed model.

Site	Nº of tests	Management systems adopted and predominant soil texture
Embrapa, MS	**WVC-WOVC**	
L1	4 – 4	Rotated grazing and stocking rate 100 kg / ha of Nitrogen, Oxisol - silty soil.
L2	3 – 3	Rotated pasture and stocking rate 200 kg / ha of Nitrogen, Oxisol - silty soil.
L3	2 – 2	Rotated grazing and stocking rate 300 kg / ha of Nitrogen, Oxisol - silty soil.
L4	6 – 6	Continuous grazing system, Oxisol - silty soil.
L5	7 – 7	System of 4 years of pasture followed by 4 years of tillage, Oxisol - silty soil.
L6	6 – 6	Continuous tillage system, Oxisol - silty soil.
Guariroba Basin, MS		
L7	4 – 4	Degraded pasture, Entisol - sandy soil.
L8	4 – 4	Recovered pasture, Entisol - sandy soil.
L9	4 – 4	Natural pasture, Entisol - clayey sand soil.
L10	4 – 4	Natural pasture, Entisol - sandy soil.
Salobra River Basin, MS		
L11	3 – 3	Pasture, Oxisol - sandy soil.
L12	3 – 3	Pasture, Oxisol - silty soil.
L13	3 – 3	Pasture, Entisol - sandy soil.
		Urban Area of Campo Grande, MS
L14	3 – 3	Urban area, Oxisol, clay silt soil.
L15	3 – 3	Urban area, Oxisol - sandy soil.
L15	3 – 3	Urban area, Oxisol clay soil.
Caiabi River, Sinop, MT		
L16	3 – 3	3rd year pasture system, before soybean and corn cultivation, Oxisol - clay soil.
L17	3 – 3	Pasture system 1st year after 5 years of cultivation of soy and corn, Oxisol - clay soil.
L18	3 – 3	1st year soybean system after 4 years of pasture, Oxisol - clay soil.

WVC: test plot with vegetation cover; WOVC: test plot without vegetation cover.

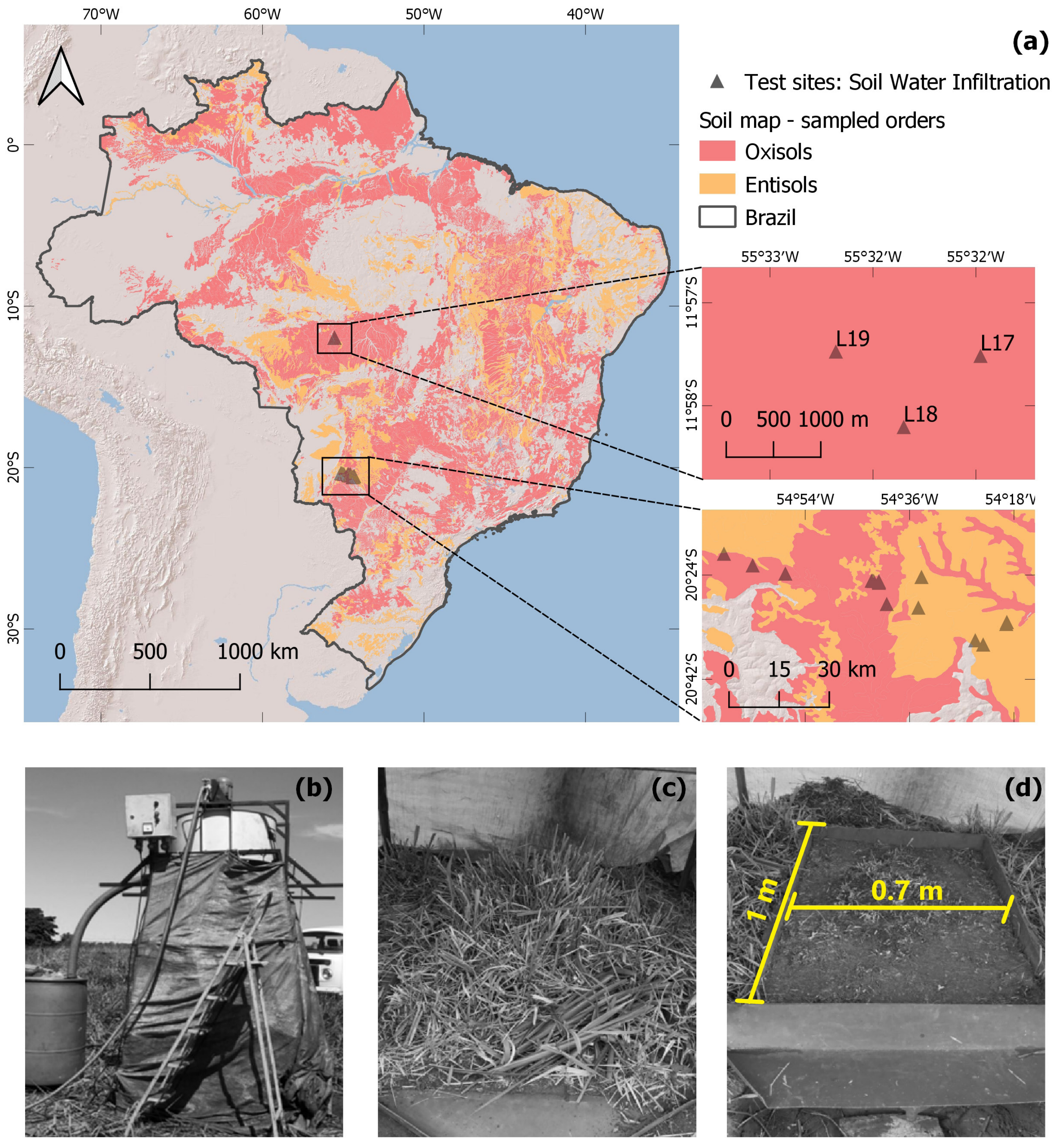

Figure 1. Location of study areas (a) in the cities of Campo Grande, MS and Sinop, MT; Portable rainfall simulator (b) and plots with (WVC) (c) and without (WOVC) (d) vegetation cover and plot dimensions.

in more than 1,800 infiltration rate observations for conditions with and without vegetation cover, respectively.

We also validated the model using the statistical metrics in the efficiency comparison between the Kostiakov-Lewis model and the model we are proposing. The results of the statistical performance evaluation metrics were compared with values found in the literature from studies with validated infiltration models. Having these comparisons, the efficiency of the model was verified in estimating the water infiltration rate in the soil.

Kostiakov-Lewis model

To develop the proposed model, we used the Kostiakov-Lewis equation (Equation 1) as a reference. The model was chosen taking into account the efficiency comparison of several models, as described in the introduction to this work. The procedure consisted of fitting Kostiakov-Lewis equations using the infiltration tests outcomes carried out with and without vegetation cover in the field. The time values and the final rates of water infiltration of each test were also used, obtained by averaging the last four measurements along soil water infiltration curves.

$$i = i_f + \propto kt^{\propto - 1} \quad (1)$$

Where i is the infiltration rate (mm/h); i_f is the final infiltration rate (mm/h); t is the time in seconds and α and k are parameters for fitting the equation.

Considering the Kostiakov-Lewis equation for the conditions with vegetation cover, the time and difference between the final infiltration rates, attempts were made to estimate the results of infiltration rate without vegetation cover. The similar procedure done for the conditions of absence of coverage, seeking results close to the tests with vegetation coverage. All adjustments were developed using non-linear regression.

The results of the adjustment attempts were compared with the data from the field tests and with the results of the Kostiakov-Lewis equations. We also use statistical metrics to assess the level of adjustment of the results in each attempt. After defining the factors that presented the best adjustments, we defined the model, which we call the Conversion model. We then evaluated the values of the adjustment parameters of the Conversion model equations, comparing them with already existing indexes and physical coefficients in an attempt to find one that could represent it.

DATA ANALYSIS

The Pearson correlation coefficient (ϱ) made it possible to assess the potential for correlation between attributes. It was used to assess the potential for correlation between infiltration rates with and without vegetation cover. The classification of the correlation (ϱ) according to their strength can be found on Table 2.

The most commonly found statistical metrics in the literature (Almeida et al., 2018; Panachuki et al., 2006), R^2 - Coefficient of determination; CRM - Coefficient of residual mass; CU - Coefficient of utilization; EF - Efficiency; NSE - Nash-Sutcliffe Efficiency Index; PBIAS - Percent bias; SEE - Standard error of estimate; MAE - mean absolute error; SD - Standard deviation; RMSE – Root mean square error; MSE - Mean square error, were used to verify the efficiency of the Conversion and Kostiakov-Lewis models in relation to the observed field data. See Table S1 for detailed descriptions of statistical metrics.

RESULTS

Analyses made using the Pearson Coefficient were performed to identify the potential correlation between final infiltration rates in tests with and without vegetation cover (Table 3).

The proposed model comprises two similar equations. One equation is to convert the values of the soil infiltration rate with coverage to values without soil coverage, (Equation 2). The other equation converts values of the infiltration rate in the soil without cover into values with soil cover (Equation 3). The model will hereafter be called the Conversion model.

$$i_{wovc} = \left(2 - 2^{t^{-k}}\right) \cdot \left(i_{fwvc} - i_{fwovc}\right) + i_{wvc} \quad (2)$$

$$i_{wvc} = \left(2 - 2^{t^{-k}}\right) \cdot \left(i_{fwovc} - i_{fwvc}\right) + i_{wovc} \quad (3)$$

Where *iWOVC* and *iWVC* correspond to infiltration rates with and without coverage, respectively (mm h^{-1}); *ifWOVC* and *ifWVC* the final infiltration rates with and without coverage (mm h^{-1}); t is the time in minutes, where k is the adjustment parameter.

The values for the adjustment parameter k varied according to the soil texture, with average values of 0.88 for clayey and silty soils and 0.44 for sandy soils. After evaluating some indexes and physical coefficients, we found that the k value is close to double the values of the Surface Runoff Coefficient (C).

We correlated the data obtained by the Kostiakov-Lewis and Conversion models with the data observed in the field (Figure 2). Thus, a comparative analysis was made between the correlations, based on the observed data. The statistical indexes for checking the efficiency of the models were determined considering the values estimated by the models in relation to the data obtained in the field (Table 4).

The R^2, Coefficient of Utilization (CU) and Coefficient of Residual Mass (CRM) values were also determined for the adjustment equations of the models in relation to the data obtained through the field tests. The results were presented in graphs showing frequency distribution histograms, comprising the results of the Kostiakov-Lewis and Conversion models, thus facilitating the comparison (Figure 3).

The cumulative frequency of the results of the R^2, CU and CRM indices was determined by a range that gradually distances from the preferred values of the indexes. The values obtained

Table 2. Pearson correlation index classification. Adapted from Sabilla et al. (2019).

Value of Pearson Correlation	Correlation
>+0.9 or <-0.9	Very Strong
+0.7< ϱ <+0.9 or -0.7> ϱ >-0.9	Strong
+0.5< ϱ <+0.7 or -0.5> ϱ >-0.9	Moderate
+0.3< ϱ <+0.5 or -0.3> ϱ >-0.5	Weak
+0.3> ϱ >-0.3	Negligible

Table 3. Pearson coefficient for infiltration test with and without vegetation cover.

Test Campaign	Pearson coefficient	Correlation Potential
Embrapa, MS	0.91	Very strong
Guariroba Basin, MS	0.97	Very strong
Salobra River Basin, MS	0.72	Strong
Campo Grande, MS	0.92	Very strong
Sinop, MT	0.84	Strong

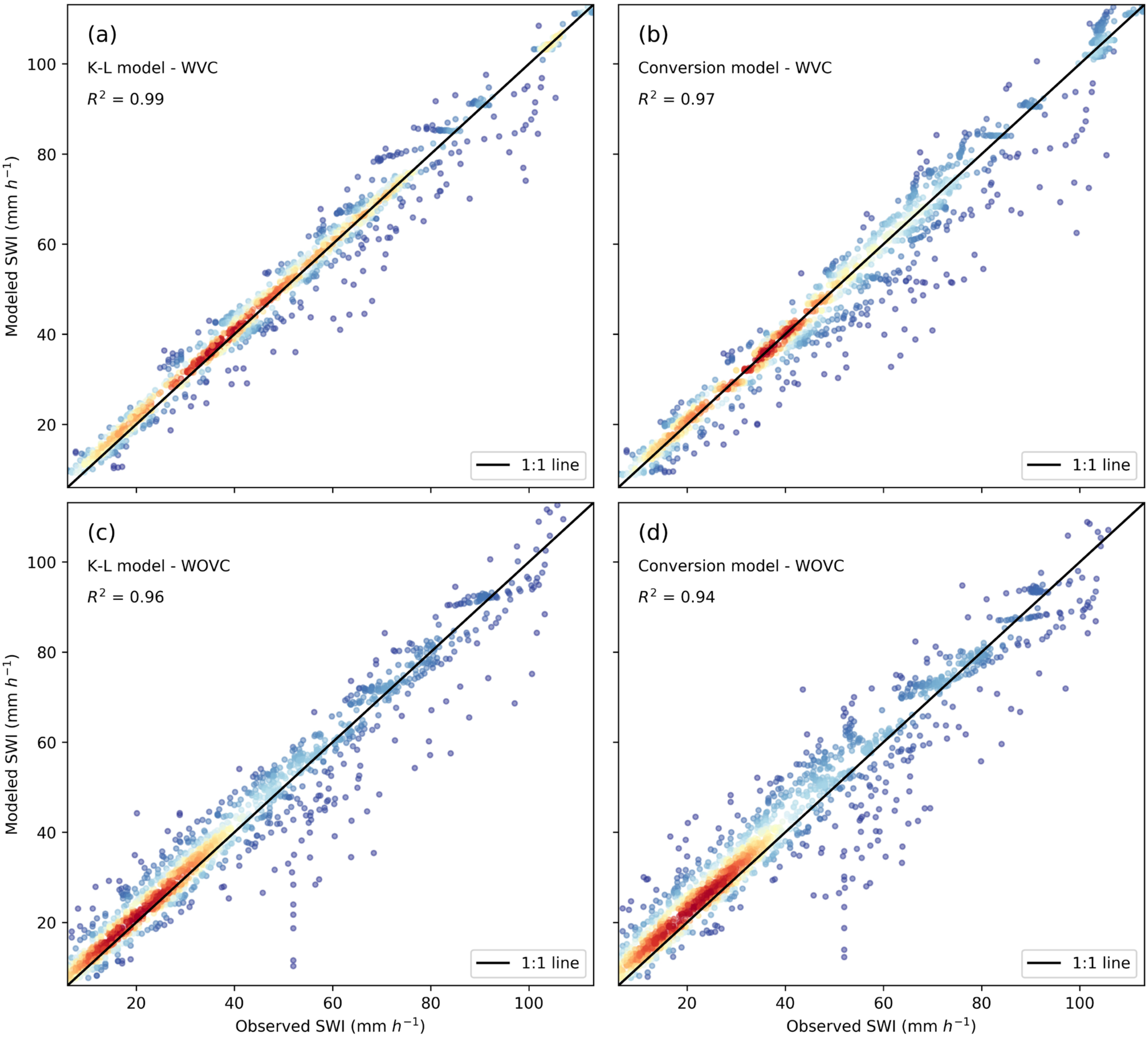

Figure 2. Correlation between field observed data and estimates obtained by the Kostiakov-Lewis (K-L) and Conversion models in vegetated plots (WVC) (a and b, respectively); and in without vegetation plots (WOVC) for the same models (c and d, respectively).

Table 4. Statistical indexes to verify the efficiency of the Kostiakov-Lewis and Conversion models.

Indexes	WVC		WOVC		Optimal value
	K-L	Conversion	K-L	Conversion	
R^2	0.985	0.972	0.955	0.939	1
CU	1.032	0.998	1.070	1.087	1
CRM	-0.011	0.012	-0.025	-0.057	0
EF	0.985	0.971	0.953	0.931	1
PBIAS (%)	4.150	5.524	9.130	12.143	0
SD	0.122	0.171	0.216	0.263	0
SEE (%)	3.380	4.715	5.159	6.278	0
MAE	2.159	2.874	3.293	4.379	0
MSE	11.420	22.216	26.604	39.397	0
MSRE (mm/h)	3.379	4.713	5.158	6.277	0
NSE	0.985	0.971	0.953	0.931	1

R^2: Coefficient of determination; CRM: Coefficient of Residual Mass; CU: Coefficient of Utilization; EF: Efficiency; NSE: Nash-Sutcliffe Efficiency Index; PBIAS: Percent bias; SEE: Standard error of estimate; MAE: mean absolute error; SD: Standard deviation; MSRE: Mean square root error; MSE: Mean square error; WVC: test plot with vegetation cover; WOVC: test plot without vegetation cover; K-L: Kostiakov-Lewis.

for the Kostiakov-Lewis and Conversion models are presented side by side (Table 5).

The performance comparison among the Conversion and Kostiakov-Lewis models and the results observed in the field tests can be better visualized in the infiltration curves presented in graphs (Figure 4). All infiltration testing campaigns used in this work are represented in the graphs with infiltration curves.

DISCUSSION

The results of the analyses from the Pearson's Coefficient showed that there is a potential for correlation classified as strong to very strong between the final infiltration rates of the tests with and without vegetation cover (Table 3). This potential confirms the ability of this relationship to be translated by a correlation based on modeling the equations of adjustment.

The results of the models adjusted to the field data (Figure 2) demonstrated that the Kostiakov-Lewis and Conversion models show dispersion in the results, either from the method itself, or due to the methodology of conducting the field tests. These graphs show that the data obtained by the proposed methodology presented greater dispersions than those observed

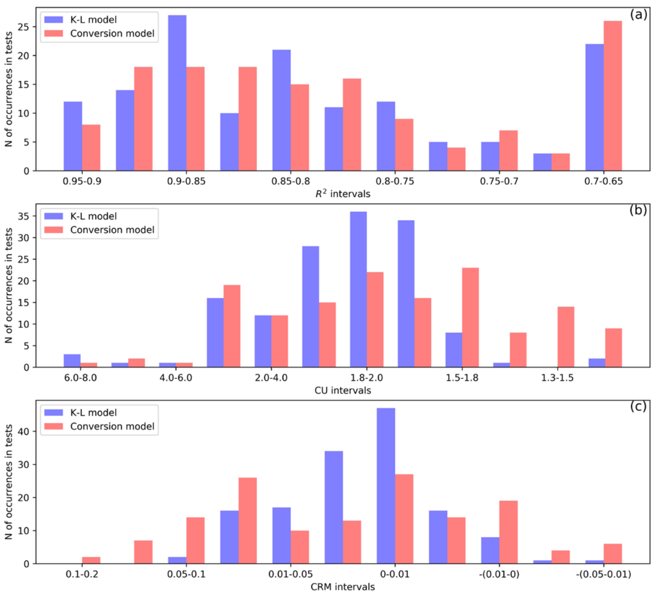

Figure 3. Frequency histograms of the R^2 (a), CU (b) and CRM (c) indexes in relation to the Kostiakov-Lewis (K-L) and Conversion models.

by the Kostiakov-Lewis model, and that tests without vegetation cover show greater variability than those with vegetation cover.

The greater variability and dispersion in the results obtained by the Conversion model, compared with the Kostiakov-Lewis methodology, can also be observed in the various statistical indexes presented in Table 4. This greater dispersion occurs due to the proposed model using the Kostiakov-Lewis model as a reference and, thus, the estimation errors of the Kostiakov-Lewis model are added to the estimation errors of the Conversion model.

Figure 2 and Table 4 demonstrated that the mean values of R^2 are above 0.9 for all cases in the two models under study. The difference of the R^2 results between the Kostiakov-Lewis and Conversion models is 0.013 and 0.016 for the tests with and without vegetation cover, respectively. The frequency distribution graph of the R^2 values (Figure 3) demonstrated that the Conversion model follows the same distribution pattern as the Kostiakov-Lewis model, with higher concentrations of R^2 results between the values of 0.95 and 0.75, which demonstrates a similar performance of the two models.

In Table 5, showing cumulative frequency distribution, we observe that the first range, R^2 between 1 and 0.95, is the one that presents the greatest difference between the two models with 4 more units in favor of the Kostiakov-Lewis model. This difference demonstrates greater accuracy of the Kostiakov-Lewis model. On the other hand, in the other classes, where R^2 is below 0.95, the number of tests for the two models is similar. The tests that resulted in low R^2 values for the Kostiakov-Lewis model also showed low values for the Conversion model.

Almeida et al. (2018) also used the Kostiakov-Lewis model to study the water infiltration rate using a rain simulator in soybean plantations and pastures. The authors obtained results of R between 0.74 and 0.93 and between 0.86 and 0.96, for the cases with and without vegetation cover, respectively. In terms of R^2, the values were between 0.55 and 0.86 for exposed soil and 0.74 and 0.92 for soil with soybean plantation. The same authors obtained R values between 0.23 and 0.77 for pasture resulting in R^2 from 0.05 to 0.60. The values presented for R^2 for the Kostiakov-Lewis and Conversion models are above those presented by the authors mentioned.

We observed that for the vegetation cover condition, the conversion model presented a value of 0.998, very close to 1000 (ideal value), different from the Kostiakov-Lewis model, which presented a metric indicating a worse fit (1032). The efficiency of the Conversion model demonstrates the potential for estimating the infiltration rate based on the conversion of results with and without vegetation cover. For values without vegetation cover,

Table 5. Accumulated distribution of the results of the Kostiakov-Lewis and Conversion models.

Accumulated Distribution of Results by Range								
R^2			CU			CRM		
	K-L	Conversion		K-L	Conversion		K-L	Conversion
0.95	12	8	**0.7 - 1.3**	42	39	**-0.05 to 0.05**	114	76
0.90	26	26	**0.5 - 1.5**	79	69	**-0.1 to 0.1**	132	104
0.80	63	62	**0.2 - 1.8**	107	98	**-0.2 to 0.2**	140	130
0.70	95	93	**0 - 2**	121	119	**-0.3 to 0.3**	141	134
bellow	142	142	**<0 and 2 <**	142	142	**above**	142	142

R^2: Coefficient of determination; CU: Coefficient of Utilization; CRM: Coefficient of Residual Mass; K-L: Kostiakov-Lewis.

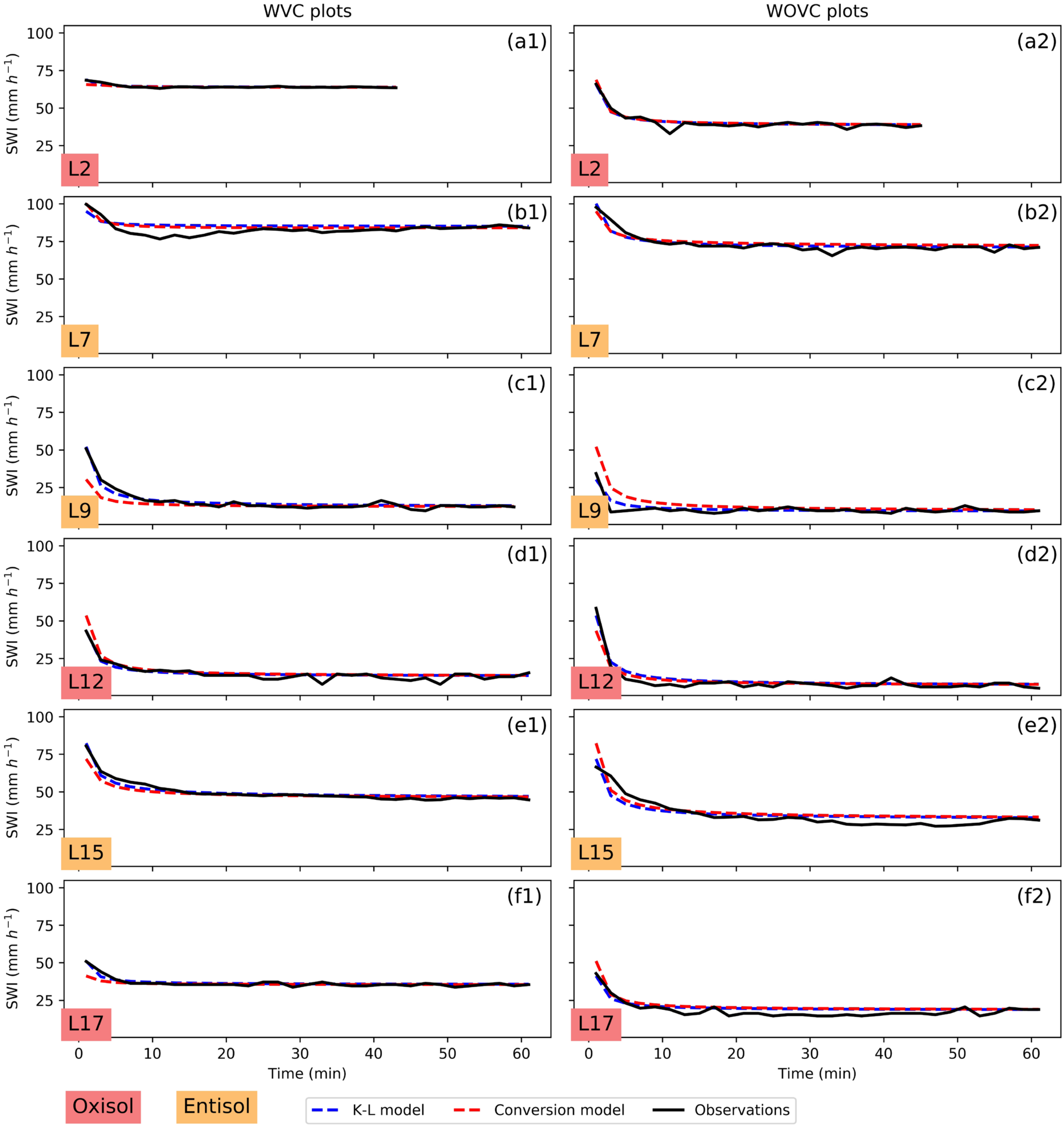

Figure 4. Comparative soil water infiltration (SWI) curves from observed field data and results from Kostiakov-Lewis (K-L) equation and the developed conversion model for multiple sites (a-f), in vegetated (1) and bare soil (2) plots.

the Conversion model was less efficient than the Kostiakov-Lewis model.

In the graph of frequency distribution of the coefficient of utilization (CU) (Figure 3), we observed that the results of the Conversion model showed greater dispersion compared to the Kostiakov-Lewis model. The distribution differences between the models were evident when comparing the histograms in the first two ranges: EF values between 0 and 0.5. In these ranges, the Conversion model features 23 units and the Kostiakov-Lewis only two units.

Despite the differences between the models in the distribution of the index (CU), Table 5 showed a small difference between the models, especially for the 0.7-1.3 range, with a difference of only three units. In the first range, this small difference between the models points to the potential of the proposed model in estimating the infiltration rate values. The first range is the closest to the preferred value which is the unit. Panachuki et al. (2006), who also evaluated the Kostiakov-Lewis model through field tests with rain simulator, obtained values of (CU) between 1.27 and 2.35, which confirms that the results of the Conversion model are compatible with the pattern presented in other studies.

The negative values of the Coefficient of Residual Mass (CRM) Distribution Curve, shown in Table 4, indicated that the Kostiakov-Lewis model overestimated the infiltration rate for both cases, with and without vegetation cover. Regarding the Conversion model, the (CRM) values of 0.012 and -0.057 indicated an underestimation and an overestimation for cases with and without coverage, respectively. The CRM values corresponding to -0.011 and 0.012 for the two models in tests with vegetation cover, showed an equidistance of the desirable value, which is zero, demonstrating that the two models presented equivalent efficiency. For tests without vegetation cover, the results of -0.025 and -0.057 demonstrated less efficiency of the Conversion model.

We observed a greater dispersion of CRM in the Conversion model when compared with the results presented by the Kostiakov-Lewis model. This dispersion can be seen in the frequency histogram graphs and in the accumulated frequency table. However, if we consider the values between -0.2 and 0.2, the third range (CRM) of Table 5, it can be observed that more than 90% of the results of the Conversion model and 98% of those referring to the Kostiakov-Lewis model are included. These percentages demonstrate that the Conversion model does not deviate much from the Kostiakov-Lewis model. Carvalho et al. (2015) also used the Kostiakov-Lewis model in the study of water infiltration in corn plantations, obtaining CRM values between -0.19 and 0.16, corresponding to the same range in which most of the results of this study fit.

The other coefficients, EF, PBIAS, SD, SEE, MAE and MSE, presented in Table 4, show results compatible with those already observed, confirming that the Kostiakov-Lewis model is more efficient than the Conversion. They also demonstrate that the models are more efficient with vegetation cover than without the vegetation cover, and confirm that the efficiency of the two models are close, which confirms the capacity of the Conversion model to estimate the infiltration rate.

Almeida et al. (2018) obtained the Root Mean Square Error (RMSE) values between 2.89 mm/h and 5.85 mm/h, in soil without vegetation cover. For soybean planting, the authors obtained (RMSE) between 3.62 mm/h and 7.27 mm/h. According to the same authors, for pastures, the RMSE values were between 5.20 mm/h and 13.62 mm/h. Zakwan (2018) evaluated six models for determining infiltration rates, obtaining the RMSE values between 2 mm/h and more than 30 mm/h as a result. The results found by the aforementioned authors confirm that the Conversion model presented usual levels of RMSE values, for models of infiltration rates, shown in Table 4.

Regarding the Nash-Sutcliffe Efficiency (NSE) Index, Almeida et al. (2018) presented values between 0.59 and 0.92 for soil without cover, values between 0.54 and 0.86 for soybean plantation and between 0.05 and 0.82 for pasture. The authors considered the models adequate, taking into account the NSE and RMSE factors obtained. The NSE values obtained for the Kostiakov-Lewis and Conversion models (Table 4) are compatible and even indicating greater efficiency when compared with those presented by the aforementioned authors.

Duan et al. (2011), who studied the efficiency of five water infiltration models in lawn soils presented results of Efficiency (EF) with values between 92% and 99%. The EF values (Table 4), when converted to percentages, result in values between 97.1% and 98.5% for situations with vegetation cover and between 93.1% and 95.3% for situations without vegetation cover. The results obtained by the authors correspond to the same range of values observed for the Kostiakov-Lewis and Conversion models, presented in this work.

Regarding the graphs showing two tests for each campaign (Figure 4) it was demonstrated that there was no influence of the type of planting system or of the type of crop on the efficiency of the Conversion model, which can be adopted in all land covers. The Conversion model presents the best result for well-defined infiltration curves, which are within the standard normally expected.

Observing the infiltration curves, we found that the Conversion model presents infiltration curves close to the data obtained in the field and also to the Kostiakov-Lewis model, except for the first determination point, corresponding to the time of 1 minute. This is because the first factor in the equation is equal to zero at this time. Therefore, we believe that the first point should be used with caution. Despite this, the proposed model presents a better fit in the horizontal part of the curve, in which the values of final infiltration rates are very close to the field data and to those obtained by the Kostiakov-Lewis model.

We noted that the runoff coefficient had the potential to represent the adjustment parameter k of the Conversion model, needing only to be increased twice. The values of 0.88 and 0.44 of k, obtained for clay/silty and sandy soils, respectively, correspond to twice the average of the values found in the literature for the runoff coefficient. The runoff coefficients for pastures and land cultivated in sandy soil are 0.029 and 0.007-0.063, respectively (Anache et al., 2019). For clay soils, the values are 0.020 and 0.040-0.281 for pasture and cultivated land, respectively (Oliveira et al., 2016).

The Conversion model can be tested using other models to estimate soil infiltration rates, as the proposed model equation is not limited by the Kostiakov-Lewis model. In addition, the Conversion model can be tested in real situations, estimating the effect of measures to recover degraded areas, for example.

CONCLUSION

There is a potential for strong to very strong correlations between final infiltration rates of tests with and without vegetation cover. The correlation can be represented by the proposed Conversion model, which showed the ability to estimate water infiltration rates in soil with vegetation cover, based on Kostiakov-Lewis equations without vegetation cover. The model also has the ability to estimate infiltration rates in soil without vegetation cover, using equations from the Kostiakov-Lewis model for soil with vegetation cover.

Our findings indicate that the Conversion model can be used in several types of planting and vegetation cover systems. The model is less efficient in predicting the values of infiltration rates, when compared with the Kostiakov-Lewis model. However, the statistical indexes showed that the Conversion model presents acceptable behavior, compatible with established models presented in the literature.

The proposed model showed better performance in estimating the rate of water infiltration in soils with cover than without vegetation cover. The adjustment parameter of the Conversion model equations showed that it corresponded to twice the Surface Runoff Coefficient (C).

The Conversion model presented the limitation in estimating the first point of determination, corresponding to the time of 1 minute, however it is capable of showing efficiency in estimating the values of the final infiltration rates.

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SUPPLEMENTARY MATERIAL

Supplementary material accompanies this paper.

Table S1. Statistical indexes used to evaluate the model's performance.

This material is available as part of the online article from http://www.scielo.br/j/rbrh