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Land Use Changes and Sediment Yield on a Hilly Watershed in Central-East Argentina

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Abstract

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Watershed management strategies need suitable techniques to be available in order to quantify sediment yield, among other relevant issues. The aim of this work was to estimate the sediment yield on a hilly watershed, for two different land use scenarios (years 1966 and 2011) and rainfall events (106 mm and 65.5 mm). The Modified Universal Soil Loss Equation was used to estimate the sediment yield produced by a single rainfall on the watershed of the Belisario Creek, placed south-west of the Buenos Aires province, Argentina. The information was processed using the Geographic Information System Idrisi Taiga®. Modelling the 45-year distant land use scenarios allowed to estimate the high level of degradation that is currently taking place on the watershed. Also, we detected different responses through different areas of the watershed; the same rainfall event in the 2011 land use scenario compared to the 1966 scenario showed a 400% increment in sediment yield in the upper sub-watersheds, together with an almost 100% increment near the sink. Here we propose the urgent need to elaborate a sustainable plan for the watershed of the Belisario Creek, in order to establish action criteria that could help improve natural resources management. The methodology used could be also applied to neighbouring watersheds with similar characteristics in the region.

Keywords: GIS; MUSLE; soil loss; territorial management

Disasters caused by floods and sediment transport have enlarged their damages on people and properties, due to increase in frequency and magnitude of typhoons and intense rainfalls caused by changes on global climatic patterns (Kim *et al.* 2008). Several researchers aimed to establish a link between land use, erosion and sediment yield, showing that interactions between soil types, land use, sediment production, and transport can be quite complex, in particular in areas with changing land use and agricultural practices (Tramblay *et al.* 2010). Also, recently the importance of an adequate management of sediment movement in a watershed has been recognized (Abe *et al.* 2012). Sediment yield in a hilly region is able to cause a variety of problems at a watershed scale, such as reduction of reservoirs storage capacity and negative impacts on the environment. Many of these problems are directly related with suspended solids flowing downstream in the watershed. Knight *et al.* (2013) demonstrated that conservation practices applied in agricultural watersheds can have a positive impact on downstream water quality and ecology.

Among the available soil erosion and sediment yield models, the Universal Soil Loss Equation (USLE), the Modified Universal Soil Loss Equation (MUSLE) and their revised versions are some of the most commonly used models in the world (Sadeghi 2004). The MUSLE was developed by Williams (1975), replacing the pluvial erosivity factor of the USLE (Wischmeier & Smith 1960), by a factor accounting for runoff energy. This factor is the result of the runoff volume and the peak flow generated by a specific rainfall event. As noted by Williams (1981), MUSLE equation has certain advantages over

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USLE, especially in simulating sediment yield from a watershed. The advantages include its application to individual rainfall events and greater accuracy, because runoff generally accounts for more sediment yield variation than does rainfall (Smith *et al.* 1984).

At present, the MUSLE equation is applied in storm-wise sediment yield prediction because it does not require experimental data regarding rainfall, channel geometry, and hydraulics of entire stream systems, which otherwise would be required by other models. The MUSLE equation optimizes hydrologic model parameters to estimate sediment yield (Sadeghi *et al.* 2007); hydrologists have also used the model to predict sediment and sediment associated contaminants at a watershed scale (Noor *et al.* 2012). The equations MUSLE, RUSLE, and Soiloss (Rosewell 1993) were used in Australian watersheds for estimation of sediment yield; although the three equations provided accurate predictions, the MUSLE was the most accurate (Erskine *et al.* 2002).

In Argentina, the Buenos Aires province has the highest demographic and industrial concentration in the country, the largest agriculture and livestock production with a huge agriculture expansion within the last 150 years (Rodriguez Capitulo *et al.* 2010). South-west of this province, an area with a particularly hilly topography is exposed to hydric and eolic erosion, flooding, soil and vegetal degradation, plus desertification, gradually contributing to environmental damage, also impacting on human life. Although there is enough scientific information related to water resources at regional scale, information available at a watershed scale is scarce. Therefore, the aim of this work was to estimate sediment yield in a hilly watershed, for two different land use scenarios and rainfall events, in an extended time period. This work can be beneficial to local authorities, providing information useful for territorial planning and management strategies in areas of growing demographic and tourism activity expansion.

MATERIAL AND METHODS

Study area. The study area was the watershed of the Belisario Creek, placed on the Serranian System of Ventania, in the southwest of the Buenos Aires province, Argentina, located at 38°04'S latitude and 61°55'W longitude (Figure 1). The Belisario Creek is a tributary of the El Oro Creek, which flows into the Sauce Grande River. This is the main river in the southwest Pampa (Quattrocchio *et al.* 2008), and the main water source of the Paso de Las Piedras dam that supplies water to the cities of Bahia Blanca (300 000 inhabitants) and Punta Alta (60 000 inhabitants) (Marucci *et al.* 2011). The area is occupied by two major types of plant communities: short-needlegrass on poor soils and tall-tussock grasslands on rich soils (Loydi *et al.* 2010).

The watershed of the Belisario Creek has a total area of 2596 ha, with altitudes between 350 and 1100 m a.s.l. (Delgado & Gaspari 2010). Natural grassland with presence of rocks prevails in the upper watershed. In the medium and lower part of the watershed, the main land use is degraded natural grassland, caused by the constant presence of livestock through many years; there is also presence of

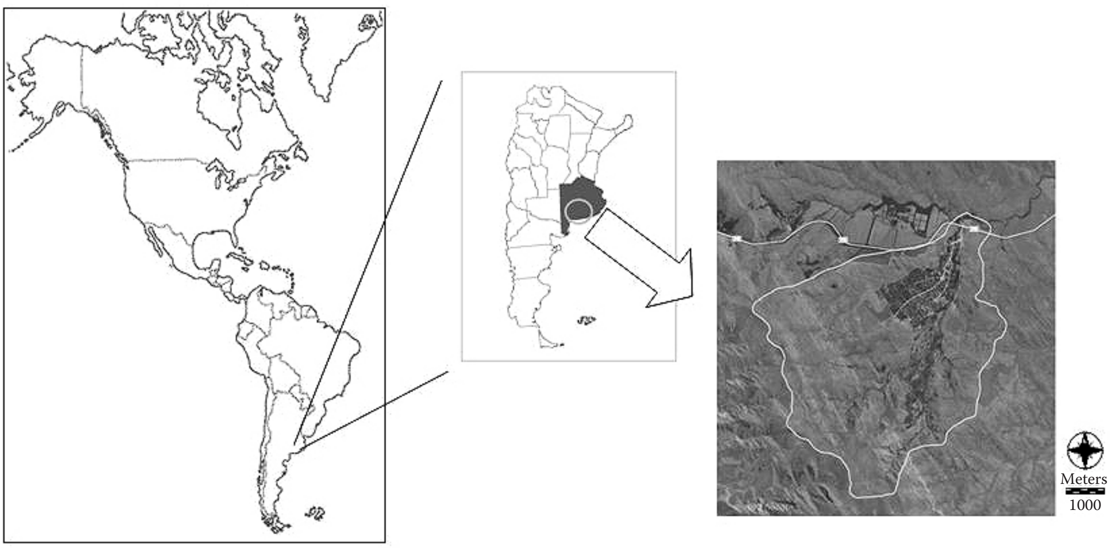

Figure 1. Location of the study area in the province of Buenos Aires, Argentina

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agriculture activity with planted forest in small areas. The tourist village of Villa Ventana is placed in the lower part of the watershed, with a major process of tourist and population expansion (1000 inhabitants reported in 2011), accounting for additional demand on services and resources (Delgado 2012).

MUSLE equation. Sediment yield estimation in the watershed was calculated with MUSLE equation (expressed in t per watershed), for a specific pluvial event. Analysis at a sub-watershed scale was also performed in order to identify different behaviours of the management units, useful for the design of management proposals for the watershed. MUSLE equation was applied on two different scenarios of land use: year 1966 and 2011. The most relevant changes between both scenarios are: conversion of conventional agriculture areas to agriculture with conservation practices; but on the other hand, there was detected a reduction of the forested area by 227 ha (which were assigned to the semi-urban area); and also the emergence of the degraded grassland areas due to overgrazing (763 ha) (Delgado *et al.* 2013). The 1966 scenario was established based on aerial photographs and information gathered from interviews to local people; the 2011 scenario was defined through field observations and satellite images obtained from Google Earth©.

According to Pinto *et al.* (2004), thematic layers were elaborated and processed with the Geographic Information System Idrisi Taiga®. Sediment yield was analyzed both at watershed and hectare scale in order to allow comparisons over time and space. Digitalized contour lines, based on the Topographic Sheet No 3963-6-1 (IGM 1979), were rasterized and interpolated in order to generate the Digital Elevation Model (DEM) and the Slope map. Sub-watersheds were manually digitalized, based on drainage and topographic characteristics.

USLE's R factor, representing rainfall erosivity, was replaced by the effect of runoff energy on the erosive process throughout runoff volume (Q, in m^3), and the peak discharge (q, in m^3/s) in the MUSLE equation (Eq. 1).

$$Y = 11.8 \times (Q \times q)^{0.56} \times K \times LS \times C \times P \qquad (1)$$

where:

Y – sediment yield in the watershed, for a specific pluvial event (t/watershed)
K – soil erodibility factor
LS – slope length, gradient factor
C – crop management factor
P – erosion control-practice factor

Q and q values for each sub-watershed were obtained from hydrological simulations done with HEC-HMS 3.5® model (US Army Corps of Engineers) using the Curve Number methodology for flow quantification (SCS USDA 1972), for the two different land use scenarios: year 1966 and 2011 (Delgado 2012).

The other MUSLE factors were previously estimated (Delgado 2012) at a watershed scale. For the present study, each factor was calculated at a sub-watershed scale.

Sediment yield was estimated with the MUSLE both for the entire watershed of the Belisario Creek and for a sub-watershed scale, established at a hectare level. We used a sediment yield classification (t/ha) defined as follows: Very Low Risk (< 5 t/ha); Low Risk (5–15 t/ha); Moderate Risk (15–25 t/ha); High Risk (25–50 t/ha) and Very High Risk (> 50 t/ha).

For the estimation of temporal variation we used the module Land Change Modeler integrated within the SIG Idrisi Taiga Information System to analyze differences over sediment yield between a combination of both land use scenarios and the two rainfalls used in simulations.

Characterization of rainfall. Two rainfalls of different magnitude and intensity were used. Figure 3 represents a hyetograph of both events, including curve of accumulated rainfall (mm) with a time interval of 30 min. Both rainfall events were chosen based on data from the three meteorological stations with the largest data record in the region: Tornquist (–38°15'; –62°21') for the period 1911–1993, Coronel Pringles (–37°59'; –61°21') for the period 1911–1992, and Coronel Suarez (–37°27'; –61°55') for the period 1936–2011.

RESULTS

A total number of sixteen sub-watersheds were identified, based on the topographic characteristics (Figure 2).

Sub-watersheds 1, 4, 8, 9, and 12 were the largest ones, with over 200 ha each; sub-watersheds 5 and 6 occupied less than 50 ha. The height difference in the low part of the watershed was minimal, defining a slope < 3%. On the upper watershed, mostly in sub-watersheds 1, 4, 5, and 9, the slopes increased up to 20% in certain areas.

Characterization of rainfall. The event of the lowest magnitude (accumulated rainfall: 65.5 mm; date: 12/19/2009; length: 11 h 30 min; I_{30} max: 13 mm) corresponded to an average Gumbel distribution of

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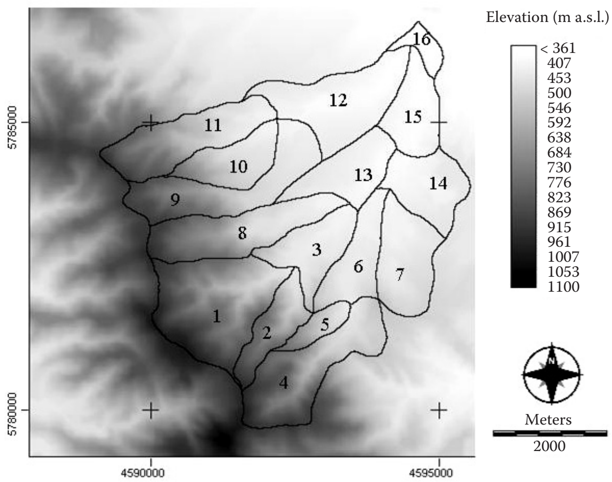

Figure 2. Sub-watersheds of the Belisario Creek, over the Digital Elevation Model (m a.s.l.)

0.23 and a return period of 1.3 years. On the other hand, the event with the highest magnitude (accumulated rainfall: 106 mm; date: 12/24/1963; length: 6 h 30 min; I_{30} max: 30 mm) corresponded to an average Gumbel distribution of 0.58 and a return period of 2.4 years.

Individual factors for each sub-watershed. With the support of GIS tools, we estimated the pondered arithmetic means (p.a.m.) of each MUSLE factor at a sub-watershed scale, for the 1966 and 2011 land use scenarios (Table 1).

The high values of the K factor over most sub-watersheds were related to the characteristics of the Soils Cartographic Units (SCU). The SCU Duf 2 comprised 856 ha and was composed by three taxonomic units that gave it a loam fine texture, medium runoff, moderated permeability, and the presence of a tuff 80 cm below ground. The SCU R comprised 1740 ha, and was present in hilly areas with high incidence of rocks.

The LS factor showed no modifications in the p.a.m. values at the sub-watershed scale, for the analyzed time period. Concerning the crop management and vegetation, the C factor value registered an increment in the 16 sub-watersheds, reflecting the process of degradation on the area, with increments above 100% in 6 of the sub-watersheds. The major changes in land use included the decrease of the Forest area, due to the development of the semi-urban area of Villa Ventana. The remaining Forest area showed a diminished C factor value due to the growth of trees and shrubs. On the other hand, the degraded grassland increased to 763 ha.

The P factor slightly decreased its value (< 5%) in the sub-watersheds that included conservation measurements, particularly contour lines; reaching to about 10% in sub-watersheds 9 and 14.

Sediment yield. Increment of sediment yield in the upper watershed is mainly due to soil degradation. In this area, we consider that persistence of this kind of land use through a 45-year period resulted in a degradation of soil as a result of anthropic action. In the middle and lower watershed the observed changes can be explained by major changes in land use. For example, in 1966 scenario, the 106 mm rainfall produced the highest sediment yield in sub-watersheds 1, 4, 8, and 9, with values above 4000 t per sub-watershed. For 2011 scenario, sub-watersheds 1 and 4 remained with the highest values, but the sediment yield was higher than 20 000 t per sub-watershed.

The analysis of the sediment yield for each sub-watershed was estimated at a hectare unit allowing us to establish the spatial distribution of the erosion risk (Figure 4) and to evaluate its trend over time.

As shown in Figure 4, only sub-watersheds 6 and 16 did not modify their range of sediment yield. The evolution of land use in these sub-watersheds had an opposite effect on the C factor value, increasing or decreasing in certain areas. This interaction

Table 1. Pondered arithmetic means of soil erodibility factor (K), slope length, gradient factor (LS), crop management factor (C) and erosion control-practice factor (P) for each sub-watershed; 1966 and 2011 scenarios

Sub-watershed	K	LS	1966		2011	
			C	P	C	P
1	0.95	4.83	0.040	1	0.110	1
2	0.95	5.24	0.040	1	0.110	1
3	0.71	1.98	0.064	1	0.115	0.98
4	0.91	4.63	0.046	1	0.115	1
5	0.94	3.54	0.047	1	0.108	1
6	0.60	1.73	0.061	1	0.075	1
7	0.83	1.67	0.066	1	0.126	1
8	0.89	3.31	0.060	1	0.124	0.97
9	0.80	2.90	0.093	1	0.143	0.91
10	0.84	2.46	0.069	1	0.130	0.96
11	0.86	3.05	0.045	1	0.114	1
12	0.73	1.57	0.088	1	0.119	0.97
13	0.60	1.55	0.072	1	0.110	1
14	0.78	1.58	0.102	1	0.138	0.90
15	0.65	1.56	0.060	1	0.078	0.99
16	0.61	1.51	0.041	1	0.063	1

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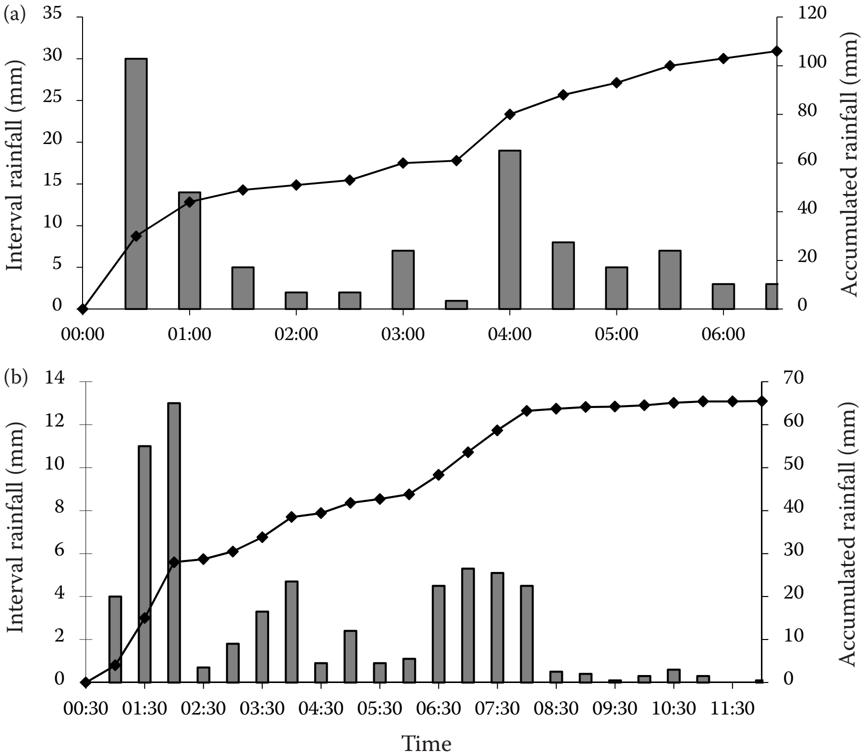

Figure 3. Rainfall used in the simulations: 106 mm (a) and 65.5 mm (b)

determined the maintenance of the sediment yield range for both scenarios in these sub-watersheds. For a better interpretation of the modifications occurring between ranges of sediment yield, the Land Change Modeler was applied (Figure 5). As it was expected, there was a decrease in the lower ranges

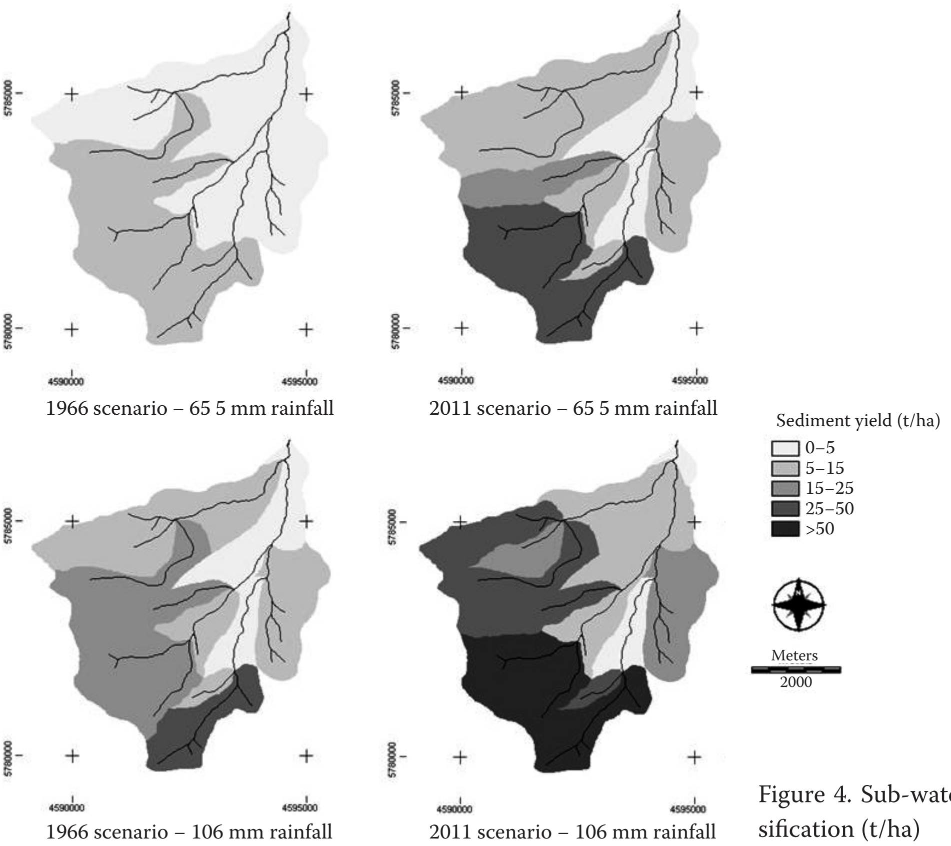

Figure 4. Sub-watershed sediment yield classification (t/ha)

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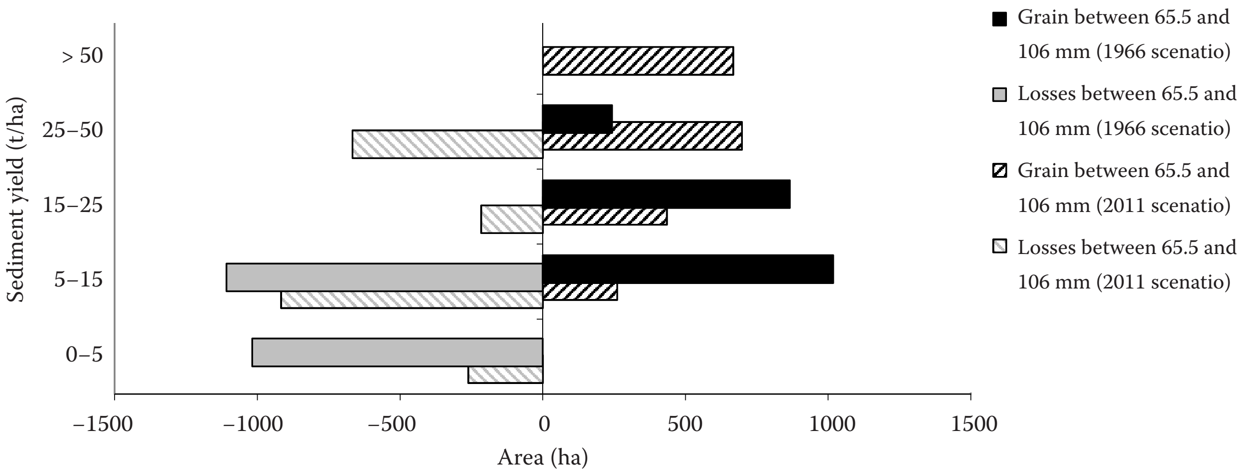

Figure 5. Changes in sediment yield ranges, for 1966 and 2011 scenarios

of risk and an increase in the higher ranges, for both scenarios, in results comparison from appliance of the 65.5 mm and 106 mm rainfalls.

Figure 6 shows the behaviour of the two rainfalls, for both land use scenarios; the trend of increase in the sediment yield is coincident with the current high risk of soil erosion in the watershed of the Belisario Creek.

The general results of the application of the MUSLE equation on the watershed of the Belisario Creek are given in Table 2.

The highest sediment yield corresponded to the 106 mm rainfall event, producing a *Y* of 65 545 t for 1966 scenario and 90 800 t for 2011 scenario. Estimations of the corresponding sediment yield per ha (*Yy*) were 25 t/ha and 35 t/ha, respectively. For the

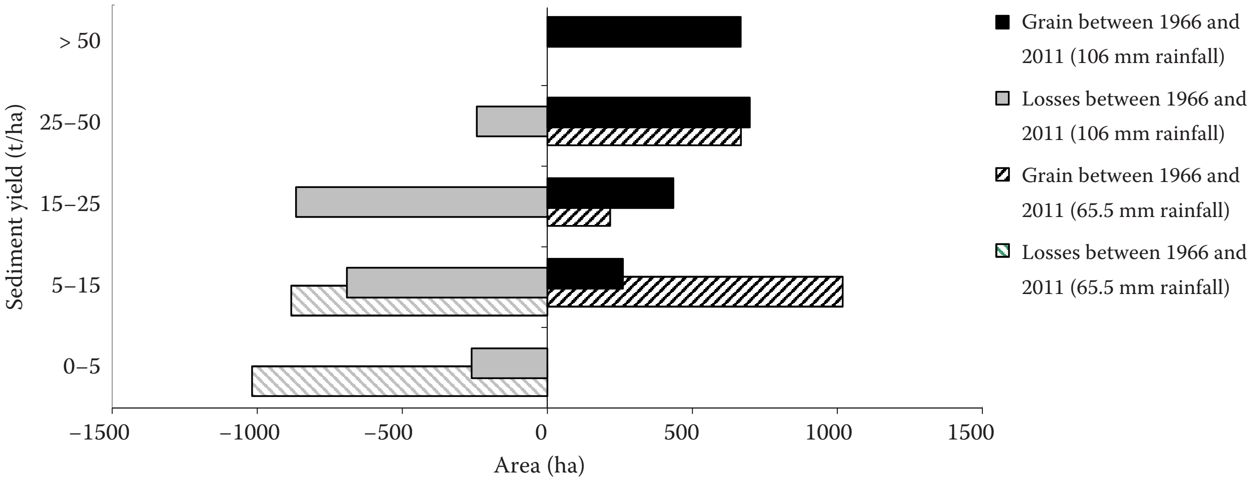

Figure 6. Changes in sediment yield ranges, for 65.5 mm and 106 mm rainfall

Table 2. Modified Universal Soil Loss Equation (MUSLE) at the watershed scale

Rainfall (mm)	1966 scenario		2011 scenario	
	Y (t/watershed)	*Yy* (t/ha)	*Y* (t/watershed)	*Yy* (t/ha)
106	65 545	25.25	90 865	35.00
65.5	24 010	9.25	36 920	14.22

Y – sediment yield per watershed; *Yy* – sediment yield per ha

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65.5 mm rainfall, these parameters were about 30% of those obtained with the 106 mm rainfall.

DISCUSSION

An urgent need to develop adequate techniques to help establish appropriate watershed management strategies have been previously suggested (Kim *et al.* 2008). In agreement with Abe *et al.* (2012), understanding the sediment movement inside a watershed might be relevant to support management strategies to help reduce its potential harmful effects. A comprehensive study on eleven watersheds from eight countries in East Asia (Park *et al.* 2011) concluded that rainfall variability is crucial for understanding seasonality and climate-induced risks concerning surface water quality. Noor *et al.* (2012) proposed the use of the MUSLE equation for sediment yield estimation when scarce data is available. Its application in optimizing the parameters for sediment yield estimation was also proposed (Sadeghi *et al.* 2007). In South America, Pinto *et al.* (2004) used the MUSLE equation together with GIS tools in the analysis of soil loss in two different land use scenarios in the south of Brazil, through a 20-year period. Present results agree well with those studies, indicating that growing trends of erosion are due to changes in land use.

In a previous report on the watershed of the Belisario Creek, the sediment yield was estimated using the USLE equation; a high risk of soil loss was suggested (Delgado 2010). However, no information was available on the effects of individual rainfall events on soil loss. Comparison between 1966 and 2011 land use scenarios allowed us to quantify these effects, both at a watershed and sub-watershed scale. Here, we corroborated the current high risk of soil loss in the watershed of the Belisario Creek, with an estimated sediment yield above 25 t/ha in approximately 50% of the watershed. These results also coincide with experimental data gathered on 27th November 2011, showing Total Suspended Solid (TSS) concentrations peaking at 140 mg/l in the sink of the watershed and a flow rate of 1.72 m^3/s (Delgado 2012). Field determinations were also done in September and October of the same year, but in the flow rates there were 0.01 m^3/s and 0.19 m^3/s, respectively, with TSS values of 34 mg/l and 46 mg/l, respectively (Delgado 2012). No other data on sediment yield measurement was available for the watershed of the Belisario Creek or any of its sub-watersheds. Related studies in North America analyzed the effect of sediments as water pollutants on wildlife, suggesting that TSS concentrations above 80 mg/l might affect some fish populations; concentrations higher than 200 mg/l were assumed to be harmful for any fish species in that region (Tramblay *et al.* 2010; Newcombe and Jensen 1996). The sediment yield of this particular watershed and the nearby ones, has the potential to affect Paso de Las Piedras dam, because they are contributing with water and also sediment to this reservoir, diminishing water quality by increasing the risk of eutrophication.

GIS tools allowed us to identify different responses through different watershed areas; when 2011 land use scenario was compared to 1966 scenario, a rainfall event produced both a 400% increment on the sediment yield in the upper sub-watersheds, and a minor increment near the sink (less than 100%). Although sediment yield for the 65.5 mm rainfall was about 30% of that obtained for the 106 mm rainfall, yet it was very high in order to assure sustainability of the watershed. In the upper sub-watersheds, the estimated sediment yield showed values above 10 t/ha; on the other sub-watersheds, the mean value was around 5 t/ha. As these numbers were calculated for a single rainfall event, their extrapolation throughout a year might be quite relevant. The small soil depth in the area highlights the potential risk for future anthropic activities.

According to Wijitkosum (2012) the reasons why soil loss is affected by the vegetation cover might be explained in various ways. Results of sediment yield associated with specific land uses agree with research on Australian watersheds (Erskine *et al.* 2002), where sediment yield increased from forestry to livestock and agriculture activities. Concerning the current area occupied by the tourist village of Villa Ventana, we estimated an increment of 400% for the sediment yield in 2011, compared with results obtained for the 1966 scenario, when this area was occupied only by forest. This specific process of urbanization in the lower watershed might be adverse to the environment and have also consequences on human life.

CONCLUSION

MUSLE equation allowed us to obtain an approximate estimation of sediment yield for two single rainfall events, considering the scarcity in data for this area, in particular concerning to pluviograph registers and also few field determinations.

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Comparison of current land use scenario to that occurring 45 years ago showed the high level of soil degradation in the watershed of the Belisario Creek, suggesting the urgent need to establish sustainable management strategies, especially considering the current expansion of demographic and tourism activities in the region. The strategies could include tasks as reinforce awareness campaigns on environmental problems for inhabitants of the watershed and tourism; implement silviculture practices in the forest established nowadays, and also consider the possibility to forest specific areas in order to contribute to cattle breeding activities, thinking in the possibility to establish silvopastoral systems as well.

The methodology used in this research could also be applied to analyze the situation of neighbouring watersheds with similar characteristics, aiming to contribute to a future territorial management for this particular geographic region.

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