Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Soil and Water Management and Conservation

Modeling the effect of terracing on runoff control in a rural catchment in southern Brazil

Larissa Werle[1], Jean Paolo Gomes Minella[2]*, Gustavo Henrique Merten[3], Douglas Rodrigo Kaiser[4], Alexandre Schlesner[1], Alice Prates Bisso Dambroz[1], Blayon Eduardo Hammes[1] and Felipe Bernardi[1]

[1] Universidade Federal de Santa Maria, Departamento de Solos, Programa de Pós-Graduação em Ciência do Solo, Santa Maria, Rio Grande do Sul, Brasil.
[2] Universidade Federal de Santa Maria, Departamento de Solos, Santa Maria, Rio Grande do Sul, Brasil.
[3] University of Minnesota-Duluth, Department of Civil Engineering, Duluth, Minnesota, United States.
[4] Universidade Federal da Fronteira Sul, Curso de Agronomia, Cerro Largo, Rio Grande do Sul, Brasil.

*** Corresponding author:**
E-mail: jean.minella@ufsm.br

Received: July 01, 2024

Approved: November 21, 2024

How to cite: Werle L, Minella JPG, Merten GH, Kaiser DR, Schlesner A, Dambroz APB, Hammes BE, Bernardi F. Modeling the effect of terracing on runoff control in a rural catchment in southern Brazil. Rev Bras Cienc Solo. 2025;49:e0240108.
https://doi.org/10.36783/18069657rbcs20240108

Editors: José Miguel Reichert and João Tavares Filho.

ABSTRACT: Extreme weather events, such as heavy rains and droughts, necessitate the rapid adaptation of production systems to prevent the degradation of natural resources and to maximize production potential. Defining adaptive practices requires an in-depth understanding of the factors that control the formation and propagation of surface runoff and the identification of specific practices tailored to each location. No-till system, coupled with complementary storm runoff management practices, is effective in controlling surface runoff and related processes. However, the planning of the capacity and allocation of these practices, considering the specific interaction of controlling factors in each catchment, is not well understood. Planning conservation practices at the catchment scale through hydrological modeling and monitoring presents an efficient alternative, as it integrates the controlling factors that govern storm runoff dynamics. This study sought to understand the influence of different levels of conservation intervention (surface runoff control practices) on the hydrological behavior of the experimental catchment of the Guarda Mor River (southern Brazil). The method relied on monitoring hydrological variables (rainfall and streamflow) at the catchment outlet and on the physiographic characterization of the catchment, including the spatial variability of soils, topography, land use, and soil management. After analyzing a significant set of rainfall-runoff events, the generation and propagation of surface runoff were modeled (calibration and validation) using the Limburg Soil Erosion Model. The impacts of two conservation intervention scenarios were tested: buffer strips plus well-managed no-till (Scenario 1) and retention broad-based terraces plus well-managed no-till (Scenario 2). Conservation practices were assessed by evaluating the following hydrologic parameters: surface runoff volume, peak flow, and time to peak. Simulation results indicate that both intervention levels effectively controlled surface runoff. Scenario 1 resulted in an average reduction in surface runoff volume and peak flow attenuation of 7 and 6 %, respectively. Scenario 2 achieved an average decrease in surface runoff volume and peak flow attenuation of 30 and 28 %, respectively. These results quantitatively demonstrate the positive impact of soil and water conservation practices on the drainage network. The impacts of the two scenarios in the time to peak were not significantly altered, except for one event. Catchment-scale conservation planning is an efficient and promising strategy for improving conservation agriculture, underscoring its importance in water resource management and promoting environmental services.

Keywords: LISEM, conservation agriculture, peak flow, monitoring, no-tillage.

INTRODUCTION

Soil and water conservation planning at the catchment scale requires evaluating the effects of different soil management techniques on hydrological and erosion processes. The effects of surface micro- and macro-roughness, as well as the protective role of plants or straw on soil physical and water-retaining properties, are fundamental in quantifying the impact of diverse practices (Abaci and Papanicolau, 2009; Rockström et al., 2010). By understanding the combined effects of multiple factors, we can simulate the optimal combination for each situation, considering the relief, soil, land use, and soil management. In southern Brazil, adopting no-till farming represented a significant advancement in soil conservation. However, over the years, there has been a gradual deviation from the fundamental principles (Reicosky, 2015; Fuentes-Llanillo, 2021; Londero et al., 2021a). The current system of grain production under no-till farming has proven inefficient in controlling surface runoff (Deuschle et al., 2019; Londero et al., 2021b), leading to numerous negative repercussions such as the resurgence of erosion (Merten et al., 2015), increased flooding and escalated sediment yield (Didoné et al., 2015; Londero et al., 2021a), and worsening water quality (Utzig et al., 2023).

One efficient and recommended method for controlling surface runoff and storing water is terracing (Ran et al., 2020; Londero et al., 2021b). Implementing terraces transforms steep slopes with long lengths into a sequence of small, independent slopes (Fashaho et al., 2020). Agricultural terracing is a mechanism for detaining surface runoff, significantly increasing infiltration and decreasing surface runoff velocity. This practice allows for the storage of water in the soil during periods of abundant rainfall and increases the water available during droughts (Freitas et al., 2021), favoring an increase in the productivity of soybean and corn, as demonstrated by Hörbe et al. (2021).

The impact of soil conservation practices on the hydrological behavior of rural catchments under no-tillage is not well understood due to the complexity of runoff generation and propagation. Therefore, the benefits of conservation practices observed on plots or hillslopes cannot be directly extrapolated to the catchment scale due to the additive effect of other uses such as roads, forests, wetlands, and river behavior itself. Nonetheless, it is crucial to measure the impact of improvements on soil hydrological behavior in croplands at the catchment outlet, as it helps understand the positive effects of these practices within the broader context of processes operating in the catchment (Rachmann et al., 2008; Gathagu et al., 2018; Giambastiani et al., 2023). Based on this, conservation planning can be optimized integrally by considering the demands of increasing agricultural productivity through better use of rainwater, as well as regulating downstream streamflows and preventing floods and the transfer of sediments, pesticides, and nutrients to water courses. This approach can benefit programs aiming to pay for environmental services, focusing on water quality and quantity.

Monitoring rainfall and runoff is critical for understanding the conversion of precipitation into surface runoff, considering the complex interplay of land uses, terrain, and soils within the catchment. Runoff behavior during a rainfall event in the catchment integrates all factors controlling its formation, as well as the components of the hydrological cycle (interception, infiltration, runoff detention, and propagation). However, no established protocol or strategy currently exists for verifying the effects of water and soil conservation practices to support catchment-scale conservation planning projects based on mathematical simulation models. Associating mathematical models with hydrological monitoring is a highly pertinent form of understanding processes and can aid in conservation planning in river catchments. Simulating the impact of conservation practices on catchments using physically-based hydrological models drastically reduces the time required to generate results compared to field experiments (Hengsdijk et al., 2004; Mekonnen et al., 2014). Although the results from hydrological models are estimates, they facilitate identifying the trend of the effects and assist in the conservation planning of catchments, provided they are accurately parameterized and calibrated.

Given this study aimed to simulate the effect of retention broad-based terraces, it was necessary to adopt a different flow simulation strategy compared to previous studies (Barros et al., 2021; Schneider, 2021; Schlesner, 2022). Unlike the 1D kinematic wave model, which commonly exhibits greater connectivity and concentration, thereby reducing the time for flow formation, the 2D dynamic wave model based on the Saint Venant equation allows cells to direct surface flow due to pressure forces to surrounding cells proportionally according to the digital elevation model. This approach is pivotal for catchments lacking significant connectivity between landscape units and for representing conservation practices. For further information on the differences between these methods, see Bout and Jetten (2018).

Quantification of the effects and representation of conservation practices under no-till conditions and their resultant effects in a mathematical hydrological simulation model remain in their infancy on a catchment scale. Testing the effects of crucial practices such as broad-based terraces, buffer strips, and surfaces with plant residues on a catchment scale is necessary to verify their efficiency. This advancement in monitoring and simulation tools for rainfall-runoff events is crucial for managing runoff from rural catchments, particularly in adapting to extreme weather events. This study aimed to represent and understand the influence of broad-based terraces and buffer strips in the simulation environment of croplands on the behavior of surface runoff using hydrological monitoring and modeling techniques in the experimental catchment of the Guarda Mor River in southern Brazil.

MATERIALS AND METHODS

Experimental location

The experimental catchment of the Guarda Mor River is located in Rio Grande do Sul State (southern Brazil), situated at the boundary of the municipalities of Silveira Martins, Ivorá, São João do Polêsine, and Júlio de Castilhos. The area covers approximately 18.5 km², with elevations between 197 and 511 m. This location is in a transitional zone between the southern plateau and the central depression (sedimentary basin). It is distinguished by its varied land use, geology, soils, and relief configurations. The region experiences a subtropical climate, classified as Cfa according to the Köppen classification system (Köppen, 1931), featuring an annual precipitation of 1,700 mm and potential evapotranspiration estimated at 829 mm. Guarda Mor river catchment, a tributary of the Soturno River (Figure 1), integrates the Jacuí River system. This system contributes to Lake Guaíba and extends to the metropolitan area of Porto Alegre, the capital of Rio Grande do Sul.

The upper part of the catchment is situated on the Southern Plateau, characterized by volcanic rocks of the Serra Geral Formation, which is divided into the Caxias unit (Riodacite) covering an area of 12.22 km² and the Gramado unit (Basalt) accounting for 3.96 km² in the middle third of the catchment. The lower segment of the catchment resides in the Sedimentary Basin (Central Depression), where rocks of sedimentary origin prevail. Here, sandstones of the Botucatu Formation (fine sandstone) predominate with an area of 2.16 km², and the Caturrita (sandstone) encompasses 1.40 km² (Figure 2).

The relief is primarily undulating in the plateau region, with 5-10 % slopes, transitioning to very steep terrain (>75 % slopes) in the middle third. In the lower part of this catchment, the terrain ranges from flat (0-2 % slopes) to very undulating (15-45 % slopes). Soil mapping was conducted using field profile descriptions combined with digital mapping (Pedron et al., 2021). The predominant soil types, based on WRB classification system

(IUSS Working Group WRB, 2015) and the Brazilian soil classification system (Santos et al., 2018) are Leptosols (Neossolos Litólicos), Nitosols (Nitossolos Vermelhos), with smaller areas of Cambisols (Cambissolos Háplicos) and Gleysols (Gleissolos Háplicos). In the middle third of the catchment, the predominant soil classes are Regosols (Neossolos Regolíticos) and Lepsols (Neossolos Litólicos). Meanwhile, in the lower segment of the catchment, there are Lepsols (Neossolos Litólicos) and Acrisols (Argissolos Acinzentados).

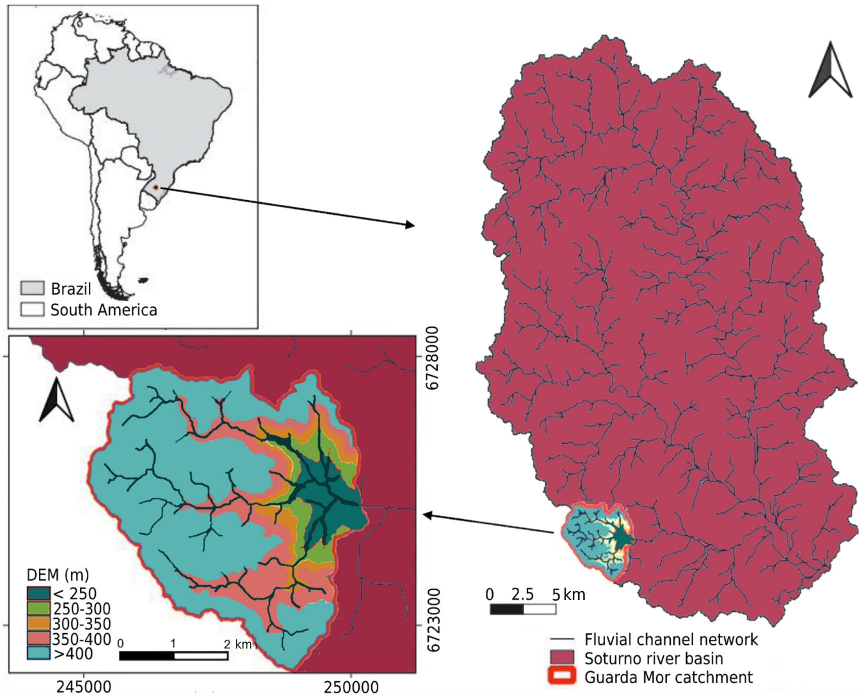

Figure 1. Location of the Guarda Mor River experimental catchment.

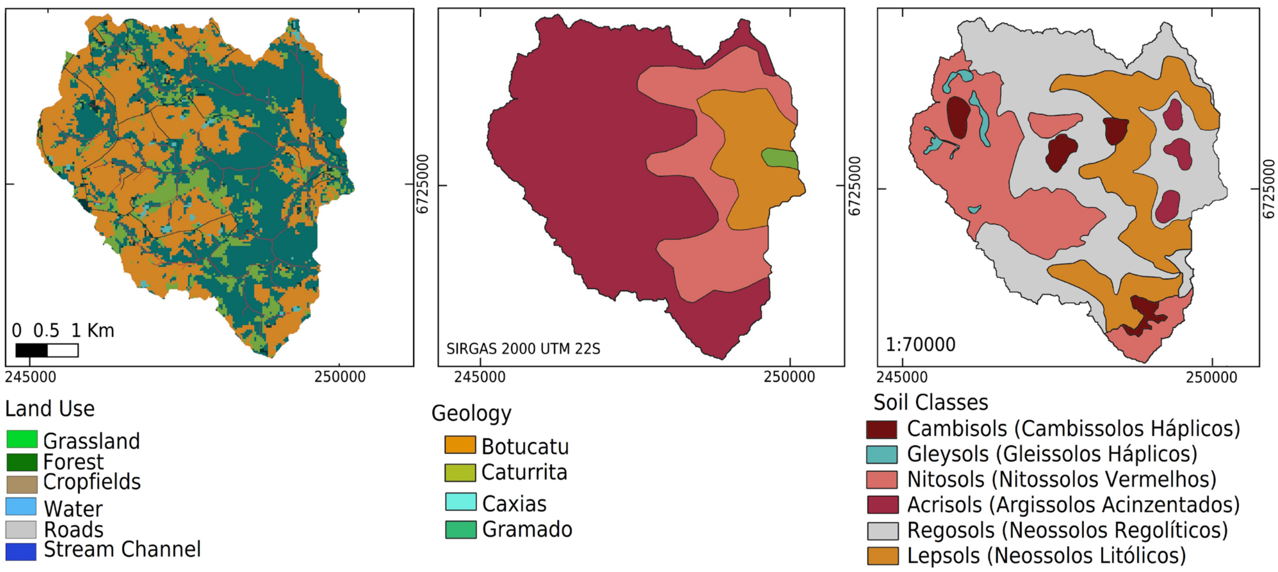

Figure 2. Land use map, geological representation, and soil types of the Guarda Mor catchment.

Land use map was created based on the normalized difference in vegetation index and field verification. According to this classification, approximately 42 % of the catchment area is dedicated to agricultural activities, forests (42 %), followed by pastures (12 %), roads (2 %), urban or paved areas (1 %), and bodies of waters (1 %). The forest is primarily located in the rugged region of the catchment (edge of the plateau). Agricultural areas mainly consist of grain production utilizing no-till farming, with soybeans grown in the summer and wheat or oats in the winter. These areas are predominantly situated in the upper part of the catchment (plateau), where most of the surface runoff originates. Despite the widespread adoption of no-till farming in the region, the croplands exhibit low phytomass content and are lacking in other conservation practices, such as crop rotation, terracing, and contour seeding. These conditions favor the formation of surface runoff, which accelerates as it flows through the river system upon reaching the steep region at the plateau edge.

Physical and hydraulic characterization of the soil

The characterization of the physical and hydraulic properties of the soil in the Guarda Mor catchment was determined at 88 points based on soil type, geology, and land use. Two samples were collected with metal rings to preserve structure at each point in the topsoil layer (0.00-0.10 m). These samples were then transported to the soil physics laboratory to determine total porosity (θ_s), saturated hydraulic conductivity (K_{sat}), and the parameters of the water retention curve.

Surface runoff monitoring and modeling

Hydrological data was initially collected during rainfall-runoff events to calibrate and validate a spatially distributed, physically-based model designed to simulate the formation and propagation of surface runoff. This also included simulated impacts of terracing on runoff.

At the outlet, a footbridge was installed over a cross-section of the Guarda Mor River to monitor liquid and solid discharges. Limnimetric rulers, along with equipment such as a water level sensor, automatic samplers, and a turbidimeter, were deployed at this location (Figure 3). Rainfall was monitored at two locations within the catchment: one near the outlet in the lower part and another in the upper part of the catchment. Each area was equipped with a pluviograph and a rain gauge, which were attended by a local observer. The pluviograph recorded rainfall data at 5-minute intervals, and these data were corrected using daily readings from the rain gauges. The rainfall erosivity at (EI_{30}) was estimated based on Ramon et al. (2017) equation, which was defined for Rio Grande do Sul State. Streamflow was monitored with a water level sensor (Campbell CR451) at 5-minute intervals. Streamflow were estimated from the water level records using a rating curve developed by Bernardi (2022).

Hydrological monitoring was conducted from April 2022 to November 2023. Out of all the events measured, 14 events of the greatest magnitude and those representing different rainfall conditions across various seasons were selected. This selection allowed for exploring events characteristic of the rainfall pattern at different times of the year under specific land use and coverage conditions. Hydrological monitoring made it possible to understand the processes operating within the catchment and characterize the rainfall events that occur to represent them accurately within a mathematical model.

The mathematical modeling of rainfall-runoff events was conducted using the physically-based Limburg Soil Erosion Model (LISEM) version 6.848, with a temporal resolution of 10 seconds and a spatial resolution of 10 m. This model employs spatialized information (parameters) about land use and soil type, along with attributes of the topography (digital elevation model) and the drainage network to describe the main components of the hydrological cycle during an event at the catchment scale (De Roo, 1996). Some parameters were spatialized based on land use, and others were spatialized according to soil type. The ones utilized in the land use map included saturated hydraulic conductivity (K_{sat}), total porosity (θ_s), matric potential (ψ_m), initial moisture content (θ_i), Manning's roughness parameter (*n*), vegetation cover, crop height, leaf area index, and random roughness (RR). Since depth is an intrinsic characteristic of each soil type, this parameter was assigned within the soil map.

The LISEM simulates surface runoff; thus, it is imperative to separate it from base flow using the measured streamflow data. It was done by analyzing the hydrograph, in which the inflection point on the hydrograph determines the start and end of surface runoff, according to the graphical separation method presented by Tucci (1998). The model mimics surface runoff and erosion using mathematical equations related to plant interception, micro-depression storage, water infiltration into the soil, and the generation and propagation of surface runoff. The model also simulates the disintegration, transportation, and deposition of sediment. In this study, we focused solely on the hydrological aspects, with the goal that the model would adequately represent surface runoff and its retention at a catchment scale.

Water infiltration into the soil is estimated using the Green-Ampt model, a simplification of the Darcy equation for vertical water flow. The potential of the infiltration rate determines whether surface runoff occurs, which is contingent on the precipitation intensity. Surface runoff is generated when the water stored in depressions overflows, and precipitation occurs at an intensity exceeding the infiltration capacity. In this instance, surface runoff propagation was performed using the 2D dynamic wave, which employs the numerical elevation model to direct flow. As retention terraces intercept surface runoff in the converging zones of the slopes and redistribute it to diverging zones, the 2D dynamic wave method utilizing the numerical elevation model was preferred over the 1D kinematic wave method, which uses flow direction (Figure 4). This is because the water detention on the terraces causes the runoff to spread over it.

The K_{sat} and θ_s data were obtained from a field survey of the different soils and land use units. It was performed by sampling 88 points in the catchment using three repetitions (Bernardi, 2022; Werle, 2024). Due to the high variability, particularly for the variable

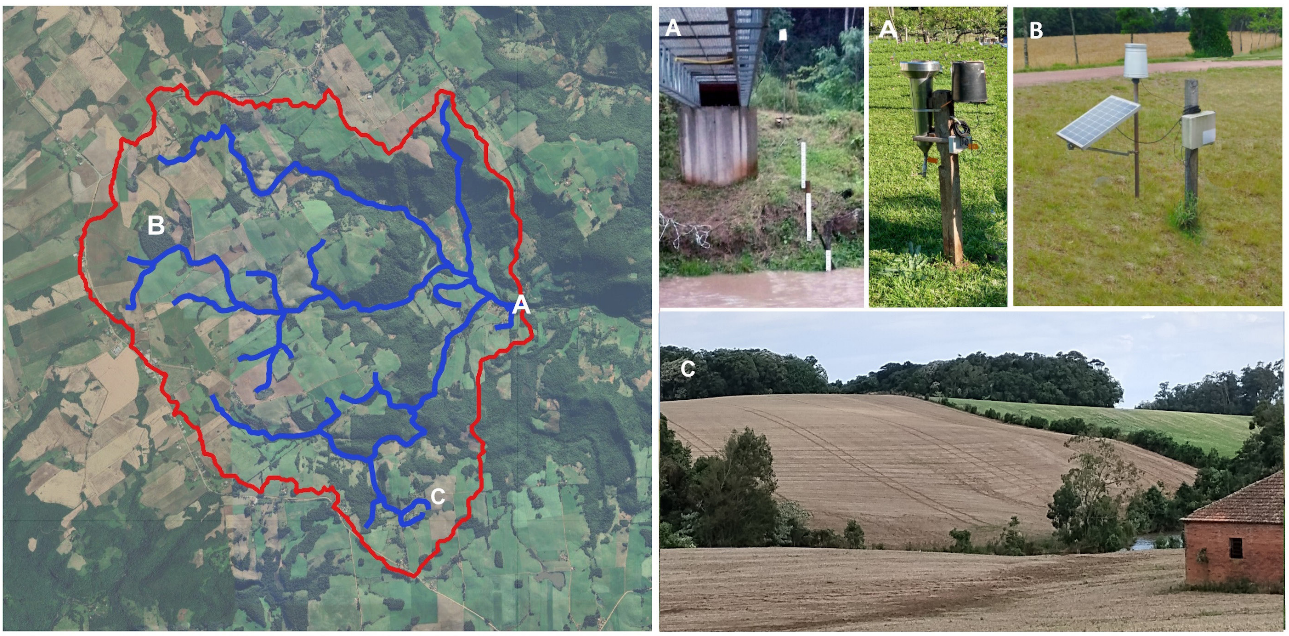

Figure 3. Locations of the monitoring section and rain gauges.

K_{sat} within the same land use, it was decided to use the median as a measure of central tendency to represent K_{sat} and θ_s for each land use class. The median more accurately represents the typical value of the sample. The RR value was determined in a similar experimental catchment in southern Brazil (Deuschle et al., 2019; Schneider, 2021). Manning's *n* values were described in Engman (1986) for land uses compatible with those found in the Guarda Mor experimental catchment.

Moreover, θ_i is challenging to measure due to the spatial and temporal uncertainties on a catchment scale. For this reason, it was estimated based on the accumulated rainfall over three days prior to the rain event. This model's most sensitive parameter was used as the principal calibration parameter. The matric potential was assigned based on an intermediate value from the textural class (HEC RAS, 2020). The values for vegetation in croplands (vegetation cover, crop height, and leaf area index) were determined from the agricultural calendar observed in this catchment and data from Deuschle et al. (2019), Dambroz et al. (2022), and Bernardi (2022). The vegetation variables were adjusted according to the time of year of each simulated event.

The calibration strategy for the events was based on representing the total volume, peak flow, and peak time by trial and error. The adjustment prioritized peak flow due to its greater reliability in representing surface runoff. If there was no good fit, the parameter K_{sat} was maintained as measured, and Manning's *n* was maintained as initially estimated.

The efficiency analysis in terms of calibration and adjustment was carried out using the coefficient of efficiency (COE) proposed by Nash and Sutcliffe (1970) for the flow data along the hydrograph. The percentage of bias (P_{BIAS}) assessed the efficiency of the conservation scenarios for the total volume of runoff, peak flow, and peak time. The efficiency of the LISEM was evaluated using the Nash-Sutclife coefficient (NS) and the following ranges as a reference: NS >0.75 was considered "very good," 0.65< NS <0.75 was "good," 0< NS <0.65 was "bad," and NS <0 "unacceptable" (Moriasi et al., 2007). For P_{BIAS}, P_{BIAS} < ±10 % was considered "very good," ±10 % ≤ P_{BIAS} < ±15 % was "good," ±15 % ≤ P_{BIAS} < ±25 % was "satisfactory," and ≥ ±25 % was "unsatisfactory" (Moriasi et al., 2007).

For the model's calibration and validation, 14 events were selected, with ten events for calibration (Events 1–10) and four events (Events 11–14) for validation. The average values of K_{sat} and *n* obtained in the calibration were used in the validation events, and the antecedent moisture content was estimated from the amount of antecedent rainfall. Validation uses parameters extracted from the calibration, eliminating the need for trial-and-error adjustment of parameters.

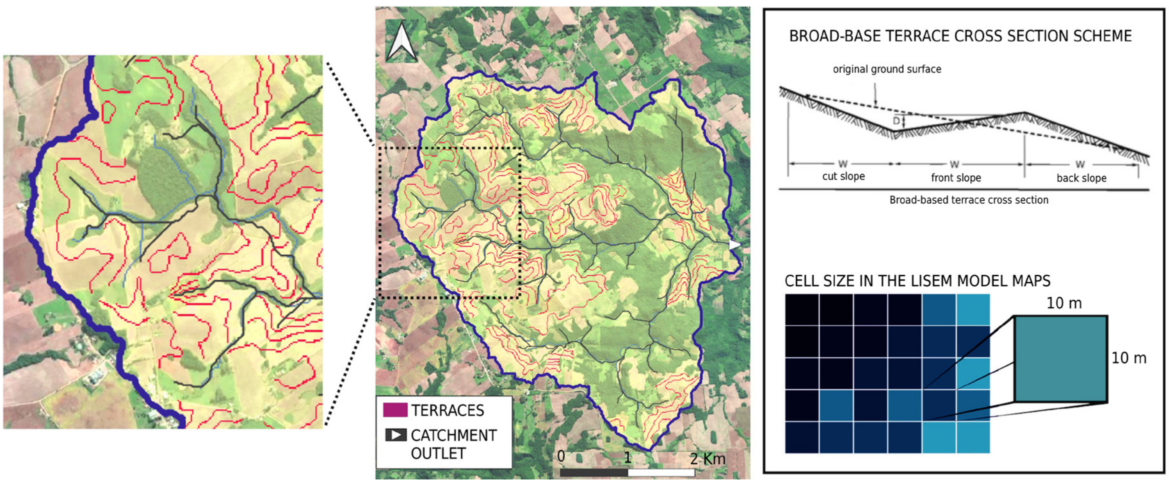

Figure 4. Layout and dynamics of contour lines in agricultural areas in the catchment that gave rise to the allocation of retention terraces and buffer strips in the simulation environment.

The conservation scenarios were proposed in the agricultural areas of the catchment to evaluate their effects on controlling the surface runoff observed at the catchment's outlet. The simulation of conservation intervention levels was tested on six significant rainfall events with return periods ranging from 0.1 to 5 years. One of these occurred during a critical rainfall period in Rio Grande do Sul, causing significant damage to the rural and urban environments. The results obtained are the outcome of integrating the effects of changes to croplands with the impacts of other land uses (unpaved roads, forests, and pastures) that have not undergone intervention. Two levels of conservation intervention were tested, including three conservation measures:

i. **Scenario 1 (S1):** Enhancement of infiltration parameters due to the increased amount of phytomass and crop rotation (well-managed no-till farming), associated with 10 m wide buffer strips composed of material with high friction against surface runoff and a high infiltration rate.

ii. **Scenario 2 (S2):** Improvement in infiltration parameters due to the increased amount of phytomass and crop rotation (well-managed no-till farming), associated with the presence of retention broad-based terraces with a cross-section of 2 m^2.

The allocation of buffer strips and retention broad-based terraces was based on contour lines obtained from the DEM with a contour interval of 4 m (Figure 3). Therefore, the number of retention broad-based terraces and buffer strips per hillslope simplifies the ideal number, which could be tailored considering the unique aspects of each slope, such as its steepness or soil type. The cross-sectional area of approximately 2 m^2 is an estimate of the minimum necessary for the desired effect of controlling runoff through infiltration terraces specific to that location. The retention broad-based terrace was represented in the simulation environment as a depression, which the model accounts for as a reservoir to be filled. These depressions (reservoir) are represented in the pixels where the contour lines (4 m equidistance) cross through the croplands. From that, the retention broad-based terraces are spatially distributed in the croplands of the entire catchment.

Specific vegetation and soil characteristics were assigned to the buffer strips, taking into account the high porosity found in areas with dense vegetation and the different types of roots (fasciculate and pivoting) that create varied subsurface conditions (Nicoloso et al., 2008; Prando et al., 2010; Mallmann, 2017). Manning's *n* was assigned based on results from Schneider (2021) in areas with high vegetation cover for both vegetation strips and well-managed agricultural areas. Thus, greater infiltration (K_{sat} and θ_s), lower runoff velocity (*n*), increased RR, and vegetation characteristics that enhance friction against runoff (soil cover, crop height, and leaf area index) were considered for the buffer strips.

The well-managed no-till areas were represented similarly to the buffer strips. These sites also had increased infiltration (K_{sat} and θ_s), reduced runoff velocity (*n*), augmented RR, and vegetation characteristics that provide enhanced friction to runoff (soil cover, crop height, and leaf area index). However, these changes were less significant than in the buffer strip areas, considering that well-managed no-till areas are affected by the intensive use of agricultural machinery and the presence of commercial croplands that do not exhibit significant residual vegetation cover, such as soybeans.

Table 1. Parameters used to characterize Scenarios 1 and 2

Conservation practices	K_{sat}	θ_s	*n*	SC	CH	LAI	RR
	mm h^{-1}	cm^3 cm^{-3}			m	m^2	cm
Well-managed no-till	80	>0.49	0.5	1	1	3	4
Buffer strips	200	0.58	0.5	1	2	4	5

K_{sat}: Saturated hydraulic conductivity (mm h^{-1}); θ_s: total porosity (cm cm^{-3}); *n*: Manning's coefficient (-); SC: soil cover fraction (-); CH: crop height (m); LAI: leaf area index (m^2); RR: random roughness (cm).

RESULTS AND DISCUSSION

Characteristics of the monitored events

We analyzed 14 events in 2022 and 2023, representing different rainfall conditions and times of the year. It was evident that these two years exhibited significantly different rainfall patterns. While the latter half of 2022 was characterized by a drought, the same period in 2023 experienced more intense rainfall, correlating to a critical flooding period in Rio Grande do Sul. These distinct conditions underscore the imperative for strategies that adapt cultivation systems to manage the data stemming from excessive rainfall by maximizing water storage within the soil profile and enhancing the recharge of underground reserves to mitigate drought effects.

According to the analysis in table 2, the events with the highest runoff coefficients (C >50 %) occurred in the second half of 2023. Event 10 exhibited the highest C value (76 %) compared to the others. This event also recorded the highest QE, QP, and EI30 values, indicating its significant degradation potential. The events with the next highest CE values (>50 %) were events 6, 8, and 9. In other words, half of the events in the latter half of 2023 analyzed here resulted in over half of the rainfall volume being lost through surface runoff. Despite the uncertainties associated with the runoff separation method employed (Chow, 1994), the C's are notably high for the agricultural conditions of this catchment. Clearly, there is a strong influence of the relief in the plateau edge region as well as the magnitude of the events, but the effects of soil management are pivotal factors in controlling runoff in this catchment.

Calibration and validation of hydrological variables

For model calibration, ten events (Events 1–10) were utilized, while four events (Events 11–14) were selected for validation. The set of events was selected to represent different magnitudes and times of year. Results obtained in the calibration are shown in table 2 and figure 5. The adjustments for Q_P (peak flow) and T_P (time to peak) showed better results when compared to Q_E (total runoff volume). However, Q_E can provide a better result when adjusting Q_E at the expense of Q_P and T_P. In this study, we prioritized Q_P, considering its greater importance in degradation processes such as concentrated erosion and fluvial erosion. Events with high rainfall intensities, such as event 10, and those with multiple peaks, presented greater difficulty in the calibration process, which led to less satisfactory results. Other authors have also reported the difficulty of calibrating events of greater magnitude and with more than one peak with the LISEM (Silva et al., 2021; Basso et al., 2024).

As described above, the variables Q_E, Q_P, and T_P were calibrated by adjusting the parameters K_{sat}, θ_i, and n. The parameter θ_i had the greatest interference in the calibration process, demonstrating its importance in controlling surface runoff, despite the challenge of representing it spatially in the catchment. This parameter was calibrated based on previous rainfall by trial and error. Even with a dense hydrological sampling grid, representing the spatial and temporal variability of θ_i in the landscape is complex (Swarowsky et al., 2012). The interaction between the controlling factors (relief, soils, land use, and climate) determines a spatial and temporal complexity that leads to high uncertainty in defining this important model input parameter. The difficulty of representing θ_i and its interference in modeling surface runoff with LISEM in southern Brazil was also reported by Silva et al. (2021), Bernardi (2022), and Schlesner (2022). The heterogeneity of runoff generation in catchments is related to the response of soil moisture to precipitation. Moisture depends on rainfall characteristics, topography, and soil characteristics (Singh et al., 2021). Some areas saturate more quickly, either due to the presence of restrictive layers or the expansion of wetlands (Cheng et al., 2014; Machado et al., 2022). Because of these characteristics, moisture conditions exhibit significant spatiotemporal variability and are difficult to measure on a catchment scale (Suo et al., 2017; Gou et al., 2022).

Table 2. Hydrological characteristics of the selected events

Event	Date	P3	P_T	D	EI_{30}	Q_T	Q_B	Q_E	Q_P	T_P	C	TR
		mm	mm	min		m³	m³	m³	m³ s⁻¹	min	%	yrs
1	04/26/2022	40	29	190	15882	188009	90243	97673	11	230	17	0.3
2	06/21/2022	0	30	985	125	272710	166722	105933	3	815	18	0.1
3	07/14/2022	48	56	605	21521	512371	136800	375570	57	340	35	0.5
4	07/16/2022	71	23	270	4838	212424	117818	94606	11	215	21	0.1
5	09/18/2022	0	40	830	8395	33649	14188	19606	1	965	3	0.2
6	07/12/2023	0	103	585	25166	1270755	222937	1047638	107	530	54	5.1
7	09/07/2023	123	72	520	47778	221677	89091	132377	16	410	10	1.3
8	09/12/2023	0	96	1530	38798	1558109	572536	985330	37	435	53	1.2
9	10/16/2023	0	80	1525	22868	1345551	380753	964616	51	625	63	0.7
10	11/12/2023	10	89	905	61075	1693311	391706	1301163	180	235	76	1.5
11	08/03/2022	0	38	635	3452	97412.3	53452	43916.4	4	695	6	0.2
12	09/04/2023	14	81	1485	31863	822223	349466	472496	12	1295	30	0.7
13	07/07/2023	0	87	1090	14640	362215	161738	200430	6	1060	12	1.2
14	11/02/2023	0	76	1505	41264	360395	229617	130798	10	670	9	0.6

P_3: 3 Days previous rainfall; P_T: total precipitation; D: rainfall duration; EI_{30}: rainfall erosivity at maximum rainfall of 30 minutes (J mm m^{-2} h^{-1}); Q_T: total volume; Q_B: total volume of baseflow; Q_E: total volume of surface runoff; Q_P: peak flow; T_P: time to peak; C:runoff coefficient.

Table 3. Observed and simulated hydrological variables in the calibrated events

Event	Date	P_T	EI_{30}	Q_E		Q_P		T_P	
				Obs	Sim	Obs	Sim	Obs	Sim
		mm	-	m³	m³	m³	m³	min	min
1	04/26/2022	29.4	15882	97673	102478	11	11	230	230
2	06/21/2022	30.0	125	105933	100153	3	4	815	790
3	07/14/2022	56.3	21521	375570	545960	57	53	340	335
4	07/16/2022	23.2	4838	94606	108311	11	11	215	210
5	09/18/2022	39.9	8395	19607	18310.9	1	1	965	945
6	07/12/2023	102.5	25166	1047638	1558086	107	86	530	530
7	09/07/2023	72.2	47778	132377	243885	16	17	410	435
8	09/13/2023	96.1	38798	985332	1099158	37	39	435	665
9	10/16/2023	79.8	22868	964616	1095392	50	47	625	615
10	11/12/2023	88.8	61075	1301163	1319327	180	93	235	240

P_T: total precipitation; EI_{30}: rainfall erosivity at maximum precipitation of 30 minutes (J mm m^{-2} h^{-1}); Q_E: total volume of surface runoff; Q_P: peak flow; T_P: time to peak; Obs: observed value; Sim: simulated value.

In the runoff monitoring and modeling study carried out by Barros et al. (2021), high K_{sat} values were measured on the hillslopes despite high runoff values, requiring a significant adjustment of this parameter during the calibration of the LISEM. Schlesner (2022), however, by representing in detail the areas of variable inflow in the catchment, more accurately represented the areas that contribute to runoff formation. Areas of variable inflow, areas of saturation, and impermeable sites are challenging to represent and require detailed study to identify and accurately depict the catchment. In this manner, hydrologically fragile areas were identified through field observations and topographic indices, determining the moisture conditions before events with less uncertainty. The results obtained in the calibration were positive and demonstrated the LISEM's ability to represent challenging areas.

The P_{BIAS} and COE values for the calibrated events are presented in table 4. The COE indicates the fit in terms of the hydrograph shape; thus all events were classified as having a "very good" fit, with the exceptions of events 6 and 7, which were classified as "unsatisfactory," according to the criteria established by Moriasi et al. (2007). The results for Q_E were deemed "very good" for events 1, 2, 5, and 10, "good" for events 4, 8, and 9, and "unsatisfactory" for events 3, 6, and 7. As for Q_P, the outcomes were considered "very good" for events 1, 3, 4, 7, 8, and 9, "good" for event 2, "satisfactory" for event 6, and "unsatisfactory" for events 5 and 10. Lastly, the results for T_P were regarded as "very good" for all events, except for event 8, which was evaluated as "unsatisfactory" (Table 4).

We proceeded to the validation stage with four events based on the calibration results. The K_{SAT} and *n* values used in the validation were calculated by averaging the calibrated values, and $θ_i$ was estimated by analyzing the previous rainfall. However, the COE and P_{BIAS} efficiency analysis was only considered "very good" for event 11.

Poorer results obtained in the validation, especially for events 12 and 14, are associated with the challenge of determining $θ_i$. While accumulating previous rainfall is a critical factor, it proves insufficient for spatially describing this parameter. Generally, it was observed that the values of Q_E and Q_P from the validation were overestimated compared to the observed results due to the elevated moisture values input into the model. The spatial variability of parameters introduces uncertainties in the validation process, indicating a need for a more robust dataset of events to derive more appropriate parameters, thereby enhancing the validation efficiency. On the other hand, Batista et al. (2019) discuss the validation stage in erosion studies, noting that the uncertainty inherent in the dynamics of environmental processes and studies introduces a fundamental challenge to validation efforts. In such contexts, calibrating specific events represents the most logical approach to interpreting results.

Despite these challenges, the measured values of K_{sat} and the *n* values determined by were found to be adequate for representing infiltration and runoff propagation on a hillslope, as noted by Schneider (2021) in no-till croplands. Only $θ_i$, which poses additional difficulty due to its high temporal and spatial variability, required comprehensive adjustment (independent of preceding rainfall). Given this, and considering the objective of this work, calibrated events were deemed sufficient for quantifying the effect of runoff reduction in calibrated events, notwithstanding the minimal significance of calibrating the parameters K_{sat} and *n*.

Table 4. Analysis of the efficiency of the LISEM in calibrating hydrological variables

Event	Date	P_{BIAS}			COE (-)
		Q_E	Q_P	T_P	
			%		
1	04/26/2022	5	-2	0	1.0
2	06/21/2022	-6	15	-3	0.8
3	07/14/2022	45	-8	-2	0.8
4	07/16/2022	15	3	-2	1.0
5	09/18/2022	-7	28	-2	0.8
6	07/12/2023	49	-19	0	0.5
7	09/07/2023	84	3	6	0.3
8	09/12/2023	12	7	53	0.9
9	10/16/2023	14	-6	-2	0.9
10	11/12/2023	1	-48	2	0.8

Q_E: total runoff volume; Q_P: peak flow; T_P: time to peak.

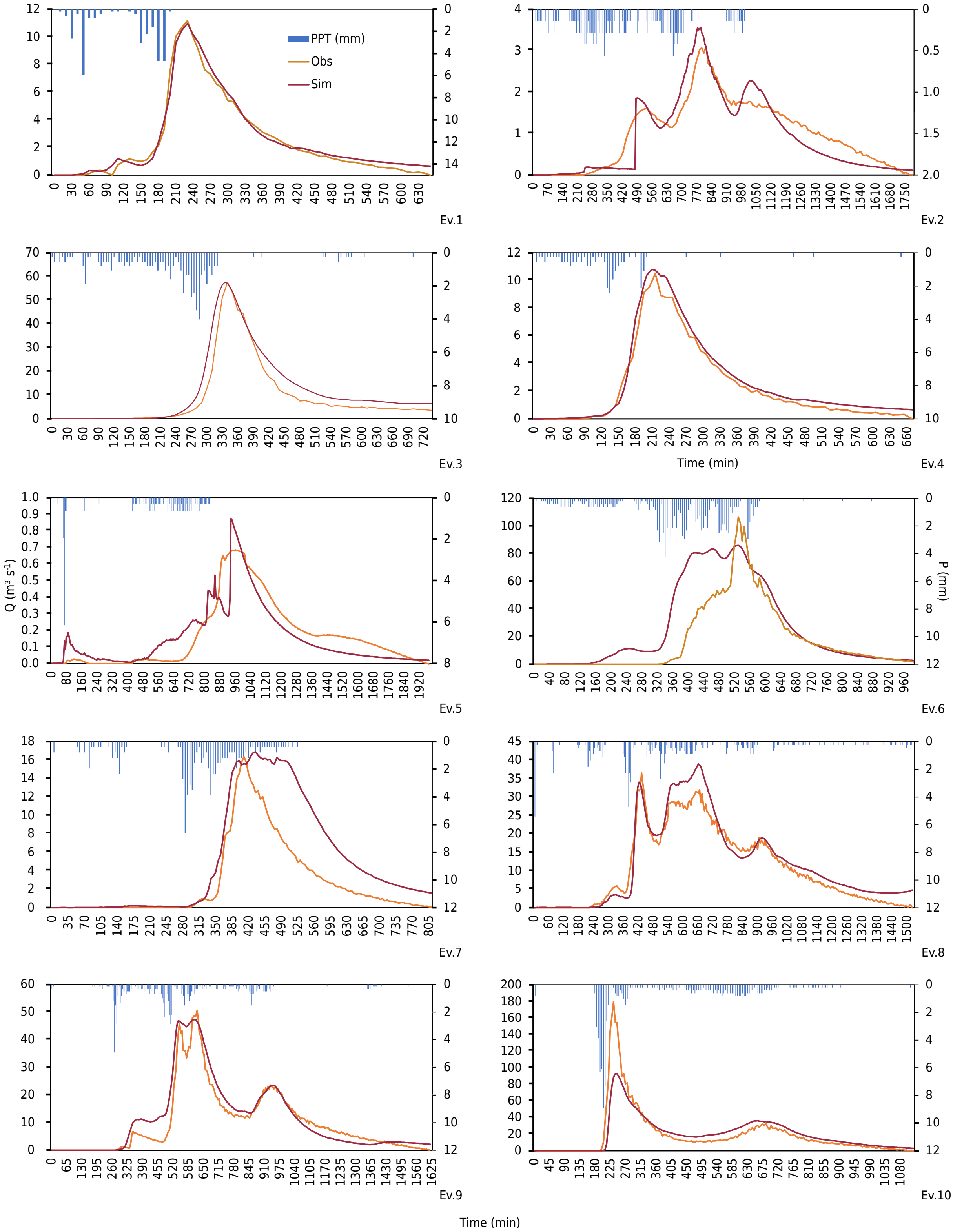

Figure 5. Hydrographs of the calibrated events.

The modeling results underscore the importance of hydrological monitoring, as it enabled the initial moisture parameter adjustment based on monitored streamflow data. Consequently, impacts observed upstream are mirrored in the outflow, rendering the catchment a critical unit for conservation planning. The intrinsic relationship established by hydrological monitoring in support of mathematical modeling plays a pivotal role in developing strategies for adapting production systems and making informed decisions.

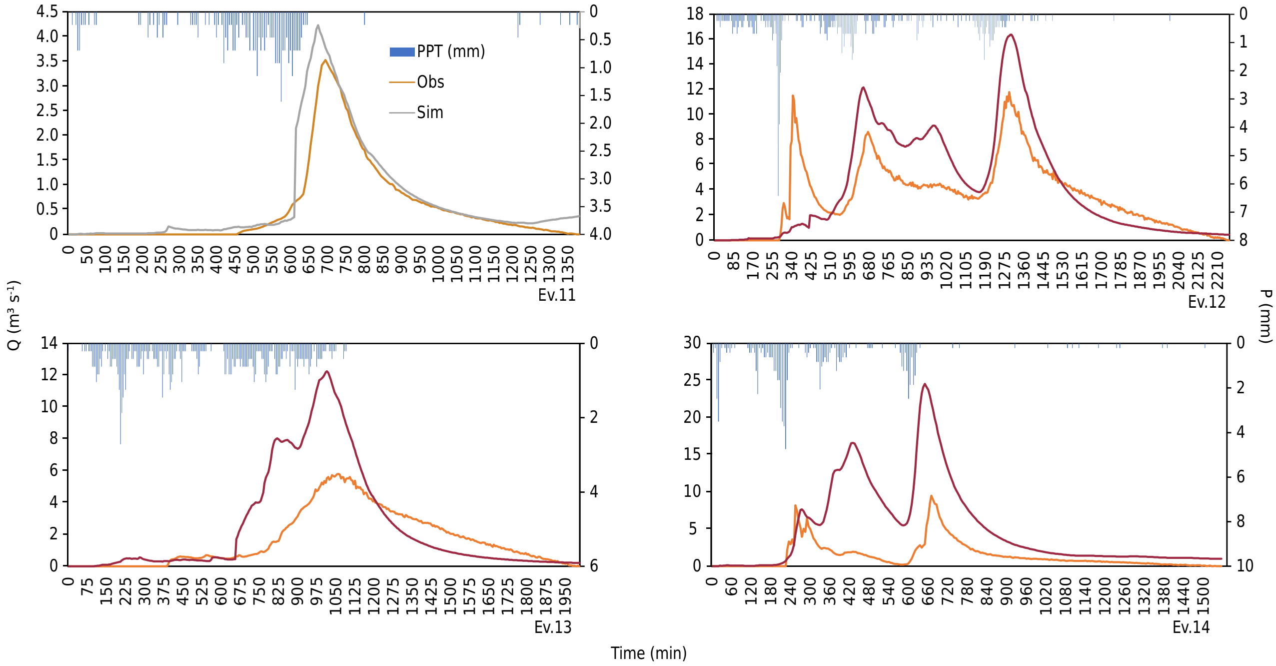

Figure 6. Hydrographs of the events used for validation.

Utilizing these tools collectively facilitates an integrated landscape analysis, leading to identifying hydrologically vulnerable areas within the catchment. An additional benefit of monitoring to support modeling is evaluating the impacts of various scenario configurations before their actual field implementation. This approach significantly accelerates the time required to generate results compared to conducting field experiments (Mekonnen et al., 2014). Clearly, accurately representing the predominant hydrological processes at each site is crucial for ensuring effective outcomes. Achieving this necessitates an extensive, detailed study accompanied by field observations to depict the dominant processes at each location adequately. In this investigation, croplands were identified as important contributors to surface runoff, considering the impacts observed in the simulations. The absence of complementary conservation practices, such as retention broad-based terraces, significantly affects the flash flood at the catchment outlet, as observed by Didoné et al. (2017) and Han et al. (2020).

Various studies advocate for the application of mathematical models to simulate soil and water conservation scenarios on the catchment scale (Gathagu et al., 2018; Melaku et al., 2018). While there is consensus on the advantages of implementing conservation practices in agricultural areas, some studies are hampered by a lack of measured data to underpin the findings (Rachmann et al., 2008; Giambastiani et al., 2023). Despite evaluations of the impacts resulting from the introduction of conservation practices, whether on slopes or in catchment simulations, there is a dearth of research utilizing modeling and monitoring as planning strategies. The impacts are often assessed post-implementation of these practices, serving to evaluate human activity over time. Hengsdijk et al. (2004) emphasize the significance of quantitative data in evaluating conservation practices before implementation and the challenges associated with obtaining this data.

Conservation scenarios

The strategy for representing retention broad-based terraces and buffer strips in the simulation environment was based on contour lines obtained from the numerical elevation model with an equidistance of 4 m and by modifying the physical parameters related to water and vegetation. The 2D dynamic flow simulation more accurately depicts the effect of terraces compared to the 1D flow simulation, but requires significantly more time. As previously mentioned, since the retention terraces intercept surface runoff in the converging zones of hillslopes and redistribute it to diverging zones, the 2D method allows for the runoff halted on the terraces to be redistributed across them. The simulation time for the most prolonged rain events reached 12 h, whereas the 1D method can be completed in less than 1 h. This increased time is due to the 2D method being more dynamic and spatially distributed, necessitating a more complex calculation base.

The two levels of conservation intervention, denoted as S1 and S2, exhibited a notable decrease in the values of Q_E and Q_P. However, intervention level S2 presented a more substantial impact. The decreases in Q_E for both S1 and S2 led to a reduction in C value, which was more pronounced for S2. This suggests enhanced infiltration and water utilization through the implementation of terracing. The T_P values were not significantly altered by the scenarios, showing a variation of only 10 minutes, except for Event 9, which exhibited a variation of 30 min (Table 5 and Figure 7).

By evaluating the results presented in table 4, we can quantify the effects of S2 in reducing Q_E and Q_P and compare with S1. Hence, S2 demonstrated an average reduction of 30 and 28 % in calibrated Q_E and Q_P, respectively. In contrast, S1 exhibited an average reduction of 7 and 6 % for Q_E and Q_P.

Conservation intervention level S1 exhibited the highest Q_E for event 3 (9 %). Events 6 and 8 witnessed a reduction of 5 %, events 9 and 10 experienced a reduction of 6 %, and event 1 had a reduction of 8 %. Regarding Q_P, event 10 showed the highest percentage reduction of 15 %. The rest of the events underwent a reduction of less than 10 %, except for event 6, which showed no reduction in Q_P. Buffer strips play a critical role in controlling surface runoff and intercepting sediment. These barriers function as filters, maximizing infiltration through vegetation presence and slowing the velocity of surface runoff.

Table 5. Results of the change in intervention levels for Scenarios 1 and 2 in relation to the calibration simulation and percentage change (P_{BIAS}) in relation to the calibrated phase

Date		Q_E	Q_P	T_P	C	P_{BIAS}		
						Q_E	Q_P	T_P
		m	$m^3 s^{-1}$	min	%			
07/14/2022 (Ev3)	Cal	545960	53	335	52			
	S1	496837	52	330	47	-9	-1	-1
	S2	336636	40	330	32	-38	-24	-1
07/12/2023 (Ev6)	Cal	1558086	86	530	81			
	S1	1469415	83	530	78	-6	0	-3
	S2	1238591	70	530	66	-21	-18	0
09/12/2023 (Ev8)	Cal	1099158	39	660	61			
	S1	1041082	37	670	58	-5	-6	2
	S2	827761	28	670	46	-25	-28	2
10/16/2023 (Ev9)	Cal	1095392	47	615	73			
	S1	1028071	44	545	69	-6	-7	11
	S2	814035	34	540	55	-26	-28	-12
11/12/2023 (Ev10)	Cal	1319327	93	240	79			
	S1	1230595	79	235	74	-7	15	-2
	S2	1011010	67	240	61	-23	-28	0
08/03/2022 (Ev11)	Cal	57435	4	675	8			
	S1	52722	4	660	7	-8	-6	-2
	S2	30899	3	655	4	-46	-40	-3

Ev: event; Cal: calibrated; S1: Scenario 1; S2: Scenario 2; Q_E: runoff volume; Q_P: peak flow; T_P: time to peak; C: runoff coefficient.

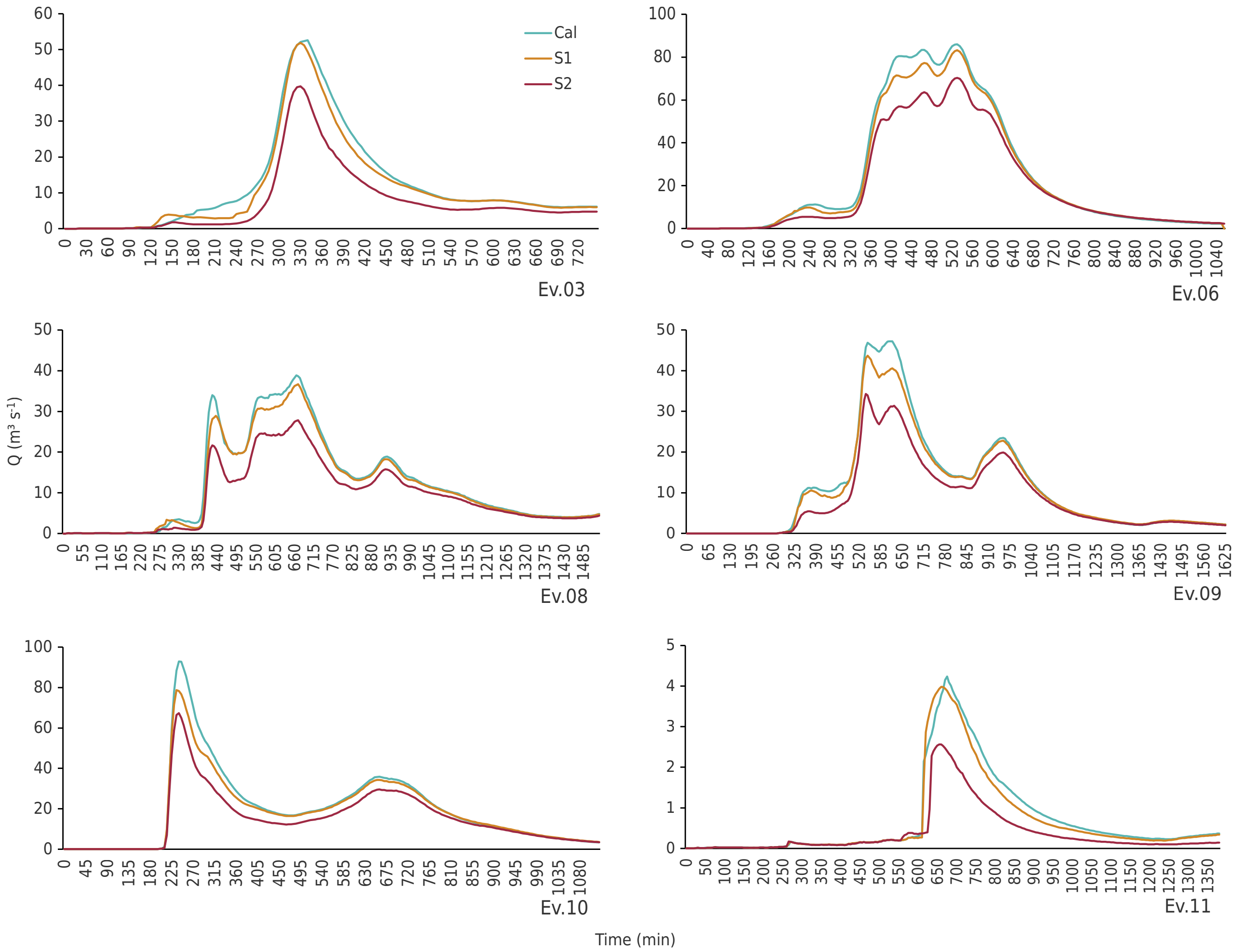

Figure 7. Hydrographs representing the conservation intervention Scenarios 1 and 2.

Zhang et al. (2022) found a 39 % reduction in surface runoff with the deployment of buffer strips on a sandy slope in China. Nevertheless, this contribution diminished as rainfall intensity and slope gradient increased. The resistance provided by buffer strips also promotes sediment deposition. Gathagu et al. (2018) assessed the implementation of conservation practices to gauge effects before field deployment and found that three-meter filter strips and contour cultivation decreased the average annual sediment yield at the catchment outlet by 46 and 36 %, respectively. When a 10 m buffer strip was implemented, a 66 % reduction in average annual sediment production was observed.

The behavior of surface runoff and infiltration on September 12, 2023, considering S1 (well managed agricultural area + buffer strips), is illustrated in figure 8. Surface runoff is predominant in cropland with shallow soils (e.g., Leptosols and Regosols) and similar in cropland with deep soils and in forests. Therefore, buffer strips were effective in reducing surface runoff, particularly in cropland with deep soils. Conversely, in areas with shallow soils, buffer strips contributed less significantly to surface runoff reduction. The same rationale applies to the infiltration process in the catchment. In shallow soils, infiltration was lower than in deeper soils, thereby rendering buffer strips in shallow soils less efficient.

Conservation intervention level S2 made the most significant contribution to reducing surface runoff. Events 1 and 3 showed the greatest reduction in $Q_{E,}$ 46 and 38 %, respectively. Events 6, 8, 9, and 10 exhibited reductions of 20, 25, 26, and 23 %. The Q_P demonstrated a greater reduction for Event 1 (39 %), while Events 3, 6, 8, 9, and 10 showed reductions of 24, 18, 28, 27, and 28 %. The allocation of terraces as a complementary practice for water and soil management has proven essential for events with a return period greater than two years. These results corroborate those obtained by Londero et al. (2021b), who indicated an average reduction in surface runoff of 56 % in catchments with the presence of terraces. However, it is important to note that in this study, the value of Q_E has a significant contribution from other sources of runoff since the variable is measured in a heterogeneous catchment, unlike the article cited above, where the runoff comes only from the slope under cultivation and with the practice. Giambastiani et al. (2023) indicated a reduction in surface runoff with contour seeding and with increased roughness through "keylines," which are small trenches (0.20 m high and 2 m apart) built to direct the flow of runoff to the divergent region of the slope, thereby avoiding the concentration of runoff. However, the "keylines" effects are temporary and involve a significant amount of revolved soil, which intensifies the carbon loss through oxidation and exposes the soil to erosive agents. Strohmeier et al. (2015) evaluated plots and found that stone structures arranged on a contour reduced sediment yield by 40 % and surface runoff by 66 % compared to plots without conservation structures, emphasizing the importance of roughness and increased friction to surface runoff.

In another study, Rachman et al. (2008) employed bench terraces combined with other conservation practices (vegetation) to reduce runoff by 22 % and sediment by 79 % compared to individual effects (9 and 58 %). Through measured data, Melaku et al. (2018) evaluated the effects on sediment yield of two similar catchments after the construction of stone and soil hillocks built along the contour on the agricultural slopes of one of them. The authors observed a 25-38 % reduction in the catchment's total sediment yield with the presence of the conservation practice. The results simulated with the SWAT model for this catchment underestimated the actual observed values.

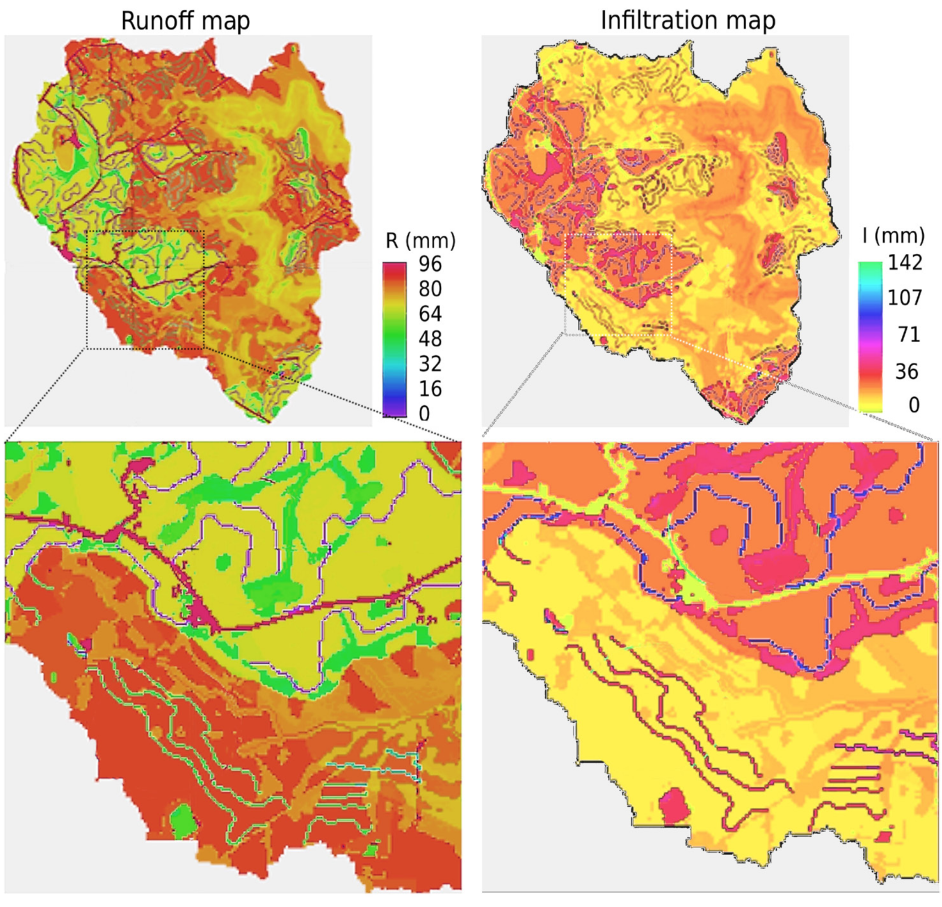

Figure 8. Representation of the surface runoff control and infiltration in the cropland of the catchment.

Controlling surface runoff and maximizing infiltration in these areas increased water storage and availability for plants (Freitas et al., 2021), which is especially important during droughts. Furthermore, retention terraces contribute to an increase in crop yields; Hörbe et al. (2021) indicated an increase in soybean yields of 12 % and corn yields of 10 % in areas with retention terraces.

The partial use of the no-till system and issues such as soil compaction, which affect infiltration and reduce roughness, lead to the formation and propagation of surface runoff on agricultural slopes (Hamza and Anderson, 2005). Consequently, agricultural areas become more vulnerable from a hydrological perspective, missing the opportunity to store more water and causing larger impacts on water resources (Merten et al., 2015; Londero et al., 2021b). Therefore, catchments are crucial for conservation planning in slopes under agricultural production. By introducing conservation practices in these areas, surface connectivity between the slope and the drainage network can be reduced, helping to increase infiltration at the site and reducing downstream impacts (Minella et al., 2008; Kaiser, 2009).

The LISEM was efficient in describing the surface runoff formation and propagation and the effects of terracing in the catchment scale. The modeling of these processes is challenging given the spatial variability of control factors such as soil properties, relief, land use, and soil management. The existing parameters in the LISEM equations adequately capture the processes influenced by agricultural management practices, mainly saturated hydraulic conductivity, antecedent moisture, porosity, Manning's coefficient, soil cover, aggregate stability, and soil cohesion. To evaluate mechanical structures as terraces, we need more complex, physically based, and distributed models with higher spatial resolutions (Im et al., 2012). As operational challenges, there is the need for greater preparation of the modeling environment and greater knowledge of the processes and variables that control these processes, their equations and their parameters, such as those indicated by Govers et al. (2011). The LISEM (De Roo, 1996) is one of the few that already has some standard conservation practices embedded and allows for the representation of others, considering the processes on the scale of the event, sub-daily and even sub-hourly. Most studies involving LISEM have had a restricted objective so far for its calibration and validation, as in Barros et al. (2021). However, some have already been used for practical evaluation of the effect of soil covers (Hessel et al., 2010), forested basins (Rodrigues et al., 2014), impact of the road system on erosion (Silva et al., 2021), degradation by fires (Wu et al., 2021), impact on the river system (Vargas et al., 2021), impact of erosion in rural catchments under no-till (Ebling et al., 2022), and places with hydrological fragility such as riparian forests and humid regions, which control the dynamics of surface runoff (Grum et al., 2017).

A recent survey on erosive models carried out by Borrelli et al. (2021) points out that the RUSLE (Renard et al., 1997), USLE (Wischmeier and Smith, 1978), WEPP (Laflen et al., 1991), SWAT (Arnold et al., 2012), WATEM/SEDEM (Van Oost et al., 2000) and LISEM (De Roo et al., 1996) models are among the most used in the literature in recent decades, according to their proposals and aptitudes. The RUSLE, USLE, and SWAT are empirical and are most often used to represent soil losses over small and large catchments. RUSLE (Pandey et al., 2021) differentiates itself by evaluating practices to protect against the direct impact of raindrops by soil cover. It estimates soil losses by type of cover (factor C) and use of conservation practices (factor P). Didoné et al. (2017) evaluated the effect of no-tillage through the model, validating its use. The study by Arega et al. (2024) on a catchment in Ethiopia, detected a limitation of the model due to the existence of erosive processes in the form of gully that miss in the model. The SWAT is a catchment semi-distributed that operates on a daily timescale. Osei et al. (2019) predicted a 30-year (2021–2050) streamflow for the Owabi catchment under two land uses and three climate change scenarios with SWAT. The model proved to be efficient in determining the catchment hydrology parameters and has the potential to be used for further modeling of water quality and pollution to aid in effective water management. Bonumá et al. (2014) used SWAT to evaluate three scenarios of management practices: conventional tillage, minimum tillage, and no-tillage, with a 50 % reduction in the fertilizer application rate for 30 years in the dynamics of erosion and phosphorus losses, indicating that the adoption of conservationist preparations reduces the pollutant effect of the element. Conservation practices of soil cover have greatly reduced soil losses, but they have not yet been sufficient to prevent the harmful spread of excess surface runoff, even in no-tillage systems, notably in tropical and equatorial regions due to the large volume of precipitation.

CONCLUSIONS

The application of the 2-dimensional dynamic wave method in the Limburg Soil Erosion Model (LISEM), which relies on Manning's equation to guide water flow, successfully illustrated the impact of broad-based terraces, thereby enabling the quantification of two disparate runoff control strategies. Conservation Scenario 1, which combines well-managed no-till practices with buffer strips, demonstrated an average reduction in runoff, specifically 7 % in total event runoff (Q_E) and 6 % in peak discharge (Q_P). Conversely, implementing mechanical water management structures as retention terraces (i.e., Conservation Scenario 2) showed a more significant average decrease in runoff within the catchment area—30 % for Q_E and 28 % for Q_P, respectively. Our findings underscore the utility of integrating hydrological monitoring of experimental catchments with event-scale runoff modeling in the planning and management of rural catchments. The results highlight the effectiveness of conservation practices within agricultural land and underscore their vital role in mitigating surface runoff (peak and volume) in a catchment. Additionally, these findings enhance the value of research and programs aimed at compensating producers for delivering environmental services. By quantifying the impact of agricultural practices on the hydrological response of a catchment, this work affirms farmers' pivotal role in diminishing impacts through adopting sustainable agricultural practices.

DATA AVAILABILITY

The data will be provided upon request.

FUNDING

This study was supported by the National Council for Scientific and Technological Development - CNPq, and Foundation of Support for Research of the State of Rio Grande do Sul – FAPERGS.

AUTHOR CONTRIBUTIONS

Conceptualization: Douglas Rodrigo Kaiser (equal), Gustavo Henrique Merten (equal), Jean Paolo Gomes Minella (lead) and Larissa Werle (equal).

Formal analysis: Alexandre Schlesner (equal), Felipe Bernardi (equal), Jean Paolo Gomes Minella (lead) and Larissa Werle (equal).

Investigation: Alice Prates Bisso Dambroz (equal), Blayon Eduardo Hammes (equal), Felipe Bernardi (equal), Jean Paolo Gomes Minella (lead) and Larissa Werle (equal).

Methodology: Jean Paolo Gomes Minella (lead) and Larissa Werle (equal).

Project administration: Jean Paolo Gomes Minella (lead).

Supervision: Jean Paolo Gomes Minella (lead).

Writing – original draft: Alexandre Schlesner (equal), Alice Prates Bisso Dambroz (equal), Blayon Eduardo Hammes (equal), Douglas Rodrigo Kaiser (equal), Felipe Bernardi (equal), Gustavo Henrique Merten (equal), Jean Paolo Gomes Minella (lead) and Larissa Werle (equal).

Writing – review & editing: Alexandre Schlesner (equal), Alice Prates Bisso Dambroz (equal), Blayon Eduardo Hammes (equal), Douglas Rodrigo Kaiser (equal), Felipe Bernardi (equal), Gustavo Henrique Merten (equal), Jean Paolo Gomes Minella (lead) and Larissa Werle (equal).

REFERENCES

Abaci O, Papanicolaou AT. Long-term effects of management practices on water-driven soil erosion in an intense agricultural sub-watershed: Monitoring and modelling. Hydrol Process. 2009;23:2818-37. https://doi.org/10.1002/hyp.7380

Arega E, Deribew KT, Moisa MB, Gemeda DO. Assessment of soil erosion and prioritization of conservation and restoration measures using RUSLE and Geospatial techniques: The case of upper Bilate watershed. Geomat Nat Haz Risk. 2024;15:2336016. https://doi.org/10.1080/19475705.2024.2336016

Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White MJ, Srinivasan R, Santhi C, Harmel RD, Van Griensven A, van Liew MW, Kannan N. SWAT: Model use, calibration, and validation. T ASABE. 2012;55:1491-508. https://doi.org/10.13031/2013.42256

Barros CAP, Govers G, Minella JPG, Ramon R. How water flow components affect sediment dynamics modeling in a Brazilian catchment. J Hydrol. 2021;597:126111. https://doi.org/10.1016/j.jhydrol.2021.126111

Basso M, Baartman J, Martins M, Keizer J, Vieira D. Predicting post-fire hydrological and erosive catchment response during rainfall events. A comparison of OpenLISEM and MOHID Land models. J Hydrol. 2024;636:131258. https://doi.org/10.1016/j.jhydrol.2024.131258

Batista PVG, Davies J, Silva MLN, Quinton JN. On the evaluation of soil erosion models: Are we doing enough? Earth-Sci Rev. 2019;197:102898. https://doi.org/10.1016/j.earscirev.2019.102898

Bernardi F. Caracterização e modelagem dos processos erosivos com interface canal-encosta em bacias de elevado gradiente topográfico: o caso da bacia experimental do rio Guarda Mor [thesis]. Santa Maria: Universidade Federal Santa Maria; 2022.

Bonumá NB, Rossi CG, Arnold JG, Reichert JM, Minella JP, Allen PM, Volk M. Simulating landscape sediment transport capacity by using a modified SWAT model. J Environ Qual. 2014;43:55-66. https://doi.org/10.2134/jeq2012.0217

Borrelli P, Alewell C, Alvarez P, Anache JAA, Baartman J, Ballabio C, Bezak N, Biddoccu M, Cerdà A, Chalise D, Chen S, Chen W, Girolamo AM, Gessesse GD, Deumlich D, Diodato N, Efthimiou N, Erpul G, Fiener P, Freppaz M, Gentile F, Gericke A, Haregeweyn N, Hu B, Jeanneau A, Kaffas K, Kiani-Harchegani M, Villuendas IL, Li C, Lombardo L, López-Vicente M, Lucas-Borja ME, Märker M, Matthews F, Miao C, Mikoš M, Modugno S, Möller M, Naipal V, Nearing M, Owusu S, Panday D, Patault E, Patriche CV, Poggio L, Portes R, Quijano L, Rahdari MR, Renima M, Ricci GF, Rodrigo-Comino J, Saia S, Samani AN, Schillaci C, Syrris V, Kim HS, Spinola DN, Oliveira PT, Teng H, Thapa R, Vantas K, Vieira D, Yang JE, Yin S, Zema DA, Zhao G, Panagos P. Soil erosion modelling: A global review and statistical analysis. Sci Total Environ. 2021;780:146494. https://doi.org/10.1016/j.scitotenv.2021.146494

Bout B, Jetten VG. The validity of flow approximations when simulating catchment-integrated flash floods. J Hydrol. 2018;556:674-88. https://doi.org/10.1016/j.jhydrol.2017.11.033

Cheng X, Shaw SB, Marjerison RD, Yearick CD, DeGloria SD, Walter MT. Improving risk estimates of runoff producing areas: Formulating variable source areas as a bivariate process. J Environ Manage. 2014;137:146-56. https://doi.org/10.1016/j.jenvman.2014.02.006

Chow VT, Maidment DR, Mays LW. Hidrología aplicada. Santafé de Bogotá, Colombia: McGraw-Hill; 1994.

Dambroz APB, Minella JPG, Tiecher T, Moura-Bueno JM, Evrard O, Pedron FA, Dalmolin RSD, Bernardi F, Schneider FJA, Cerdan O. Terrain analysis, erosion simulations, and sediment fingerprinting: a case study assessing the erosion sensitivity of agricultural catchments in the border of the volcanic plateau of Southern Brazil. J Soils Sediments. 2022;22:1023-40. https://doi.org/10.1007/s11368-022-03139-6

De Roo APJ. The Lisem project: An introduction. hydrological processes. Hydrol Process. 1996;10:1021-5. https://doi.org/10.1002/(SICI)1099-1085(199608)10:8%3C1021::AID-HYP407%3E3.0.CO;2-I

De Roo APJ, Wesseling CG, Jetten VG, Ritsema CJ. LISEM: A physically-based hydrological and soil erosion model incorporated in a GIS. IAHS Publication. 1996;235:395-403.

Deuschle D, Minella JPG, Hörbe TAN, Londero AL, Schneider FJA. Erosion and hydrological response in no-tillage subjected to crop rotation intensification in southern Brazil. Geoderma. 2019;340:157-63. https://doi.org/10.1016/j.geoderma.2019.01.010

Didoné EJ, Minella JPG, Evrard O. Measuring and modelling soil erosion and sediment yields in a large cultivated catchment under no-till of Southern Brazil. Soil Till Res. 2017;174:24-33. https://doi.org/10.1016/j.still.2017.05.011

Didoné EJ, Minella JPG, Merten GH. Quantifying soil erosion and sediment yield in a catchment in southern Brazil and implications for land conservation. J Soils Sediments. 2015;15:2334-46. https://doi.org/10.1007/s11368-015-1160-0

Ebling ÉD, Reichert JM, Minella JPG, Holthusen D, Broetto T, Srinivasan R. Rainfall event-based surface runoff and erosion in small watersheds under dairy and direct-seeding grain production. Hydrol Process. 2022;36:e14688. https://doi.org/10.1002/hyp.14688

Engman ET. Roughness coefficients for routing surface runoff. J Irrig Drain Eng. 1986;112:39-53. https://doi.org/10.1061/(ASCE)0733-9437(1986)112:1(39)

Fashaho A, Ndegwa GM, Lelei JJ, Musandu AO, Mwonga SM. Effect of land terracing on soil physical properties across slope positions and profile depths in medium and high altitude regions of Rwanda. S Afr J Plant Soil. 2020;37:91-100. https://doi.org/10.1080/02571862.2019.1665722

Freitas LDR, Gubiani PI, Mulazzani RP, Minella JPG, Londero AL. Terracing increases soil available water to plants in no-tillage. Rev Bras Cienc Solo. 2021;45:e0210046. https://doi.org/10.36783/18069657rbcs20210046

Fuentes-Llanillo R, Telles TS, Soares Junior D, Melo TR, Friedrich T, Kassam A. Expansion of no-tillage practice in conservation agriculture in Brazil. Soil Till Res. 2021;208:104877. https://doi.org/10.1016/j.still.2020.104877

Gathagu JN, Mourad KA, Sang J. effectiveness of contour farming and filter strips on ecosystem services. Water. 2018;10:1312. https://doi.org/10.3390/w10101312

Giambastiani Y, Biancofiore G, Mancini M, Di Giorgio A, Giusti R, Cecchi S, Gardin L, Errico A. Modelling the effect of keyline practice on soil erosion control. Land. 2022;12:100. https://doi.org/10.3390/land12010100

Gou Q, Guo W, Li Y, Liu J, Wang G. Dynamic changes in soil moisture in three typical landscapes of the Heihe River Basin. Front Environ Sci. 2022;10:1049883. https://doi.org/10.3389/fenvs.2022.1049883

Govers G, Licciardello F, Zema DA, Zimbone SM. Evaluation of the WEPP model in a Belgian agricultural watershed. J Environ Sci Eng. 2011;5:184-98.

Grum B, Woldearegay K, Hessel R, Baartman JEM, Abdulkadir M, Yazew E, Kessler A, Ritsema CJ, Geissen V. Assessing the effect of water harvesting techniques on event-based hydrological responses and sediment yield at a catchment scale in northern Ethiopia using the Limburg Soil Erosion Model (LISEM). Catena. 2017;159:20-34. https://doi.org/10.1016/j.catena.2017.07.018

Hamza MA, Anderson WK. Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil Till Res. 2005;82:121-45. https://doi.org/10.1016/j.still.2004.08.009

Han J, Ge W, Hei Z, Cong C, Ma C, Xie M, Liu B, Feng W, Wang F, Jiao J. Agricultural land use and management weaken the soil erosion induced by extreme rainstorms. Agr Ecosyst Environ. 2020;301:107047. https://doi.org/10.1016/j.agee.2020.107047

Hydrologic Engineering Center River Analysis System - HEC RAS. HEC-RAS hydraulic reference manual. Version 6.0 Beta. Davis, CA: HEC RAS; 2020.

Hengsdijk H, Meijerink GW, Mosugu ME. Modeling the effect of three soil and water conservation practices in Tigray, Ethiopia. Agr Ecosyst Environ. 2005;105:29-40. https://doi.org/10.1016/j.agee.2004.06.002

Hessel R, Jetten VG, Liu B, Qiu Y. Evaluating effects of soil and water management and land use change on the loess plateau of China using LISEM. In: Morgan RPC, Nearing MA, editors. Handbook of erosion modelling. Hoboken, Nova Jersey: Wiley-Blackwell; 2010. p. 223-48. https://doi.org/10.1002/9781444328455.ch12

Hörbe T, Minella JPG, Schneider FJA, Londero AL, Gubiani PI, Merten GH, Schlesner A. Managing runoff in rainfed agriculture under no-till system: potential for improving crop production. Rev Bras Cienc Solo. 2021;45:e0210015. https://doi.org/10.36783/18069657rbcs20210015

Im SS, Kim M, Kim JH, Paik K. Comparison of RUSLE and LISEM for the evaluation of spatial distribution of simulated sediment yield. J Korean Soc Hazard Mitig. 2012;12:199-206. https://doi.org/10.9798/KOSHAM.2012.12.5.199

IUSS Working Group WRB. World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. Rome: Food and Agriculture Organization of the United Nations; 2015. (World Soil Resources Reports, 106).

Kaiser DR. Nitrato na solução do solo e na água de fontes para consumo humano numa microbacia hidrográfica produtora de fumo [dissertation]. Santa Maria: Universidade Federal Santa Maria; 2006.

Köppen W. Climatologia: Fundo de cultura econômica. México: Buenos Aires; 1931.

Laflen JM, Elliot WJ, Simanton JR, Holzhey CS, Kohl KD. WEPP Soil erodibility experiments for rangeland and cropland soils. J Soil Water Conserv. 1991;46(1):39-44.

Londero AL, Minella JPG, Schneider FJA, Deuschle D, Merten GH, Evrard O, Boeni M. Quantifying the impact of no-till on sediment yield in southern Brazil at the hillslope and catchment scales. Hydrol Process. 2021a;35:e14286. https://doi.org/10.1002/hyp.14286

Londero AL, Minella JPG, Schneider FJA, Deuschle D, Menezes D, Evrard O, Boeni M, Merten GH. Quantifying the impact of no-till on runoff in southern Brazil at hillslope and catchment scales. Hydrol Process. 2021b;35:e14094. https://doi.org/10.1002/hyp.14094

Machado R, Cardoso T, Mortene M. Determination of the runoff coefficient (C) in catchments based on analysis of precipitation and flow events. Int Soil Water Conserv Res. 2022;10:208-16. https://doi.org/10.22541/au.160465150.00296934/v1

Mallmann MS. Infiltração de água no solo condicionada pelo uso de plantas de cobertura. [dissertation]. Santa Maria: Universidade Federal Santa Maria; 2017.

Mekonnen M, Keesstra SD, Stroosnijder L, Baartman JEM, Maroulis J. Soil conservation through sediment trapping: A review. Land Degrad Dev. 2015;26:544-56. https://doi.org/10.1002/ldr.2308

Melaku ND, Renschler CS, Holzmann H, Strohmeier S, Bayu W, Zucca C, Ziadat F, Klik A. Prediction of soil and water conservation structure impacts on runoff and erosion processes using SWAT model in the northern Ethiopian highlands. J Soils Sediments. 2018;18:1743-55. https://doi.org/10.1007/s11368-017-1901-3

Merten GH, Araújo AG, Biscaia RCM, Barbosa GMC, Conte O. No-till surface runoff and soil losses in southern Brazil. Soil Till Res. 2015;152:85-93. https://doi.org/10.1016/j.still.2015.03.014

Minella JPG, Walling DE, Merten GH. Combining sediment source tracing techniques with traditional monitoring to assess the impact of improved land management on catchment sediment yields. J Hydrol. 2008;348:546-63. https://doi.org/10.1016/j.jhydrol.2007.10.026

Moriasi DN, Arnold JG, van Liew MW, Bingner RL, Harmel RD, Veith TL. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. T ASABE. 2007;50:885-900. https://doi.org/10.13031/2013.23153

Nash JE, Sutcliffe JV. River flow forecasting through conceptual models part I - A discussion of principles. J Hydrol. 1970;10:282-90. https://doi.org/10.1016/0022-1694(70)90255-6

Nicoloso RDS, Amado TJC, Schneider S, Lanzanova ME, Girardello VC, Bragagnolo J. Eficiência da escarificação mecânica e biológica na melhoria dos atributos físicos de um Latossolo muito argiloso e no incremento do rendimento de soja. Rev Bras Cienc Solo. 2008;32:1723-34. https://doi.org/10.1590/S0100-06832008000400037

Osei MA, Amekudzi LK, Wemegah DD, Preko K, Gyawu ES, Obiri-Danso K. The impact of climate and land-use changes on the hydrological processes of Owabi catchment from SWAT analysis. J Hydrol: Reg Stud. 2019;25:100620. https://doi.org/10.1016/j.ejrh.2019.100620

Pandey A, Gautam AK, Chowdary VM, Jha CS, Cerdà A. Uncertainty assessment in soil erosion modelling using RUSLE, multisource and multiresolution DEMs. J Indian Soc Remote Sens. 2021;49:1689-707. https://doi.org/10.1007/s12524-021-01351-4

Pedron FA, Dalmolin RSD, Moura-Bueno JM, Schenato RB, Soligo MF, Nalin RS, Freitas HM. Levantamento detalhado de solo da bacia do arroio Guarda Mor. Santa Maria: Museu de Solos do Rio Grande do Sul, Universidade Federal de Santa Maria; 2021.

Prando MB, Olibone D, Olibone APE, Rosolem CA. Infiltração de água no solo sob escarificação e rotação de culturas. Rev Bras Cienc Solo. 2010;34:693-700. https://doi.org/10.1590/S0100-06832010000300010

Rachman A, Anderson SH, Alberts EE, Thompson AL, Gantzer CJ. Predicting runoff and sediment yield from a stiff-stemmed grass hedge system for a small watershed. T ASABE. 2008;51:425-32. https://doi.org/10.13031/2013.24384

Ramon R, Minella JPG, Merten GH, Barros CAP, Canale T. Kinetic energy estimation by rainfall intensity and its usefulness in predicting hydrosedimentological variables in a small rural catchment in southern Brazil. Catena. 2017;148:176-84. https://doi.org/10.1016/j.catena.2016.07.015

Ran Q, Chen X, Hong Y, Ye S, Gao J. Impacts of terracing on hydrological processes: A case study from the Loess Plateau of China. J Hydrol. 2020;588:125045. https://doi.org/10.1016/j.jhydrol.2020.125045

Reicosky DC. Conservation tillage is not conservation agriculture. J Soil Water Conserv. 2015;70:103A-8A. https://doi.org/10.2489/jswc.70.5.103A

Renard KG. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Washington, DC: United States Department of Agriculture, Agricultural Research Service; 1997.

Rockström J, Karlberg L, Wani SP, Barron J, Hatibu N, Oweis T, Bruggeman A, Farahani J, Qiang Z. Managing water in rainfed agriculture - The need for a paradigm shift. Agr Water Manage. 2010;97:543-50. https://doi.org/10.1016/j.agwat.2009.09.009

Rodrigues MF, Reichert JM, Minella JPG, Dalbianco L, Ludwig RL, Ramon R, Rodrigues LA, Borges Júnior N. Hydrosedimentology of nested subtropical watersheds with native and eucalyptus forests. J Soils Sediments. 2014;14:1311-24. https://doi.org/10.1007/s11368-014-0885-5

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Oliveira JB, Coelho MR, Lumbreras JF, Cunha TJF. Sistema brasileiro de classificação de solos. 3. ed. rev. ampl. Rio de Janeiro: Embrapa Solos; 2013.

Schlesner AA. Funções das áreas hidrologicamente frágeis na formação e modelagem do escoamento superficial na bacia experimental do Arroio Lajeado Ferreira, Arvorezinha-RS [thesis]. Santa Maria: Universidade Federal Santa Maria; 2022.

Schneider FJA. Modeling sediment yield on hillslopes under no-till farming [thesis]. Santa Maria: Universidade Federal Santa Maria; 2021.

Silva CC, Minella JPG, Schlesner AA, Merten GH, Barros CAP, Tassi R, Dambroz APB. Unpaved road conservation planning at the catchment scale. Environ Monit Assess. 2021;193:595. https://doi.org/10.1007/s10661-021-09398-z

Singh NK, Emanuel RE, McGlynn BL, Miniat CF. Soil moisture responses to rainfall: implications for runoff generation. Water Resour Res. 2021;57:e2020WR028827. https://doi.org/10.1029/2020WR028827

Strohmeier SM, Kaltenleithner M, Melaku ND. Using magnetite tracer to evaluate a novel plot experimental design for the assessment of soil and water conservation impacts of stone bunds in Ethiopia. Conference: EGU General Assembly; 2015.

Suo L, Huang MB, Duan LX, Zhang Y. Zonal pattern of soil moisture and its influencing factors under different land use types on the Loess Plateau. Acta Ecol Sin. 2017;37:2045-53.

Swarowsky A, Dahlgren RA, O'Geen AT. Linking subsurface lateral flowpath activity with streamflow characteristics in a semiarid headwater catchment. Soil Sci Soc Am J. 2012;76:532-47. https://doi.org/10.2136/sssaj2011.0061

Tucci CEM. Modelos hidrológicos. Porto Alegre: Editora da UFRGS/ABRH; 1998.

Utzig DL, Minella JPG, Schneider FJA, Londero AL, Dambroz ABP, Barros CAP, Tiecher T, Kaiser DR. Nutrient transport in surface runoff and sediment yield on macroplots and zero-order catchments under no-tillage. Catena. 2023;231:107333. https://doi.org/10.1016/j.catena.2023.107333

Van Oost K, Govers G, Desmet P. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landscape Ecol. 2000;15:579-91. https://doi.org/10.1023/A:1008198215674

Vargas MM, Beskow S, Mello CR, Moura MM, Nunes MCM, Faria LC, Aquino LS. Capability of LISEM to estimate flood hydrographs in a watershed with predominance of long-duration rainfall events. Nat Hazards. 2021;109:593-614. https://doi.org/10.1007/s11069-021-04850-2

Werle L. Planejamento conservacionista de solo e água na bacia hidrográfica do rio Guarda Mor [dissertation]. Santa Maria: Universidade Federal Santa Maria; 2024.

Wischmeier WH, Smith DD. Predicting rainfall erosion losses: a guide to conservation planning. Washington, DC: Department of Agriculture, Science and Education Administration; 1978.

Wu J, Baartman JEM, Nunes JP. Testing the impacts of wildfire on hydrological and sediment response using the OpenLISEM model. Part 2: Analyzing the effects of storm return period and extreme events. Catena. 2021;207:105620. https://doi.org/10.1016/j.catena.2021.105620

Zhang H, Meng Q, You Q, Huang T, Zhang X. Influence of vegetation filter strip on slope runoff, sediment yield and nutrient loss. Appl Sci. 2022;12:4129. https://doi.org/10.3390/app12094129