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Articles

Land imprinter hydrological impacts for grasslands in a watershed with natural rainfall and rainfall simulation

Impacto del uso del rodillo aireador para la siembra de pasto en el proceso hidrológico de una cuenca con lluvia natural y en condiciones de lluvia simulada

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Abstract

The research was carried out in Hydrological Region 36 (Nazas-Aguanaval rivers), arid land in northern Mexico. In 2017, part of the watershed was altered during the establishment of buffel grass (*Cenchrus ciliaris L.)* with the land imprinter (AR). The objective of this research was to propose a methodological framework to integrate and analyze the experimental information of a watershed in arid lands. The impact of the AR was measured by using an in situ rainfall simulator in the watershed area. As a result, the use of AR caused a delay in the onset of runoff. The production of runoff was lower in the plot under conditions of passage in the soil of the AR, with an average production of 0.000004 m^3s^{-1}, while the average production of runoff in the plots under natural conditions (control) was 0.000016 m^3s^{-1}. Additionally, the production of sediments in the plot with AR passage was significantly higher in the production of sediments with an average value of 833 mgl^{-1}, while in the experimental plot under natural conditions, the average production of sediments was

470 mgl^{-1}. It is inferred that the microdepressions captured the rainwater exerting greater retention of the liquid in the soil, which reduced the runoff and increased the infiltration of water in the watershed. The results show that, due to its size, the watershed (158.87 ha) is very sensitive to changes in precipitation regimes and vegetation cover.

Keywords: Vegetation cover, land imprinter, micro depressions, rainfall simulator, runoff, sediments.

Resumen

La investigación se realizó en la Región Hidrológica 36 (ríos Nazas-Aguanaval), zona árida del norte de México. En 2017, parte de la cuenca fue alterada durante el establecimiento de pasto buffel (*Cenchrus ciliaris L.*) con rodillo aireador (RA). El objetivo de esta investigación fue proponer un marco metodológico para integrar y analizar la información experimental de una cuenca de zonas áridas. El impacto del RA se cuantificó mediante el uso de simulador de lluvia *in situ* en el área de la cuenca. Los resultados indican que el empleo de RA provoca un retraso en el inicio del escurrimiento. De igual manera, la producción de escurrimiento fue menor en la parcela donde se utilizó el RA, con una producción media de 0.000004 m^{3}s^{-1}, mientras que la producción media de escurrimiento en las parcelas bajo condiciones naturales (testigo) fue de 0.000016 m^{3}s^{-1}. Además, la producción de sedimentos en la parcela con paso de RA fue significativamente mayor en la producción de sedimentos, con un valor medio de 833 mgl^{-1}; en tanto que en la parcela experimental bajo condiciones naturales, la producción media de sedimentos fue de 470 mgl-1. Se infiere que las microdepresiones causadas por el RA capturaron el agua de lluvia ejerciendo una mayor retención del líquido en el suelo, lo cual redujo la escorrentía y aumentó la infiltración de agua en la cuenca. Los hallazgos muestran que, debido al tamaño, la cuenca (158.87 ha) es muy sensible a los cambios en los regímenes de precipitación y la cubierta vegetal.

Palabras clave: cobertura vegetal, rodillo aireador, microdepresiones, simulador de lluvia, escurrimiento, sedimentos.

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Introduction

In Mexico, the main types of soil degradation are water, wind and chemical erosion, with water erosion being the most important (Bolaños *et al*., 2016). Some problems of soil degradation are the loss of soil structure, decrease in soil organic matter and nutrients, reduction in the availability of water in the soil, and also increase in sediments in the drainage network of the hydrographic watersheds that reduce the transport capacity and water quality (Ffolliott, Brooks, Neary, Tapia, & Garcia-Chevesich, 2013).

Arid and semi-arid lands are fragile ecosystems where there is an increased need for studies on the functioning of rainwater and surface water in relation to the pressure exerted by the different production systems (Esquivel-Arriaga, Bueno-Hurtado, Sánchez-Cohen, Velásquez-Valle, & Muñoz-Villalobo, 2015). The fragility of these ecosystems has its origin in the scarce and erratic rainfall, low vegetation cover, high rates of soil erosion and low biological diversity, among others (FAO, 2021).

The impact on the degradation of natural resources in these highly vulnerable regions has become more acute due to the intensive exploitation of these resources due to anthropic and natural issues, the latter derived from the environmental impact due to the effect of climate change (Forero, Saldarriaga, & Vargas, 2017). The foregoing makes it necessary to systematically apply planning strategies, use, and comprehensive management of natural resources with a hydrological watershed vision, as a study unit (Cotler-Ávalos, Galindo-Alcántar, González-Mora, Pineda-López, & Ríos-Patrón, 2013).

The importance of characterizing the watershed lies in the fact that the water balance of the watershed can be altered by factors such as climate, geology, hydrography, topography, type of soil and vegetation, and agricultural activities (Pereira, Almeida, Martínez, & Rosa, 2014; Alvez, Mello, Colombo, & Cuartas, 2017).

Based on the characterization of hydrographic watersheds and the analysis of the information, Sánchez, Velásquez, Esquivel, Bueno and Pedroza (2015) showed that the quantitative estimation of the water balance must be developed in experimental hydrographic watersheds where "modifiable" variables can be controlled. On the other hand, a method to reverse soil degradation is by reducing water runoff and improving water infiltration in the soil, this is possible with the increase of the vegetation cover of the soil surface (Sastre, Bienes, García, & Cuevas, 2016).

One technique used to reverse soil degradation is the land imprinter. The land imprinter was developed with the objective of revegetating degraded soils by impressing the soil (generates an increase in water storage) and the simultaneous sowing of seeds of some plants (Clary, 1989).

In grassland areas, one of the ways in which the hydrological balance can be altered is through the manipulation of native vegetation. Currently, with the purpose of increasing the availability of forage in semi-arid and arid lands, the use of the land imprinter has been considered for the establishment of grasses and the rehabilitation of deteriorated pastures (Berlanga, Beltrán, Martínez, Hernández, & Torres, 2009). The objective of this study is to propose a methodological framework to integrate and analyze the experimental information of a watershed in arid lands, regarding the impact of the management of its natural resources on the hydrological response and the production of sediments.

Materials and methods

Geographic location of the study area

The study area is an experimental watershed within the municipality of San Luis del Cordero in the state of Durango, in Mexico. It is located in Hydrological Region 36 (Ríos Nazas-Aguanaval) between coordinates 25º15'00” to 25º31'00” north latitude and 104º 07'00” to 104º33'00” west longitude, at a height of 1508 meters above sea level (Esquivel-Arriaga *et al*., 2015; Yáñez *et al*., 2018).

The surface of the watershed is 158.87 ha (Figure 1) The maximum temperatures occur from May to August reaching 40 °C, while the lowest temperatures, around 0 °C, begin in December and end in March (Bueno, Sánchez, Esquivel, Velásquez, & Inzunza, 2013).

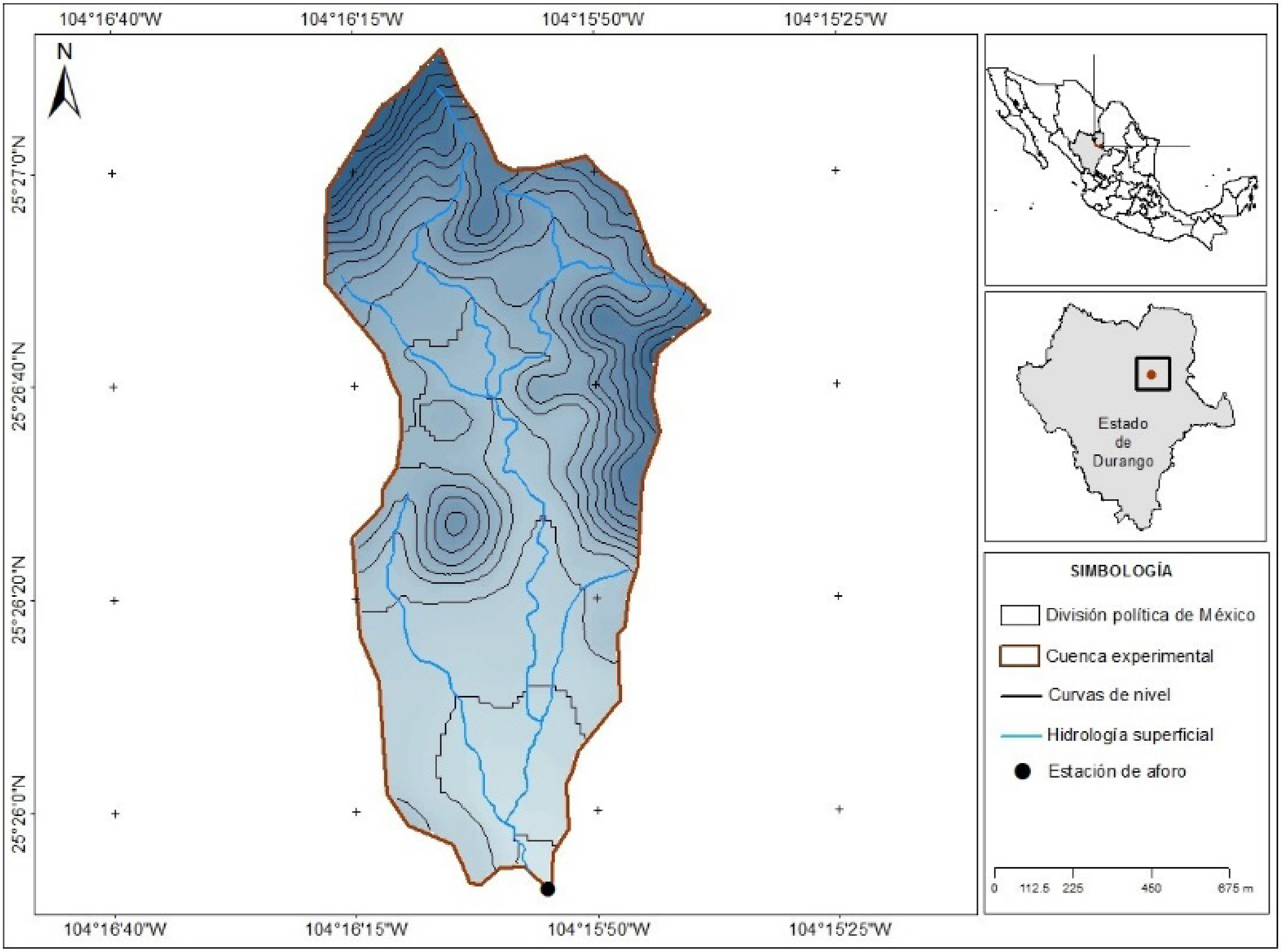

Figure 1. San Luis del Cordero experimental watershed in the hydrological region No36 in the state of Durango.

The predominant climate is semi-dry to semi-warm dry, with altitudes ranging between 1300 and 1900 meters above sea level with an average annual rainfall of 360 mm (Castillo *et al*., 2009), so in San Luis del Cordero, the development of agricultural activity is limited by the water factor. The representative texture class of the soil in the watershed is sandy loam with desert scrub-type vegetation (INEGI, 2016). The components of the superficial land cover are rock (26.85 %), bare soil (52.4 %), organic matter (4.44 %) and vegetation (15.92 %) (Sánchez, Pedroza, Velásquez, Bueno, & Esquivel, 2018).

San Luis del Cordero is a livestock area, with livestock representing 45 % of its economic income. Although there is a great emigration of its inhabitants, the cattle herds are maintained, which generates excessive grazing and the decrease of pastures; the grazing period in the communal pasture is carried out on average for 6.3 months a year (June-December); despite the attempt to increase the number of cattle, this has been limited by the lack of pasture (Castillo *et al*., 2009).

In 2017, in parts of the watershed, the land imprinter was used to sow buffel grass (*Cenchrus ciliaris L.)* with the purpose of increasing forage availability, increasing plant cover and altering physical properties of the soil. This practice involves removing part of the native vegetation (Figure 2).

Figure 2. Use of the land imprinter for planting buffel grass in areas of the experimental watershed.

In 2017, the land imprinter was used in the watershed to establish buffel grass and capture rainwater in 24 ha of the watershed, which represents 15 % of its surface (Figure 3).

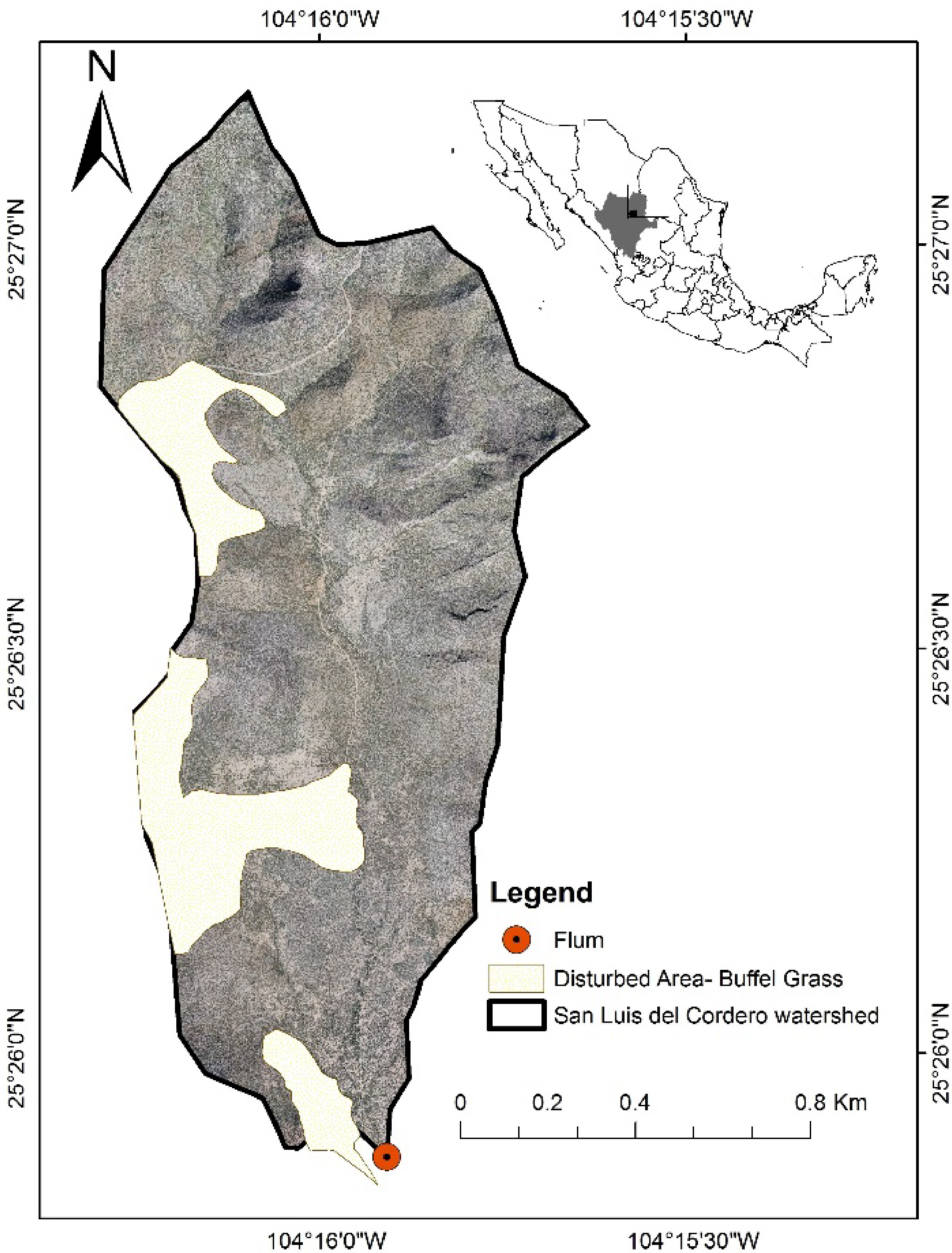

Figure 3. Buffel grass area in the San Luis del Cordero watershed.

Description of the hydrological processes in the watershed

Rainfall

Precipitation measurements in the watershed began in 2016 and runoff measurements began in 2017. To measure rainfall events within the watershed, three pluviometers (HOBO - Tipping-Bucket ®) were installed with a recording schedule every minute in rainy season and every hour for the rest of the year (Figure 4), the rain gauges have a precision of 0.2 mm per pulse and a capacity to record rainfall intensities of up to 127 mmh^{-1}; the rain gauges were arranged in the watershed taking as installation criterion the representativeness of the altitude, type of vegetation and soils.

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Figure 4. Compilation of pluviometric information in the San Luis del Cordero watershed.

Considering the previous criteria for the installation of the rain gauges, the three rain gauges were located in parts of the watershed where the land imprinter was not used, this helped the rain gauges not to remain in places exposed to livestock or the passage of machinery that could damage them. So, with respect to the intensity of the rainfall in different parts of the watershed, this analysis needs to be done as long as there is at least one rain gauge in each condition (altered by the use of the land imprinter and with native vegetation).

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Surface runoff

Runoff measurements at the study site began in 2017, using a rectangular gauge with a hydraulic section and a known height-volume relationship (Figure 5). The gauge has a width of 1.76 m, a length of 4.8 m, a height of 1 m and a slope of 0.20 %, it was designed to force the transit of the runoff through a structure of known geometry that facilitates the monitoring of the hydraulic tie, and the flux conversion (*Q*) per unit time. The gauging station was located in the lower part of the experimental watershed.

Figure 5. Hydraulic section of the flume at the outlet of the experimental watershed.

Flow height readings were made using a scale painted on the wall of the flume to the nearest centimeter. Flow height measurements were recorded every minute at the start of runoff, then every 5 minutes. Once three similar consecutive readings were obtained, the hydrograph was assumed to have reached set point and flow height readings were recorded every 5 minutes until the end of the runoff event.

Subsequently, the readings were correlated with the channel calibration curve to calculate the runoff rate (m^3s^{-1}) (Figure 6). A one liter sample of runoff was taken at each reading to estimate the sediment load from each runoff event. The hydrological information presented corresponds to the year 2017, in which 3 rainfall events were recorded in the watershed, the first on August 4, the second on August 17 in the morning and the third on August 17 in the afternoon.

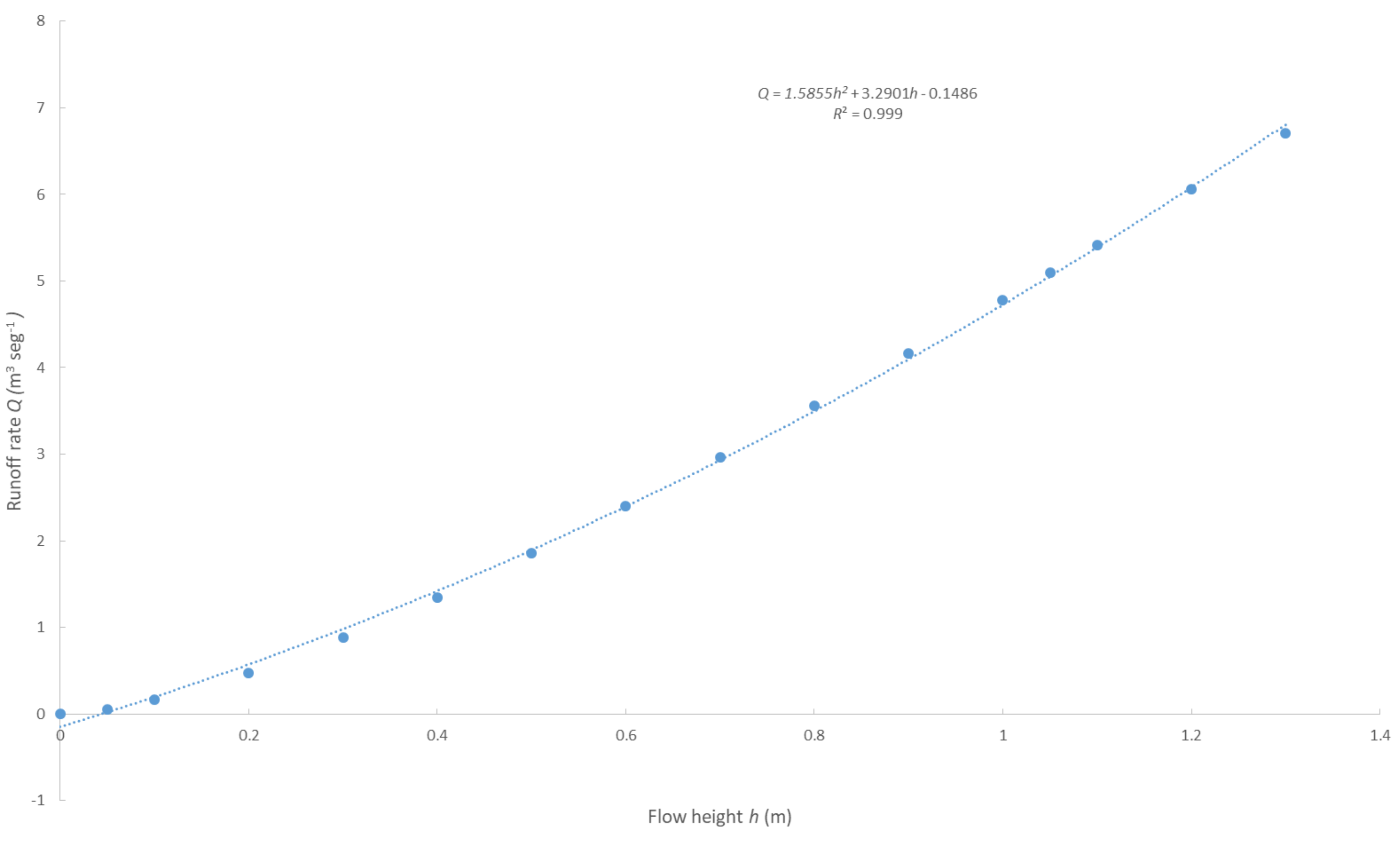

Figure 6. Relationship between the height of the hydraulic tie and the flow rate in the gauging section of the main stream of the watershed.

Simulation of rainfall in the watershed

To determine the impact of the land imprinter on the hydrological processes of the watershed, a rainfall simulation study was carried out in 2018 in areas where the land imprinter was used and areas where it was not used (Figure 7).

Figure 7. Rainfall simulator in the watershed.

The modified Miller rainfall simulator was used, which has three solenoid valves to control the intensity of the rainfall (Miller, 1987, modified by Velásquez, Esquivel, Bueno, Sánchez, & Flores, 2014). The rainfall simulations were carried out in experimental runoff plots under two treatments: area where the land imprinter was used (land imprinter) and areas where it was not used (natural condition). For each treatment, two antecedent moisture contents were considered: dry (at the time of the first simulation) and wet (24 hours after the first simulation). The simulated rainfall application was with an intensity of 60 $mm.h^{-1}$.

The experimental plots were 1 m wide by 3 long, each plot with a box to collect runoff. Before starting the rainfall simulation, each plot was labeled, the microrelief of the topsoil was measured, the ground cover was characterized, and the temperature of both the environment and the soil within the plot was measured (Figure 8). Although the watershed has steep slopes that make the soils susceptible to erosion (Muriel & Trujillo, 2013), the slope variable was not considered as a source of variation in the results of the rainfall simulation since the slope was the same in the treatments.

Figure 8. Characterization of experimental plots.

Once the runoff started, the runoff volume was quantified every minute and subsequently every 2 minutes and depending on the availability of the runoff volume, one-liter samples were taken to determine the concentration and quantity of sediments (Figure 9).

Figure 9. Rainfall simulation and runoff sampling.

Results

Experimental watershed

The average annual rainfall for the year 2016 was 502 mm and there were 68 days of rainfall. For the year 2017 there were 43 days of rainfall with an average annual rainfall of 288 mm. For the years 2016 and 2017, the annual average maximum and minimum temperatures were 29 °C and 11 °C, respectively.

The rainfall-runoff relationship of the watershed is observed in Figure 10, where a change in the performance of the runoff can be seen. For 2016, where the watershed has its natural conditions, the runoff begins with a precipitation of 9 mm, while for 2017, the runoff begins with 6 mm of precipitation. In addition, under natural conditions, a rainfall of 10 mm produced a runoff of 0.99 mm, while for 2017 a rainfall of 10 mm produced a runoff of 0.1 mm.

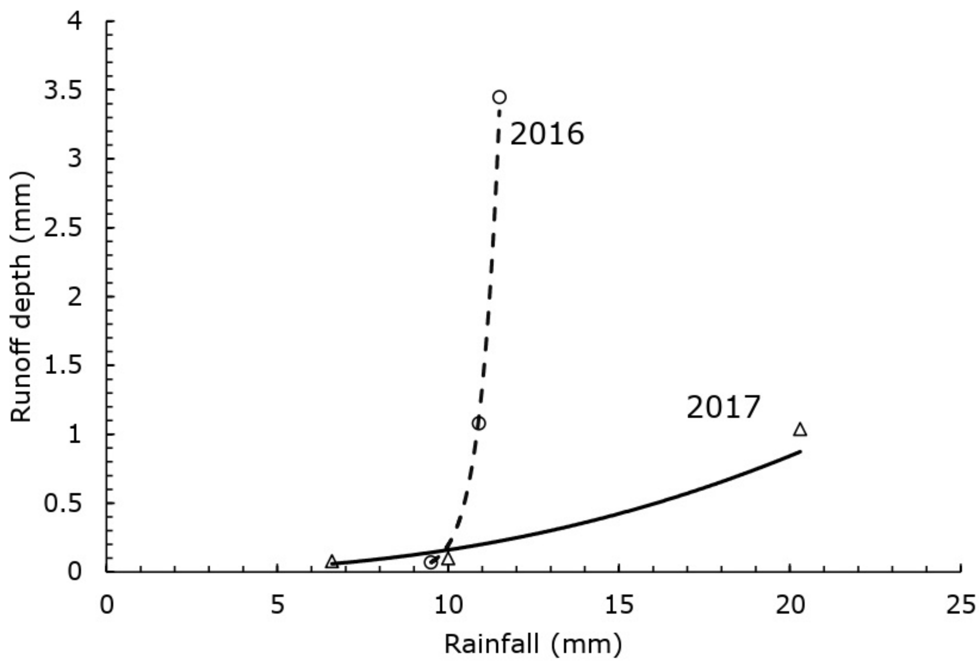

Figure 10. Rainfall-runoff relationships for the year 2016 (without land imprinter) and 2017 (with land imprinter).

From the above, it can be established that the use of the land imprinter produced an advance in the start of the runoff, but, on the other hand, the runoff in the watershed after the use of the land imprinter decreased. Figure 11 shows the results of the concentration of solids in suspension and the hydrograph of three runoff events that occurred during the year 2017; the event with the highest precipitation corresponds to August 17 in the afternoon. This event lasted 1 hour and 26 minutes, while the events of August 4 and 17 in the morning lasted approximately 1 hour.

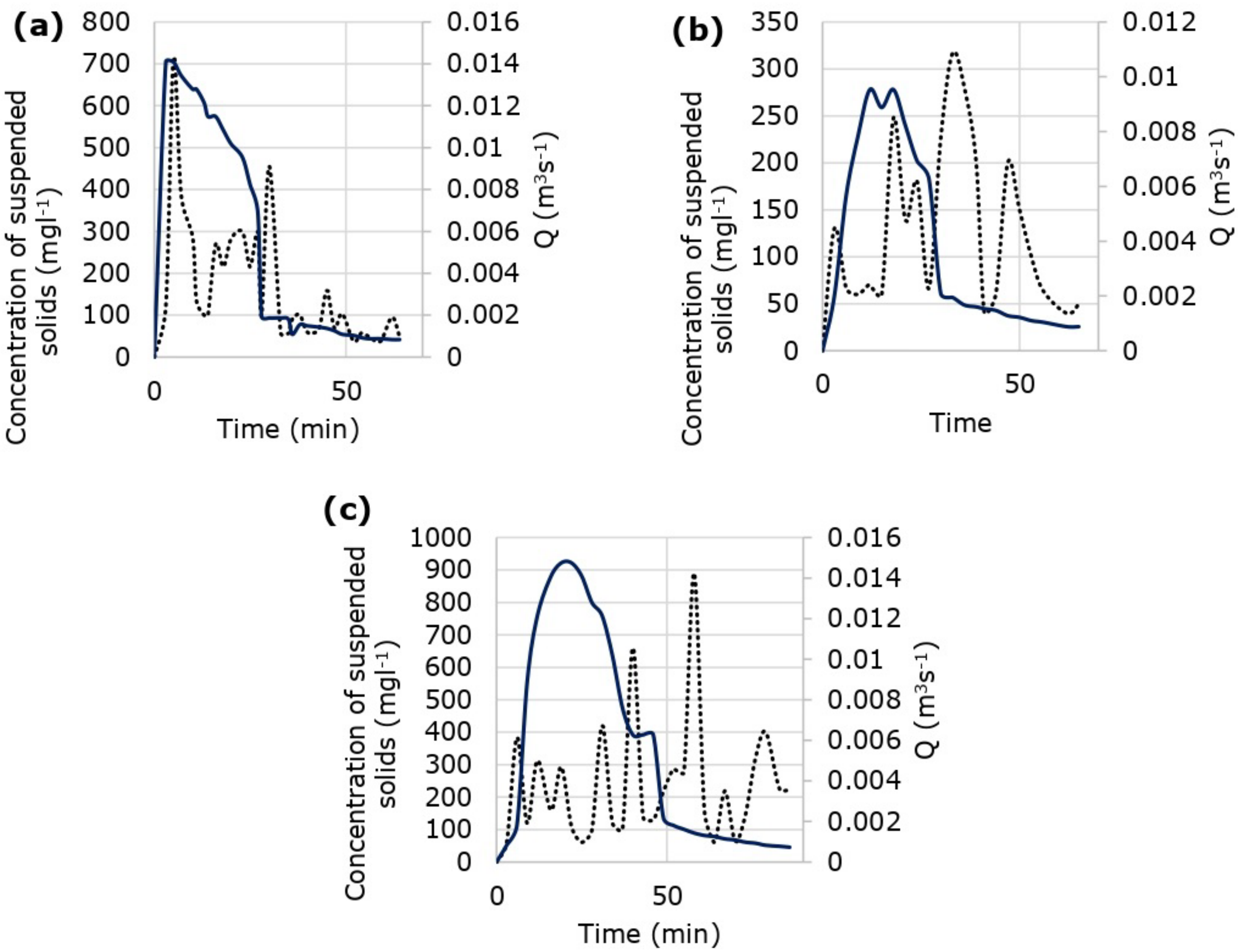

Figure 11. Concentration of suspended solids (dotted line) and hydrograph (continuous line) during 3 events in 2017, a) August 4, b) August 17 in the morning and c) August 17 in the afternoon.

The rainfall events of the year 2017 show a similar performance of the hydrograph. In the case of the event of August 17 in the afternoon, there is a greater production of sediments, this is due to the greater amount of precipitation and the antecedent humidity of the soil. On the other hand, the event of August 4 with the dry soil condition at the beginning of the rainfall showed a lower sediment production.

Rainfall simulation

From the characterization of the plots, the content of total organic matter on the surface of the plot and both environmental and soil temperatures were quantified (Table 1). Temperatures ranging from 27 to 56°C in dry soil and from 25.7 to 42 °C in moist soil are observed. On the other hand, the organic matter content was higher for the plots with the use of the land imprinter (2,028 %); mainly in repetition 1.

Table 1. Results of the characterization of the plots: R1, R2 (Repetition number), N (Natural condition), R (Land imprinter).

		Temperature Dry soil (°C)		Temperature Moist soil (°C)	
Plot	**Organic matter (kg)**	**Ambient**	**Soil**	**Ambient**	**Soil**
R1N	1.02	35.6	56	36.6	42
R1R	2,028	34.6	34.2	39.6	37.2
R2N	0.28	27.6	27	31	25.7
R2R	0.312	39.8	47.6	38.2	35.8

From the rainfall simulations, the production of runoff and sediments in the experimental plots with the effect of the land imprinter and without the effect of the land imprinter (natural condition) under dry soil and wet soil conditions were obtained (Figure 12).

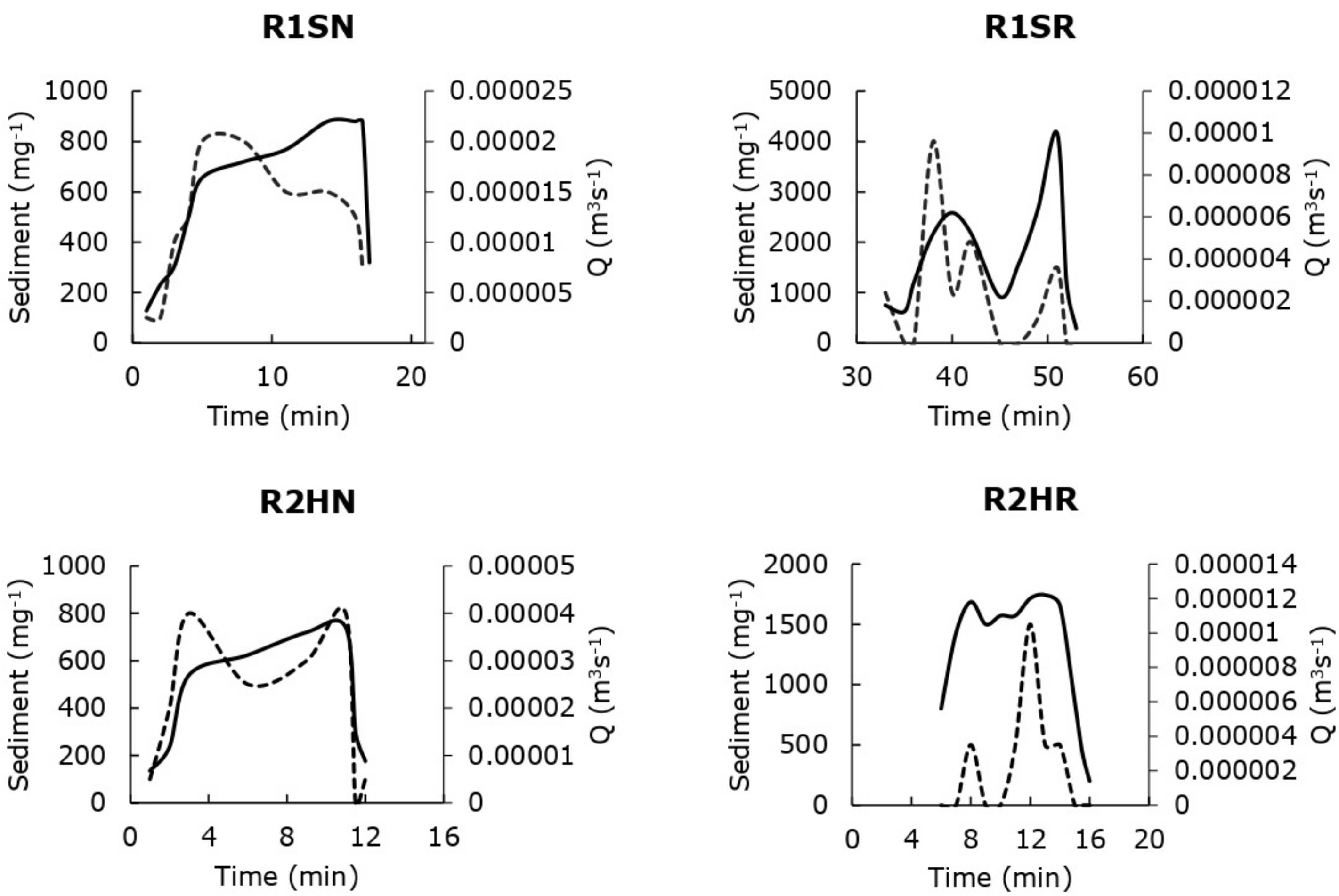

Figure 12. Sedigrams (dotted line) and hydrographs (solid line) during the simulation of rainfall with dry soil (R1SN and R1SR) and with wet soil (R2HN and R2HR).

Since the soil moisture conditions in the experimental plots were the same, from figure 12 it can be deduced that a significant change due to the use of the land imprinter was the delay in the start of runoff for both dry and wet soil.

For the dry soil condition, runoff in the experimental plot R1SN started 3 minutes after the onset of rainfall, while the onset of runoff in plot R1SR was 33 minutes after the start of rainfall. On the other hand, the runoff rate for R1SR was lower, with a mean production of 0.000004 m^3s^{-1}, while the mean runoff rate in the R1SN plot was 0.000016 m^3s^{-1}.

Contrary to the above, there was a considerable increase in sediment production in the experimental plot R1SR, where an average sediment production of 833 mgl^{-1} was obtained, while in the experimental plot R1SN the average sediment production was 470 mgl^{-1}.

For the wet soil condition, runoff occurred 4 minutes earlier in the plots without the effect of the land imprinter; the runoff rate for R1HR was lower, with a mean rate of 0.0000088 m^3s^{-1}, while the mean rate of runoff in plot R1HN was 0.000022 m^3s^{-1}. Regarding the average sediment production, for R1HR and R1HN it was 291.6 and 412.5 mgl^{-1} respectively.

Discussion

Experimental watershed

The objective of using the land imprinter is to rehabilitate soils where there is little vegetation and to avoid processes of site degradation. In the study area, the land imprinter was used to increase forage production, ignoring the potential effects of the removal of natural vegetation that impacts the habitat of microfauna, as well as the physical and biological characteristics of the soil.

The use of the land imprinter produces changes in the vegetation. A study conducted in Northern County Johnson in the state of Wyoming, where the land imprinter was used to improve pasture conditions, revealed that land treated with the land imprinter had a decrease in native grasses such as navajita (*Bouteloua gracilis*) and shrubs (Sanez, Cantú, Armenta, & Barreras, 2017).

On the other hand, the land imprinter was used for the establishment of buffel grass, and one of the qualities of buffel grass is its high yield potential, up to two and ten times more forage than native grasses, so the potential of the rangeland is not affected and the development of livestock is favored In addition to the above, the change in land use from a native grassland to the establishment of buffel grass does not represent statistically significant differences in the hydrology of the land (Valle, Cohen, Luna, Villalobos, & Rodríguez, 2014).

The change of vegetation cover, the formation of micro depressions and topsoil, carried out in 24 ha of the watershed by the passage of the land imprinter, modified the hydrology of the watershed. The mulch prevented raindrops from falling directly on the soil surface and delayed the start of runoff, thus favoring the infiltration of water into the watershed. It can be said that the vegetative cover reduces soil loss due to water erosion, it also improves the infiltration of water into the soil and reduces the speed of runoff.

This also coincides with what Esquivel, Nevarez, Velásquez, Sánchez and Bueno (2017) propose the capacity of soils to produce runoff is strongly linked to the surface state, as well as to the physical properties of the soil. In addition, Olguín and Pineda (2010) reported that the size of the watershed influences the performance of its hydrology, with small watersheds being the most sensitive to the shape of the hydrographs and the amount of runoff, the latter influenced by the physical characteristics of the river, soil and plant cover.

Therefore, the characteristics of the watershed where the study was carried out, specifically, the size of the watershed, caused the change in the surface cover of the soil to modify the patterns of runoff, infiltration, sediment production and the rainfall-runoff relationship in the entire watershed (Simanton, Hawkins, Mohseni, & Renard, 1996).

Based on the observed results of the use of the land imprinter, the hydrology of the watershed is sensitive to changes in its surface cover, even when the modified surface is small, the modification of 15 % of the watershed surface (soil cover and vegetation) causes notable changes in its hydrology.

Within the watershed there are areas that must be identified and monitored more thoroughly, such as recharge areas, in order to maintain a balance in the hydrological cycle and achieve better management of water resources. On the other hand, the results obtained in this investigation only reflect the initial effect of the use of the land imprinter, once the sown buffel grass grows and a new management of the watershed is established (animal load), the hydrology of the watershed may change.

Rainfall simulation

In addition to the delay in the onset of runoff attributed to the increased amount of organic matter on the soil surface, the use of the land imprinter caused a reduction in the amount of runoff. The reduction in runoff in the plots with the effect of the land imprinter coincides with the performance of the hydrology of the watershed for the year 2017, the year in which the land imprinter was used in the watershed and where there was a reduction in runoff. Therefore, rainfall simulation can be used as a tool to understand the performance of the hydrology of a watershed in relation to the state of its vegetation and soil cover.

In plots in natural condition, the hydrograph is typically distributed, that is, it starts in an ascending manner corresponding to the concentration of the flow until it reaches the maximum flow and then the hydrograph line descends as the flow decreases. On the other hand, the hydrograph of the plots with the effect of the land imprinter performances differently, it has two maximum flows during the rainfall simulation, the above is attributed to the micro-depressions, the runoff was initially only from the areas without micro-depressions, one once the microdepressions were filled with water, the runoff area increased resulting in a second peak in the hydrograph.

González *et al*. (2006) found that runoff is essentially conditioned by vegetation cover and rainfall intensity. Likewise, Calvo, Jiménez and De-Saá (2012), and Pérez, Moreno and Roldán (2016) concluded that the percentage of intercepted rainfall is directly proportional to the percentage of land cover. For this investigation, rainfall intensity was the same for all simulations, so the change in runoff response is directly related to vegetation cover and soil condition.

In the runoff plots where the alteration of the native vegetation was carried out, there is a greater loss of soil, this coincides with the impacts of the alteration of the vegetal cover and surface microtopography of the soil referred to by Chavéz *et al*. (2012). The alteration of the vegetation cover not only has the effect of soil erosion, but there may also be less water production, less carbon sequestration, climate change and impacts on the biodiversity of the watershed (Brüschweiler, Höggel, & Kläy, 2004; Vargas & Rosales, 2014).

Conclusions

In situ simulation conditions, the removal of soil with the use of a land imprinter as a practice that favors the establishment of buffel grass (*Cenchrus ciliaris L.*) reduced the flow of surface runoff through the formation of micro-depressions that acted as retainers of the rainwater, but with the consequent increase in the production of sediments with an impact on greater soil erosion. Additionally, the passage of land imprinter reduces of native plant cover and impacts the biodiversity of the flora, at least in a first period of time, which must be evaluated in the medium term, on a possible regeneration and plant invigoration by the practice of soil aeration and its greater power of moisture retention.

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