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ORIGINAL ARTICLE – Conservation of Nature

The Influence of Riparian Areas on Direct Surface Runoff of Precipitation Events

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Abstract

This study aims to estimate the effect of different land uses around watercourses on runoff following extreme precipitation events and, consequently, on the mitigation of these effects. The study area is a rural watershed in the state of Rio Grande do Sul, Brazil. After characterizing the area, we estimated the surface runoff of the January 2009 precipitation event, which caused two casualties: losses in soil and productive area, as well as over US$ 300,000.00 in damages to the water supply system. Subsequently, simulations were performed considering different land uses and riparian areas under different precipitation levels. The results indicate that conserving riparian forests in the surroundings of watercourses decreases direct surface runoff, whereas intense soil use in these areas favors runoff increase.

Keywords: conservation, forest hydrology, watershed management.

1. INTRODUCTION

Environmental changes caused by intensive soil use and devastation of native areas, in addition to the rising exploration of water resources, have negatively affected the environment. These changes affect watercourse runoff and cause greater environmental impact following extreme precipitation events. Moreover, direct or indirect environmental services, vital to mankind, are hindered by these changes.

Land use in Brazil is directly related to the demands of population, i.e. for the purpose of food production, expansion of urban areas, roads, among others. Over time, this use changes landscape and degrades environmental services. The most frequent effects of these changes are the decrease in availability of water for other purposes, water quality, biodiversity and forest cover (Millennium Ecosystem Assessment, 2005). According to the Food and Agriculture Organization (FAO, 2015), between 1990 and 2015, Brazil lost 2,216,000 ha of forest per year.

The Brazilian Forestry Code [Código Florestal Brasileiro] (Brasil, 2012) states legally protected areas, such as Permanent Preservation Areas (PPA), which span environmentally sensitive regions, such as the surroundings of watercourses, hilltops, and slopes.

Different terms are used for the areas surrounding watercourses, such as riparian forest areas or riparian zones, protected areas, PPA, among others. When these areas surrounding watercourses are demarcated, they are also called buffer zones.

Vitalli et al. (2009) indicate that creating protected areas is one of the measures carried out to minimize the anthropic activities effect. These areas are established worldwide to conserve areas that fall within the different existing ecosystems, ensuring the survival of species and maintenance of ecological processes.

Riparian zones are water-saturated areas of micro watersheds, found mainly along the banks and at the courses headwaters (Attanasio et al., 2012). They play an important role in the filtration of pollutants, agricultural pesticides, and sediments

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brought by surface runoff, preventing them from reaching watercourses (Vogel et al., 2009).

Riparian forests decelerate the floods and foster greater infiltration of water in the soil, since tree roots and litter (a layer of organic matter over the ground) prevent the direct incidence of rain, solar rays, and wind, avoiding erosion, which causes many nutrients to be carried away (Vogel et al., 2009).

Based on the aforementioned, hydrological precipitation-runoff models have been developed to simulate and to analyze superficial runoff, as well as to predict the effects of land use changes. Among these models, the US Natural Resources Conservation Service (NRCS) model stands out. The curve number (CN) parameter enables the identification of particularities on surface runoff potential under different uses (SCS, 1972).

Considering the different consequences of extreme precipitation events affecting the Southern region of the state of Rio Grande do Sul—particularly the one in January 2009, which caused great economic, social, and environmental damages to the municipality of Pelotas and surroundings—we sought to estimate the potential benefit of preserving environmental services to mitigate such damages.

Thus, by employing geoprocessing and remote sensing technology, we sought to simulate the effects of different land uses and rainfall on the watershed of Passo dos Carros monitoring station. The proposed methodology may be useful to inform governmental decisions regarding the development of policies and priority areas for environmental conservation. This study aimed to estimate the influence of different land uses in the surroundings of watercourses on superficial runoff of water from extreme precipitation events.

2. MATERIALS AND METHODS

2.1. Location of the study area

The monitoring station of Passo dos Carros watershed is part of Mirim-São Gonçalo watershed and it spans a portion of Capão do Leão, Pelotas, and Morro Redondo municipalities, in the state of Rio Grande do Sul (Figure 1).

The set of drainage networks in Micaela and Moreira streams in Santa Bernardina—whose springs reach elevations of 340 m and 280 m, respectively, and mouths near Passo dos Carros road—form the Fragata stream, according to the interpretation of the hydrographic network, contour lines and elevations of topographic maps “Passo das Pedras de Cima” (SH-22-Y-C-VI-2) and “Monte Bonito” (SH-22-Y-D-IV-1), of scale 1:50,000 (Ministério do Exército, 1979, 1980).

Passo dos Carros monitoring station is a daily hydrometric control section of Fragata stream, under the responsibility of the Agência Nacional de Águas (ANA – National Water Agency). The area of Passo dos Carros watershed station is around 12,983.9 ha and it is part of the Fragata/Moreira subwatershed.

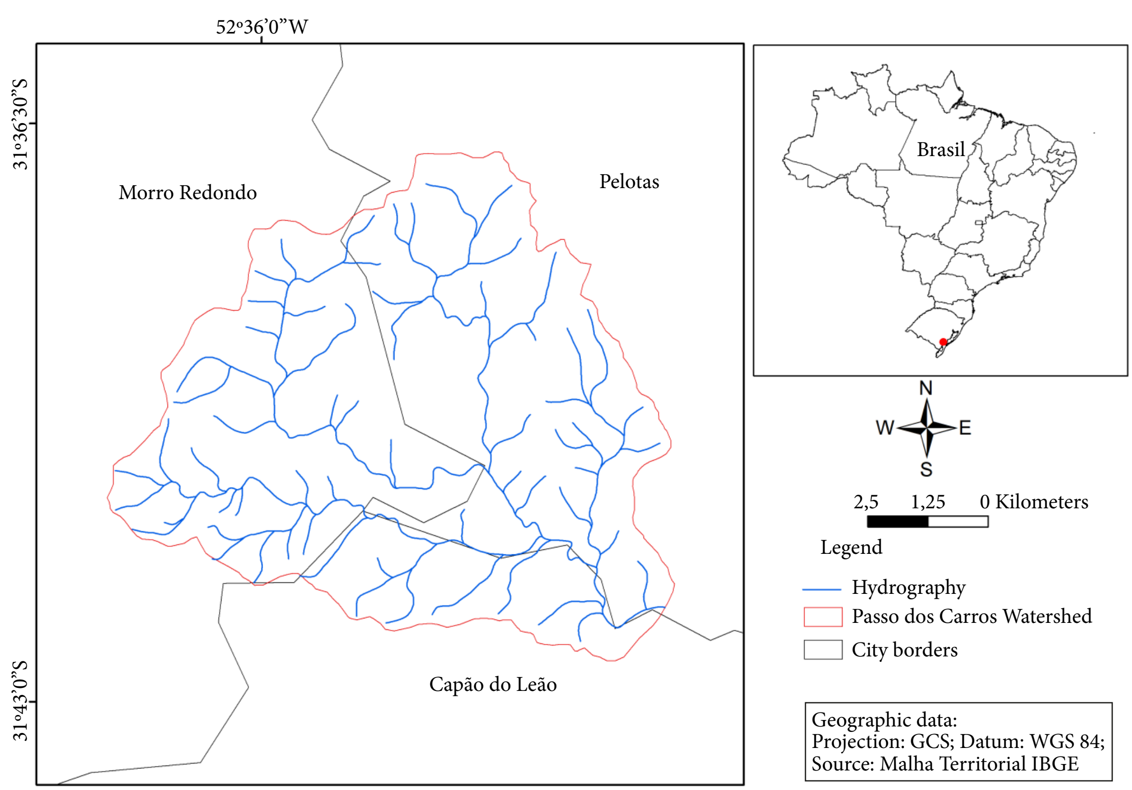

Figure 1. Location of the Monitoring Station of Passo dos Carros Watershed.

2.2. Production of the information plans of the area

The delimitation of Passo dos Carros watershed station and its hydrographic network was performed on SIG ArcGIS 9.3 (ESRI, 2008). Shuttle Radar Topography Mission (SRTM) data (NASA, 2015) was used.

The methodology used in this process is composed of four stages, which was entirely carried through on ArcGIS 9.3 software (ESRI, 2008):

a. Fill sinks, which considers the altitudes of neighboring pixels to fill the sinks, thus producing more consistent results;
b. Flow direction, which generates a regular grid defining the flow directions based on the line with greater slope in the area;
c. Flow accumulation representing the hydrographic network;
d. Watershed delimitation, which is performed by processing the direction maps of flow and accumulated flow.

The geographic distribution of the different soil types in the study area was obtained from the information found in Cunha & Silveira (1996) and the classification by Flores et al. (2009). The soil map of the study site was designed based on this database and the bounds of Passo dos Carros watershed station. The soil types found in the watershed are Argisols, Neosols, Planosols, and Gleysols.

The SRTM data were used to investigate the watershed landform. Thus, using the Slope tool of the Spatial Analyst extension (ESRI, 2008), we obtained the slope of the study area.

The Information Plan (IP) concerning land use in the watershed was designed based on the supervised classification of a mosaic of four scenes of RapidEye satellite images, from September 6, 2011, released by the Brazilian Ministry of the Environment. The RapidEye satellite constellation consists of 5 satellites and it has provided commercial images since February 2009. The Earth observation satellites in association are capable of collect more than 5 million km^2 of 5-meter resolution and 5-band images – Red, Blue, Green, Near Infrared, and Red Edge.

2.3. Calculation of the watershed runoff depth

The values for extreme precipitation event of January 2009 were obtained from the daily precipitation data of Laboratório de Agrometeorologia da Embrapa Clima Temperado (2009) [Agrometeorology Laboratory of Embrapa Temperate Climate] in Pelotas, state of Rio Grande do Sul. The superficial runoff was estimated based on these values. This refers to the precipitation portion that runs off superficially, expressed in mean water depth of Passo dos Carros station watershed.

The superficial runoff was estimated by Equation 1, determined pixel by pixel (USDA, 1986):

$$P = \frac{(I - 0.2S)^2}{(I + 0.8S)} \quad (1)$$

Where P means the superficial runoff depth (mm); I, the precipitation volume expressed as depth (mm); S, the maximum potential difference between precipitation and runoff (mm) from the precipitation outset.

The equation is valid for $p > 0.2$ S. Where $p < 0.2$ S, Q = 0. The watershed's S parameter is related to the so-called curve number (CN) by Equation 2 (Tucci, 1993):

$$S = \frac{25,400}{CN} - 254 \quad (2)$$

The CN reflects the conditions of vegetation and soil cover, ranging between impermeable (lower limit) and highly permeable coverage (upper limit).

The method proposed by the USDA (1986) to determine CN divides the soil classes into four hydrological groups (Sartori et al., 2005b). Soils can be classified into these hydrological groups according to Sartori et al. (2005a).

From the Soil IP, the soils found in the study area were divided into hydrological groups according to the classification proposed by Sartori et al. (2005a). CN values were defined based on this division along with the Land Use IP.

The ArcGis software was used to estimate the runoff by the raster calculator extension, calculated pixel by pixel. Subsequently, all of pixels values were added to obtain the total volume of water runoff in Passo dos Carros watershed. Then, the mean water depths were determined for this study area.

2.4. Hydrological simulation under different uses in different areas

Runoff was simulated for three precipitation events. Firstly, a very high precipitation event was estimated with 575 mm of rainfall, which represents the extreme event occurring in the municipality of Pelotas in 2009 (Saldanha et al., 2012). Secondly, a high precipitation event of 350 mm was simulated. The third simulation was a low precipitation event, with 140 mm. By applying the aforementioned method (USDA, 1986), the superficial runoff was obtained for each simulated precipitation in Passo dos Carros station watershed for its current use, pixel by pixel. Illustrative scenarios were designed across the entire length of the watershed to verify the runoff variations according to soil use.

Runoff simulations were performed firstly where the watershed under study was entirely covered by forests (E.C. Forest) and, then, where it was entirely covered by tilled areas (E.C. Tilled Soil), to initially obtain scenarios illustrating the area of conserved, actual, and intense use and its ensuing effects on the increase or decrease of surface runoff in the study area.

Afterwards, three buffers surrounding watercourses were delimited with 30, 50, and 100 m on each side. These buffers, also called PPA, were determined as per Law 12,651 of May 2012 of Forestry Code (Brasil, 2012), where their minimum bands, for properties above two fiscal modules, are 30 m, increased according to the watercourse width.

Thus, different uses were simulated in these buffers: conserved use, in which the entire buffer area is considered as riparian vegetation (Forest Buffer), and the use where the buffer area is considered as tilled soil (Tilled Soil Buffer). The organization chart of the process is shown in Figure 2. The effect that the size of these buffers would cause on the surface runoff of Passo dos Carros station watershed was estimated according to these different uses.

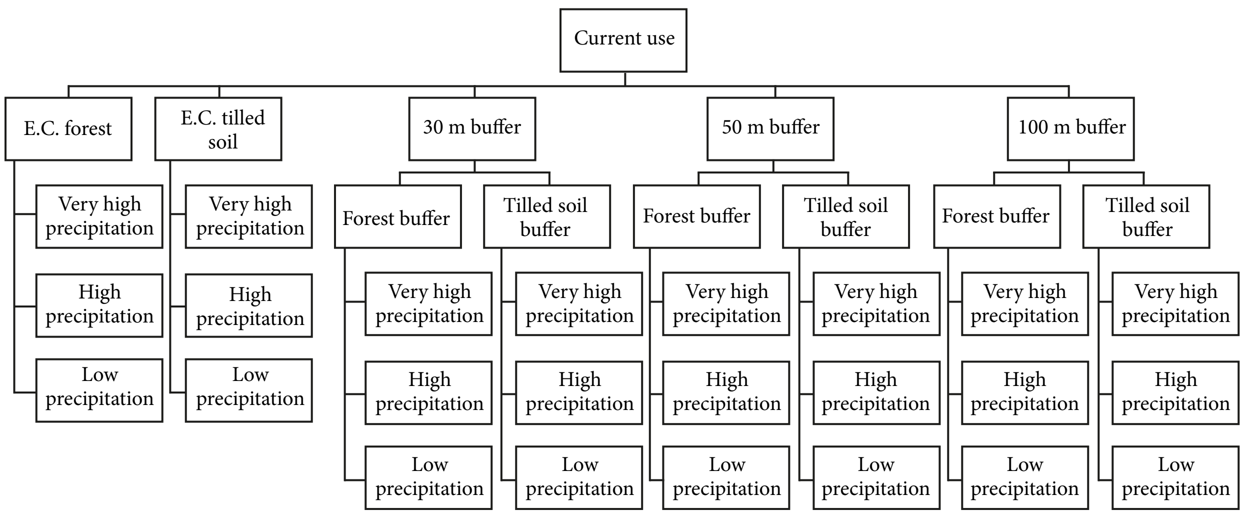

Figure 2. Organization chart illustrating the simulations (scenarios).

3. RESULTS AND DISCUSSION

3.1. Slope map of the study area

The slope bands were classified into the following landform classes, according to Santos et al. (2006): flat slope, mild slope, moderate slope, upper slope, and mountainous (Table 1). Passo dos Carros station watershed is predominantly moderate slope, ranging between 8 and 20%. The same characteristic occurs to 49% of the territory under study. The mild and moderate slope classes correspond to approximately 83% of the areas.

Table 1. Landform classes and respective slope bands of Passo dos Carros monitoring station watershed.

Landform classes	Slope bands	%
Flat slope	0 – 3	8.73
Mild slope	3 – 8	33.88
Moderate slope	8 – 20	48.97
Upper slope	20 – 45	8.39
Mountainous	> 45	0.02

Source: Santos et al. (2006).

3.2. Land use classification

Table 2 shows the (actual) land use classes of Passo dos Carros station watershed from the image taken on September 6, 2011. Most of the Passo dos Carros station watershed is classified as forestry, accounting for 43% of the total area. At the higher and more sloping portion of the watershed, this class is represented by forest in more advanced stages. On the other hand, at the lower portion, these areas are found mainly in river galleries in reduced quantity and characterized by forests in earlier stages.

The field class is the second most representative use of the watershed studied, spanning 33% of the total area. It comprises the native field areas used for animal husbandry.

The plant production class comprises pasture, tobacco and corn plantations, fruit orchards, and vegetable crops. These activities are predominant in subsistence farming of the region studied. Larger areas of this class are found at the lower portion of the watershed, where the landform ranges between flat and soft slope. The "waterfront erosion" class comprises unused areas without vegetation coverage and it is found mainly at the edge of watercourses.

Table 2. Land use classes of Passo dos Carros monitoring station watershed.

Land use class	Hectares
Field	4,353.95
Water resources	55.93
Roads	356.91
Forest	5,646.00
Plant production	1,486.36
Mining	17.61
Forestry	650.46
Arenization	20.51
Urban	396.19
Total	**12,983.92**

The "urban" and "road" classes occupy a small area—3.9% and 2.7% of the total area, respectively—which justifies the prevalence of rural landscape in the study area. The main infrastructures are residential and commercial.

The activity of a quarry found in the region consists of soil removal, rock dismantling, with explosives, and subsequent quarry blocks loading and transport for processing. This activity may account for environmental effects, as it directly affects the environment, as described in the work of Simon & Cunha (2008). This is mainly due to its proximity to one of Moreira stream tributaries, causing the devastation of the existing native forest.

3.3. Depth of runoff in the watershed

The runoff depths for the three precipitation events were estimated (Figure 3): very high precipitation (VHP), high precipitation (HP), and low precipitation (LP). Furthermore, two scenarios were simulated for the watershed: when it is covered by forests and by tilled soil.

A great increase in surface runoff is observed when the watershed is completely covered by the tilled soil use. This scenario presents a soil without vegetation cover. Consequently, several environmental services would not be rendered. Moreover, this also increases the volume of water that will reach the course mouth by direct surface runoff. The opposite situation is observed when the area is covered by forest, which indicates that conserved scenarios can reduce the amount of runoff in a river basin.

Simulating low precipitation (LP) under the current actual use condition, the mean runoff depth reached 36 mm. In the illustrative forest scenario, this value decreased to 23.5 mm, whereas for the tilled soil scenario the value increased to 48 mm. Under high precipitation, the values found were 159 mm, 133 mm, and 212 mm for the current use, forest, and tilled soil scenarios, respectively. Under very high precipitation, the values were 310 mm, 276 mm, and 371 mm.

Toniolo et al. (2013), upon analysis of the changes in surface runoff in the Vacacaí Mirim watershed, based on changes in land use and coverage in 1990 and 2009, and using the CN model, reported that the areas obtaining the highest CN were agricultural and exposed soil zones. The authors emphasize that the higher the CN, the greater the runoff following rainfall. Thus, these areas are the ones presenting the highest runoff potential.

Similarly, Fernandes et al. (2013), comparing runoff in sugar cane plantation and riparian forest areas, state that forests generate lower runoff, indicating the relevance of such areas.

Zhang et al. (2001) report that forest covers present higher evapotranspiration rates than other types of vegetation coverage. A forested micro watershed located in an area with mean annual precipitation of 1,000 mm presents approximately 800 mm of annual evapotranspiration, whereas a micro watershed covered by grasses presents 400 mm. Therefore, water yield in vegetation cover areas is significantly lower. The difference in water production reflects the different evapotranspiration rates of these types of vegetation.

An analysis of Figures 4, 5, and 6 evinces that runoff is reduced when riparian forest areas are found in the surroundings of watercourses. On the other hand, when the scenario is one of degradation or intensive use, a significantly increased runoff depth is observed.

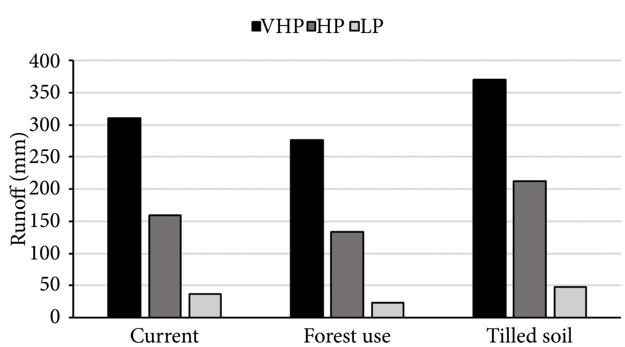

Figure 3. Graph of surface runoff under very high precipitation, high precipitation, and low precipitation.

VHP: very high precipitation; HP: high precipitation; LP: low precipitation.

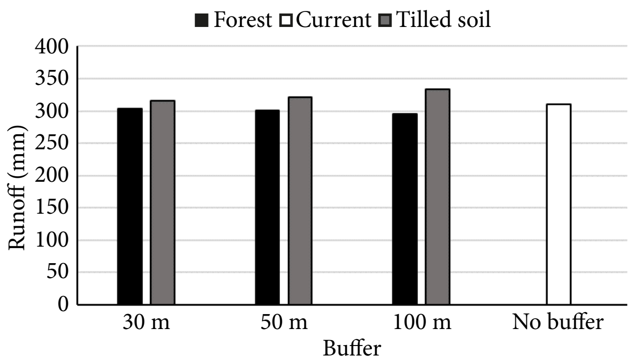

Figure 4. Graph of surface runoff under very high precipitation.

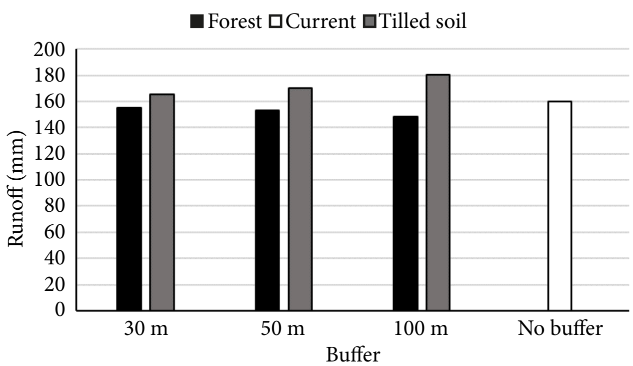

Figure 5. Graph of surface runoff under high precipitation.

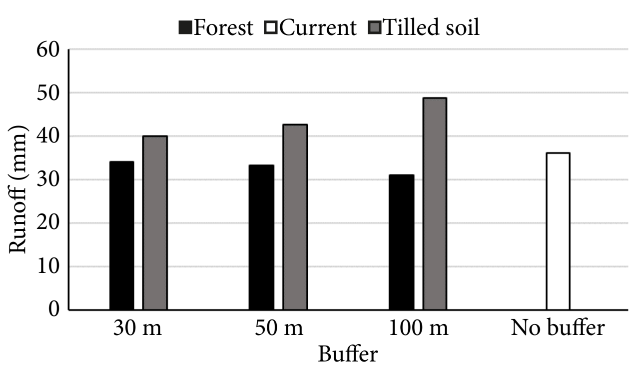

Figure 6. Graph of surface runoff under low precipitation.

When the simulated forest buffer was found to be 30 m under low precipitation, the runoff depth decreased from 36.1 mm to 34.2 mm, whereas under a 100 m buffer, this value went further down to 31.1 mm. Therefore, it is observed that riparian vegetation areas can reduce river basin runoff and, thus, the amount of water flowing into the city after extreme precipitation events.

With the simulations, it was found that runoff depths under low precipitation decreased by 5%, 8%, and 14%, respectively, for buffers of 30 m, 50 m, and 100 m in forest buffer areas. The opposite can also be verified, as upon simulation with tilled soil buffer areas, the depths increased by 11%, 19%, and 36% for 30 m, 50 m, and 100 m buffers.

This increase in runoff values of simulated tilled soil is also a consequence of the lack of plant interception, which enables the direct incidence of water on the soil. Contrarily, in forest areas, the treetops and organic matter on litter constitute a naturally intercept rainfall, resulting in reduced surface runoff and higher water infiltration in soil (Rodrigues et al., 2015).

Thus, the effect of plant interception and infiltration can be observed on the reduction of surface runoff generation.

Figures 7 and 8 show the spatialization of direct runoff per pixel in the study area, where a 100 m buffer is simulated. In a forest scenario, in the surroundings of watercourses, the values remain low, whereas they increase in tilled soil scenarios, considered as degradation situations.

The width of this riparian vegetation in the surroundings of watercourses has been addressed in environmental research. The legislation establishes fixed values of widths for riparian zones according to the water body magnitude. However, physical, chemical, and biological factors affect the efficiency of these areas. These factors have not been established for the conditions found in Brazil, particularly regarding the different types of soil and climate conditions.

Based on a wide-scope literature review of the width of buffer zones, Castelle et al. (1994) suggest efficiency between 3 and 200 m of riparian forest, depending on site-specific conditions. Minimum widths of 15-30 m are required for protection under most circumstances. On the other hand, Lees & Peres (2008) recommend riparian areas with a minimum width of 400 m (200 m on each side of the watercourse), particularly along courses over 10 m.

Highlighting the importance of riparian zones around watercourses, Schultz et al. (1997) report that large floods in the Midwest of the United States showed that changes in agroecosystems had accelerated water flow to streams. Cultivation of more than 90% of the surface contributed to faster water flow and more extensive flooding.

Upon analysis of research on the subject, Monteiro et al. (2013) point out that it is only possible to indicate widths of areas to be maintained vegetated or re-vegetated according to the type of environmental service expected, and there is no conclusion as to the adequate width to simultaneously serve several environmental services. Silva (2012) also states that, to define the PPA, it is necessary to determine the so-called area of passage of the flood as one that should not be occupied. This zone has a technical criterion of definition that depends on the local hydraulic and hydrological conditions.

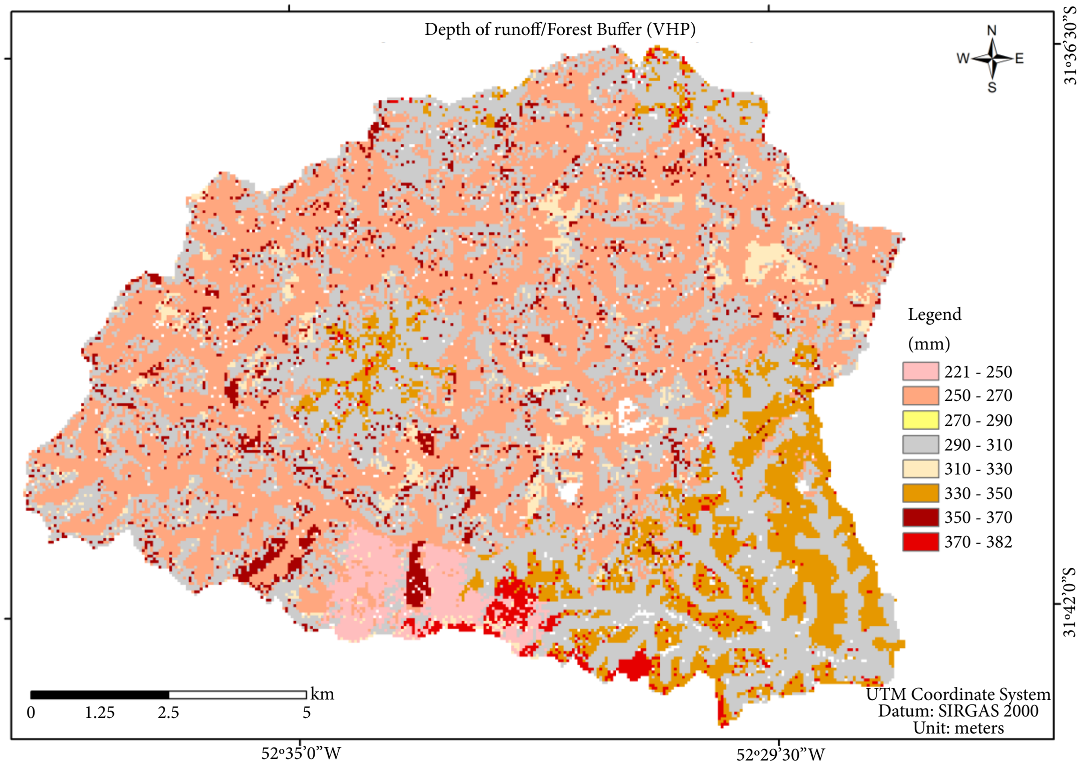

Figure 7. Image of surface runoff under very high precipitation, with forest buffer of 100 m.
VHP: very high precipitation.

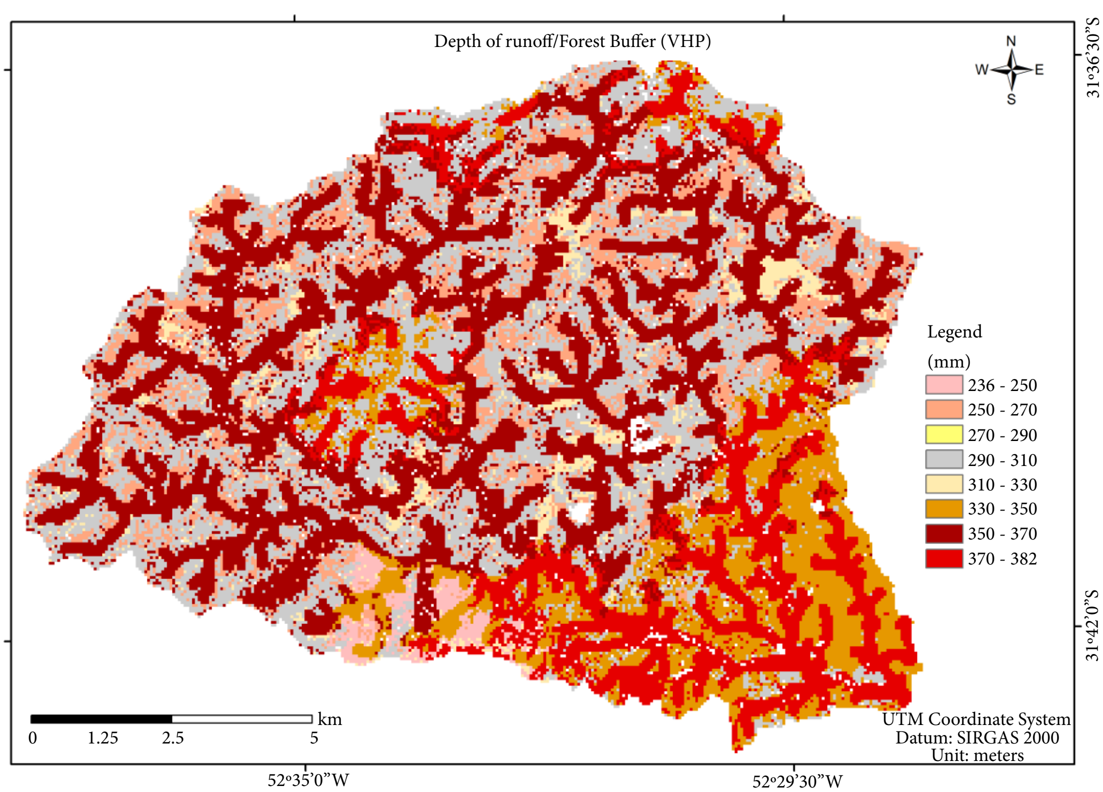

Figure 8. Image of surface runoff under very high precipitation, with tilled buffer of 100 m.
VHP: very high precipitation.

4. CONCLUSIONS

Conservation of riparian forests in the surroundings of the watercourses of Passo dos Carros station watershed enables the decrease of direct surface runoff volume by up to 14% of this runoff in the higher conservation scenarios.

Intensive use of soil and non-conservation of riparian forests around watercourses increases surface runoff volume, which can reach increments of up to 36% in tilled soil scenarios for buffers with 100 m in length.

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