SUBSURFACE FLOW INTERCEPTED BY RURAL ROADS: CHARACTERISTICS AND DISTRIBUTION ON THE LANDSCAPE

FLUXO SUBSUPERFICIAL INTERCEPTADO POR ESTRADA RURAL: CARACTERÍSTICAS E DISTRIBUIÇÃO NA PAISAGEM

FLUJO SUBSUPERFICIAL INTERCEPTADO POR CARRETERA RURAL: CARACTERÍSTICAS Y DISTRIBUCIÓN EN EL PAISAJE

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Abstract

Although rural roads enable the development of rural communities, they change the natural hydrological response of the catchment. This study was carried out in the Guabiroba River Basin, Guarapuava-PR, with the objective of identifying and characterizing the types of subsurface flow interception caused by rural road cuts associated with their spatial distribution along the river basin. For this, as methodology used, we conducted a field survey with direct observation to determine the areas of interception of subsurface flow and their distribution in the catchment Guabiroba River basin. Three major types were identified: return flow, pipe flow, and saturated troughflow. Return flow is often distributed in rivers and terraces, pipe flow is present mainly in midslopes, and saturated troughflow occurs most often in upper slopes, expelled onto the deepest embankments. It is concluded, therefore, that the types of subsurface interception and their spatial distribution can alter the natural hydrological dynamics of the basin, provoking a shorter response time than through infiltration and displacement in the soil.
Keywords: Rural catchment, hydrologic response, connectivity, saturated area.

Resumo

Embora as estradas rurais permitam o desenvolvimento das comunidades rurais, elas alteram a resposta hidrológica natural da bacia hidrográfica. Esse estudo foi realizado na bacia do Rio Guabiroba, Guarapuava-PR, com o objetivo de identificar e caracterizar os tipos de interceptação de fluxo subsuperficial causados por cortes de estradas rurais associados à sua distribuição espacial ao longo da bacia hidrográfica. Para tanto, como metodologia utilizada foram realizados levantamentos de campo com observação direta para determinar as áreas de interceptação do fluxo em subsuperfície e sua distribuição na bacia do Rio Guabiroba. Três tipos principais foram identificados e denominados como: fluxo de retorno, fluxo *pipe* e fluxo insaturado. O fluxo de retorno é frequentemente distribuído próximo aos rios e no fundo de vale, o fluxo *pipe* está presente principalmente em média vertente, e o fluxo insaturado ocorre mais frequentemente em encostas superiores, expelido nos taludes mais profundos. Conclui-se, portanto, que os tipos de interceptação subsuperficial e a distribuição espacial desses podem alterar a dinâmica hidrológica natural da bacia, provocando um tempo de resposta menor que por meio da infiltração e deslocamento no solo.
Palavras-chave: Bacia hidrográfica rural, resposta hidrológica, conectividade, área saturada.

Resumen

Pese a que las carreteras rurales permiten el desarrollo de las comunidades rurales, cambian la respuesta hidrológica natural de la cuenca. Este estudio fue realizado en la cuenca del Río Guabiroba, Guarapuava-PR, con el objetivo de identificar y caracterizar los tipos de interceptación de flujo subsuperficial causados por cortes de carreteras rurales asociadas a su distribución espacial a lo largo de la cuenca hidrográfica del Río Guabiroba. Para ello, como metodología utilizada hemos desarrollado un estudio de campo con observación directa para determinar las zonas de captura del flujo en el subsuelo y su distribución en la cuenca. Se identificaron tres tipos principales: flujo de retorno que, es frecuentemente distribuido próximo los ríos e al fondo del valle, el flujo *pipe*, que está presente principalmente en la media vertiente, y el flujo no saturado, que se produce más a menudo en laderas superiores, segregado en inclinaciones más profundas. Se concluye, por lo tanto, que los tipos de interceptación subsuperficial y la distribución espacial de éstos, pueden alterar la dinámica hidrológica natural de la cuenca, provocando un tiempo de respuesta menor que por medio de la infiltración y desplazamiento en el suelo.
Palabras-clave: Cuenca rural, la respuesta hidrológica, conectividad, área saturada.

Introduction

Road networks are fundamental for local development in rural areas (FAIZ et al., 2012), since they guarantee the improvement of the quality of life of the population and, often, this is the only form of access that the population has to basic services as well as in urban areas, such as health, education, leisure, work and others (Bryceson et al., 2008, Faiz et al., 2012). In addition, road networks are often built in various types of landforms such as mountainous areas, hillsides, river terraces, and areas near drainage networks. The distribution of these tracks in different sectors of hillslopes and the tendency to cross drainage networks affect the movement of water and sediment through the catchment (Luce; Wemple, 2001; Chappell, 2010).

Thus, roads have positive and negative effects, wherever they are located. On the one hand, they are important for socioeconomic development, especially, in developing countries (Faiz et al., 2012; Sidle; Ziegler, 2012). On the other hand, they may cause several impacts on the ecosystem, such as changes on the hydrogeomorphological processes, surface runoff, subsurface flow interception, sediment production and sediment transfer to aquatic systems (Luce, 2002; Baartman et al., 2013; Thomaz et al., 2014).

Recent attempts have been made to make the roads more harmonious with the environment, while at the same time integrating the aesthetic principles to make them more attractive to users (Bryson et al., 2008, Cheng et al., 2015). Even though, for a long time, the rural roads were recognized as an important source of surface runoff and sediment production, playing a fundamental role in the river system connectivity (Jones, 1981; Sidle; Ziegler, 2012).

The hydrological behavior of roads is key to understanding its effects on the river basins dynamics. Although, the roads present very specific problems in the field of slope hydrogeomorphology, they also exhibit a great opportunity for the science advancement, through searching solution to an important environmental problem and understanding the watersheds processes from local to global scale (Bryan; Jones, 1997; Wemple et al., 2001; Cunha; Thomaz, 2015).

In river catchments, rural roads are the focus of hydrogeomorphological studies based on surface runoff, sediment production, and its transfer to rivers (Luce, 2002; Baartman et al., 2013; Thomaz; Ramos-Scharrón, 2015). However, an approach for the characterization of types of subsurface flow intercepted by rural roads cuts and its spatial distribution along a catchment remains scarce (Bryan; Jones, 1997; Luce, 2002).

The identification and characterization of the types of interception of subsurface flow is important for understanding their active mechanisms, particularly in areas in which the roads are abandoned or have low frequency of use and maintenance (Furniss et al., 1997; Sidle; Ziegler, 2012). In addition, anthropogenic pressures and organization of the landscape is central to hydrological science research. Therefore, the aim of this study is to identify and characterize the types of interception of subsurface flow caused by rural road cuts associated to its spatial distribution along a catchment.

Material and methods

Study area

This study was conducted in the Guabiroba River catchment in Guarapuava, State of Paraná, Brazil (Figure. 1). The catchment has an area of 24 km^2 (2.400 ha), and its stream ordering is 4 in scale 1:10.000. The predominant lithology of the study area is basalt of the São Bento Formation (MINEROPAR, 2001). Four types of soil are present on the surface cover: Oxisols, Cambisol Haplic, Lithic Leptosol, and Gleysol (IUSS Working Group WRB, 2006). In addition, rock outcroppings are present in some hillslope sections.

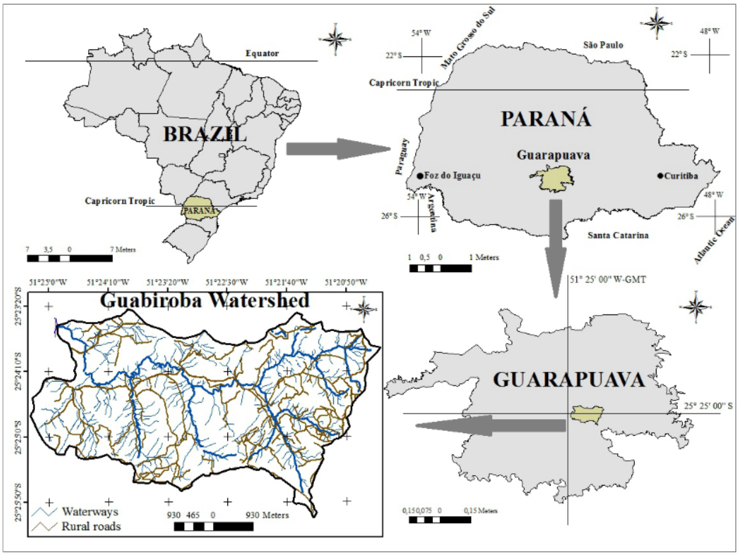

Figure 1- Location of the study area in relation to the city of Guarapuava

Source: designed by the authors (2017).

Approximately 75% of the area of the headwater region has slope between 12% and more than 30%. Köppen (1948) classified the climate in the study area as mesothermal humid subtropical (Cfa). The mean annual temperature is 17–18 °C; the rainfall is 1,800–2,000 mm; and annual evapotranspiration is 900–1,000 mm (CAVIGLIONE et al., 2000). The land use is not diverse, consisting mostly of secondary forest (53.9%), pasture (19.9%), and reforestation (11.3%).

Spatialization and characterization of types of subsurface flow interception.

In this study, it was based on an empiric-cartographic-monitoring scheme (Figure 2).

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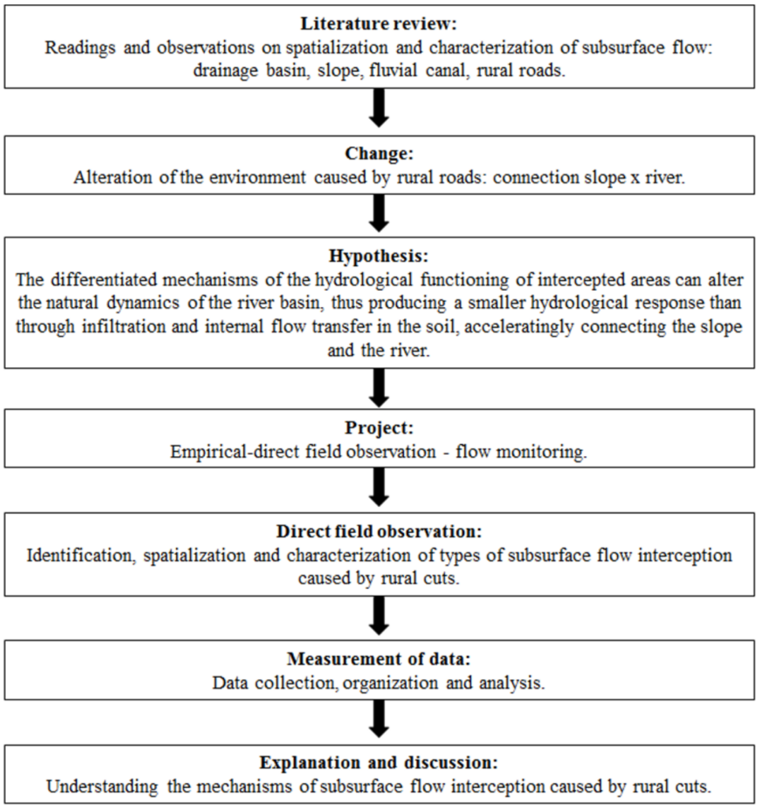

Figure 2- Theoretical-cartographic and monitoring scheme

Source: Organized by authors (2017).

The spatialization and characterization of the types of subsurface flow interception caused by rural road cuts were carried out by a preliminary identification of subsurface interception areas. We travelled on all 130 km of rural roads in the study area (total road). The objective was to observe and initially identify potential sites for interception of subsurface flow by rural roads, such as sites presenting humidity and water upwelling in the embankment and the roadbed, the presence of vegetation such as ferns or rushes (i.e., plants that grow in moist sites), and pipeline activity during rain periods (Figure 3).

Figure 3- Identification of potential areas for interception of subsurface flow by rural roads. In (a) saturated area, in (b) active pipe, in (c) water exfiltrated on the embankment of the road
Source: Organized by authors (2017).

Subsequently, the subsurface flow interception areas were spatialized. Of the total number of roads covered, 20 subsurface flow interceptions sites were recorded. It was registered that the potential areas of subsurface flow interception were distributed in different sectors of the slope, being the most common on three sections: valley bottom, midslope and upper slope. In this phase, it was observed the frequency of interception of the subsurface flow types.

It is, also, verified the characteristics of each type of the interception flow with the areas where they were located such as: location on the slope (toeslope, midslope or upper slope), shape of the terrain (concave, convex or rectilinear) and the slope inclination (flat, moderate or hilly).

The subsurface interception sites along the road system, was registered through a Global Positioning System (GPS) and with a Cartographic Digital Base of 1:30,000 scale, made available by the Guarapuava City Hall. The mapping of the landscape with the spatial distribution of subsurface flow interception areas was performed with a Geographic Information System (GIS), Quantum GIS version 2.18.5.

Jairosi (2001) informs that, with regard to geospatial data, the standardization of symbology (features) can bring results such as the mutual growth of the understanding of the geographical data in several users collaborating with the cognitive process.

Therefore, different types of interception were identified and characterized by specific nomenclature, as follows: 1- return flow, 2-pipe flow and 3- saturated flow. This designation was based on the direct observation of the characteristics that each subsurface flow presented (Anderson; Burt, 1990; Knighton, 1998). The cartographic representations in the present study are in accordance with the norms contained in the

Technical Guide T 34-700, which was elaborated by the Direction of the Geographical Service of the Brazilian Army (2000).

Results

Spatialization of interception subsurface flow sites

The total number, type of interception, and the residence time of each flow differed among hillslope sectors (Table 1). Along the 130 km roads surveyed, 20 sites of interception of subsurface flow were identified. As mentioned previously the nomenclature was designated as: return flow (7 occurrences), pipe flow (5 occurrences) and saturated troughflow (8 occurrences). These interception areas are distributed in different topographic sectors in the catchment (Figure 4).

Table 1. Spatialization of areas with interception of subsurface flow

Type of interception	Location on the road embankment	Predominant landform	Position on the slope	Total of interception observed	Flow time in consecutive days after rain
1- Return flow	Fluvial terrace, or near wetlands.	Concave	Toeslope	7	15
2- Pipe flow	Road embankment on midslopes.	Straight	Midslopes	5	10
3- Saturated troughflow	Expelled on the road embankment at upper slope.	Convex	Upper Slope	8	8

Source: data worked by the authors (2017).

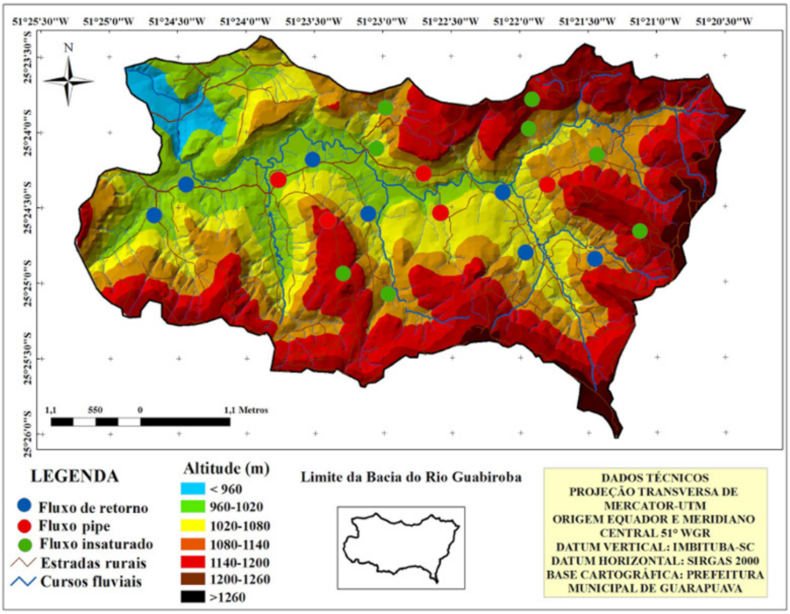

Figure 4- Spatial distribution of types of subsurface flows that occur in areas intercepted by rural roads cuts

Source: designed by the authors (2017).

The maintenance time of the intercepted flow refers to how many days the flow remains with discharge after the precipitation cessation. The time of permanence of the intercepted flow was highest in the return flow, being active up to 15 consecutive days after the rain. In addition, the flow residence time decreased from the valley floor to the ridge with 10 days in the pipe flow and 8 days in the saturated troughflow.

The return flow prevailed on the fluvial terrace and near wetlands (valley bottom) (Figure 5a). It should be noted that these interception sites are important in the generation of return flow near the drainage network. The shape of the terrain is convergent-concave and is early characterized by a hollow form conditioned by the subsurface flow toward the lower terrain of these sites. Thus, local characteristics enhance the accumulation and retention of water.

Pipe flow was present on roads predominantly located at midslope (Figure 5b). The dominant terrain in these areas is divergent-rectilinear with dispersion of the subsurface flow. These conditions hamper the appearance of drainage channels onsite and create a predominance of local water infiltration into the soil. In the five assessed pipes, the diameter between them varied widely with a mean of 14.4 ± 20.1 cm. In addition, perennial, intermittent, and ephemeral pipes were distinguished. Two pipes had constant flows, indicating perennial pipes, whereas the other three had flows that were restricted to periods of rain, indicating intermittent pipes, or that occurred only during or shortly after the rains, indicating ephemeral pipes.

It should be noted that the existing hydrologic connections within the soil in these areas resulted in the transfer of water between separated areas in the upper slope and river networks in the fluvial terrace. After being intercepted by road cuts, the water in the subsurface flow rapidly flows owing to low resistance caused by a lack of energy dissipation and steepness of the embankment (20%). These conditions result in subsurface flow with greater volume and that connected to the river channel.

Saturated troughflow prevailed on the road located at the upper slope (Figure 5c). These areas have an abrupt transition from the upper sector to the lower hillslope sector, or the fluvial terrace. The terrain is divergent–convex, which, coupled with the presence of rock fragments, results in the dissipation of water mainly in the longitudinal direction of the rural road embankment. The primary effect observed in the interception areas is that the water tends to expand laterally in the embankment when it is exfiltrated by deep road cuts. In this situation, the water is expelled parallel to the embankment and on the intersecting roadbed.

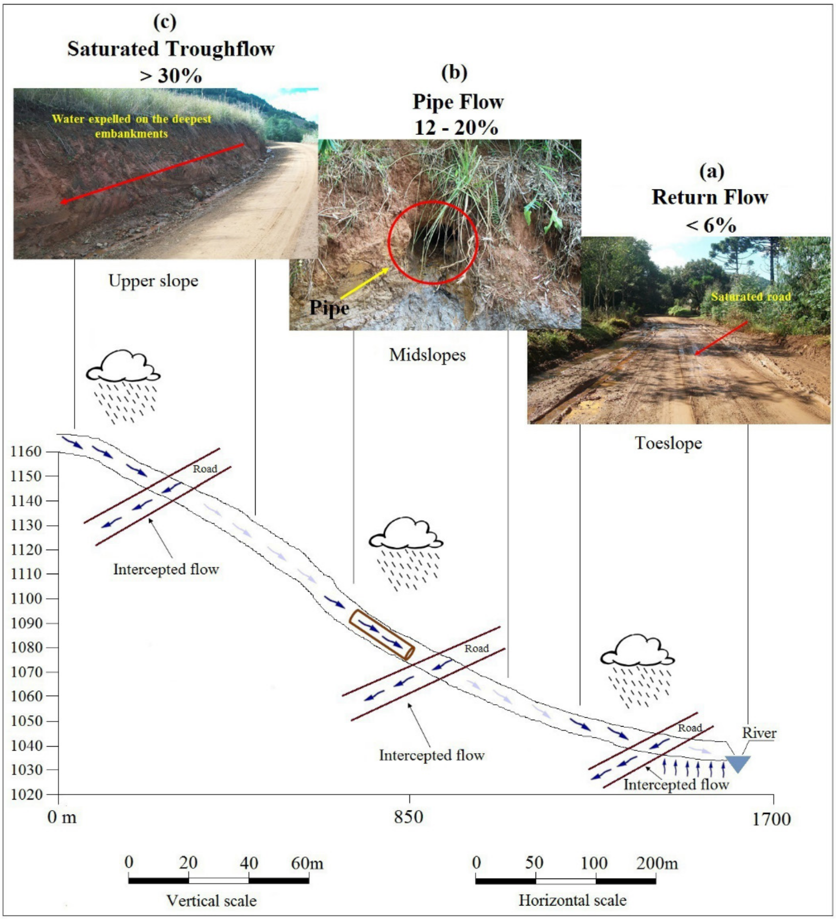

Figure 5- Conceptual model of the spatial distribution of the types of interception of subsurface flow caused by rural roads cuts according to the slope site and the steepness of the monitored areas

Source: Designed by the authors (2017).

The uniformity of the topographic gradient can assist the direction of the flow. In the identified interception areas, a preferential direction of water movement was noticeable. However, a preferred path for the displacement in which such flow expands downslope was not detected. As a result, erosion occurred on the embankment and on the roadbed.

Characterization of the types of interception of subsurface flow caused by rural roads cuts

Return flow is subsurface flow interception that occurs in shallow groundwater tables or saturated areas (i.e., return flow near a drainage network). As result of the combined action of water exfiltration and subsurface flow, the formation of a saturated shallow layer 3-15 cm in thickness was observed next to waterways and valley bottoms with gentle slopes (Figure 6a).

Pipe flow is the interception of punctual subsurface flow related to the capture of underground drainage, particularly pipes or ducts. Pipes are cavities in the ground, with preferential paths favoring the passage of tubular water drainage channels in the soil. These interconnected ducts are formed by the erosive action of subsurface flows dragging sediment and by the activity of fauna and flora. These channels were found parallel to the embankment of the road (Figure 6b).

Saturated troughflow is the interception of the subsurface water flow (non-punctual) parallel to the slope that forms a water layer with an average of 1-3 cm in depth and 300 m in length. This type of flow tends to laterally follow the road embankment, particularly at deeper road cuts (Figure 6c).

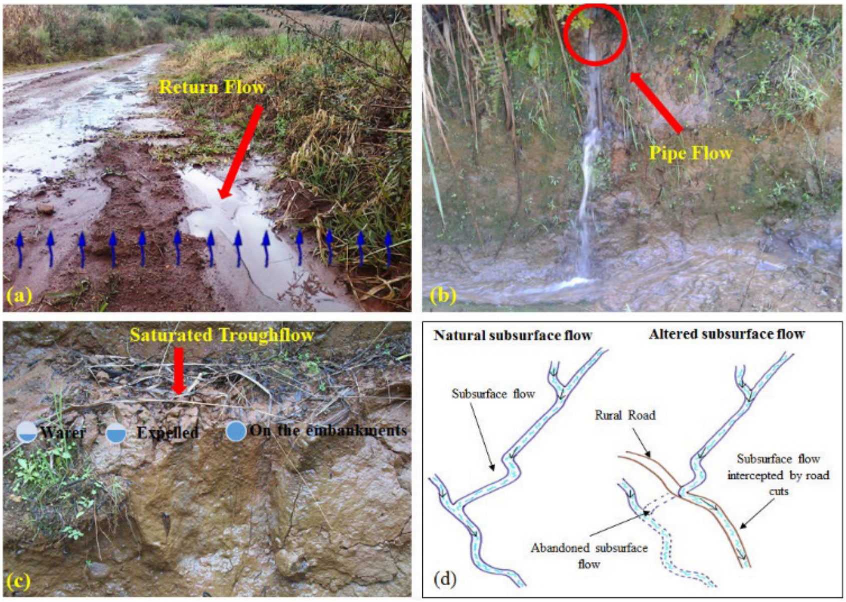

Figure 6- Characteristics of the types of interception of subsurface flow caused by rural roads. In (a) road intercepting subsurface flow in the Return flow type (prolonged saturation of the soil), in (b) road intercepting subsurface flow in the pipe flow type (punctual interception), in (c) road intercepting subsurface flow in the saturated troughflow type (water expelled parallel to the embankment), and in (d) hypothetical scheme of interception of subsurface flow caused by road cuts.

Source: Figure (d) adapted from Furniss et al., (1997).

It is observed that the interrelationships between the areas and the types of interception results primarily in interception of the subsurface flow by the road cuts and, later, water transfer and redirection of the concentrated flow into the river channel (connection with river).

The characteristics of each type of interception of the subsurface flow by rural roads, evidenced an expressive contribution to the fluvial flow. Therefore, it was observed a convergence among the three types of subsurface flow intercepted, resulting in the connection of upper slope, midslopes and toeslope areas.

Discussion

Distribution of the subsurface flow interception along the catchment

In the study area, rural roads are important for the interception of subsurface flow, particularly older roads with deeper embankments. The locations of these road types in different hillslope sectors increase their importance in hydrogeomorphological disturbances at the catchment scale. Therefore, the interception of subsurface flow changes the natural hydrology dynamics. The roads, through subsurface interception, affect the movement of water and sediment, contributing to soil and hillslope desiccation and rapid connection of the slope and river (Figure 7).

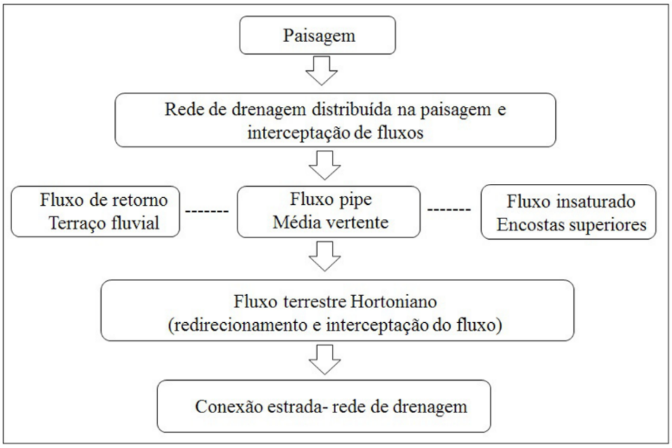

Figure 7- Conceptual model representing the types of interception of subsurface flow caused by rural roads cuts.
Source: designed by the authors (2017).

A clear difference was identified in the behavior of the type of interception occurring on toeslope, midslope, and upper slope areas. The interception of return flow occurs mainly in the river terrace areas near the drainage network. In this case, the main effect generated is prolonged soil saturation because water infiltration into the deeper soil layers is hampered.

In the interception of the pipe subsurface flow (midslope), no energy dissipation occurs, and the water is quickly infiltrated. This causes the formation of intermittent channels in the longitudinal direction of the road, leading to interception of the flow subsurface. Bryan and Jones (1997), Jones (1981), and Chappell (2010) reported that relief features with steep embankments, moderately deep permeable soils, and the formation of ducts are conditions for the flow of water in the subsurface at these sites. This type of interception may create active pipes of a few or tens of centimeters across with networks that can extend several meters into the embankment.

The interception of saturated troughflow is characterized by the predominance on the upper slopes (Wemple et al., 2001; Ziegler et al., 2012). In this case, water is released gradually in the deeper road embankment, where scattered drainage occurs parallel to the slope through the existing soil porosity. This generally reacts to changes in hydraulic gradients pressure. In this type of subsurface flow no hierarchy is present; that is, there is no preferential flow path such as that occurring in the pipe flow type (Terzaghi; Peck, 1966).

In the study area, the roads are old and have been deployed in different topographical units, frequently with no consideration to the adequacy of the terrain (Thomaz et al., 2104; Cunha; Thomaz, 2015). In addition, owing to the linear nature of the roads and their tendency to cross different types of topographic terrain, particularly drainage networks, they strongly affect the movement of water and sediment (Luce; Wemple, 2001; Ziegler et al., 2012).

As result, problems occur such as steep ramps with problematic traffic conditions and unstable embankment, which, in addition to their difficult maintenance often expose soil profiles that are susceptible to erosion. The roads are embedded in the hillside with exposed embankments also featuring tracks with no surface or subsurface drainage control, a lack of vegetation in surrounding areas, and crossings of roads and rivers (Wemple et al., 2001; Luce, 2002; Forman et al., 2003; Cunha; Thomaz 2015; Thomaz; Peretto, 2016).

Characteristics of the subsurface flow intercepted by rural roads cuts

In the studied area, rural roads are connected hydrologically to the fluvial channels through the intersections, which serve as a pathway to the concentrated subsurface flow entrance. These crossings of roads and rivers occur on the entire catchment, however, in the fluvial terraces, particularly, along the main roads, they are more frequent.

In saturated areas, there is a strong connectivity between the intercepted flow the upper slope (saturated troughflow), resulting in the sum with the flow at the midslope (pipe flow) and the intercept flow on the valley (return flow). Luce and Wemple (2001) and Bracken (2013) emphasize that this excess of intercepted subsurface flow is redirected to the river channels, possibly contributing to the flow peaks.

Overall, more than 95% of the rainfall falling over a catchment needs to pass on a hillslope before being transferred into a river channel (Knighton, 1998). In addition, water can follow several hillslope paths to reach a river, e.g., Hortonian overland flow, return flow, unsaturated and saturated troughflow and pipe flow, and groundwater flow.

The response of catchment to hillslope flow processes is dependent of the process type involved in the water transfer. Infiltration-excess overland flow can generate a storm hydrograph in few hours or minutes after a rain event. However, subsurface storm flow will display a lag time of many hours or days to generate a storm hydrograph. In short, surface runoff is faster than subsurface flow (Anderson; Burt, 1990).

Thus, the rural road cuts transform the entire intercepted subsurface flow into the Hortonian flow (i.e., fast flow). In addition, the compacted roadbed generates surface runoff, because the rainfall intensity exceeds easily the soil water infiltration capacity. Moreover, in the study area during rainstorms, the roadbed generates important infiltration-excess overland flow ranging from 17% to 58% (Thomaz; Ramos-Scharrón, 2015). The velocity of Hortonian overland flow ranges from 30 m/h^{-1} to 500 m/h^{-1} (Knighton, 1998). Therefore, the road network is crucial in the hydrograph catchment response because it transforms most parts of slow hillslope flow processes (subsurface flow) to faster flow processes (overland flow).

At some scale, the hydrogeomorphic connectivity on roads crossing rural headwaters can affect the stream dynamics, and the storm flow can be controlled completely by the road hydro-geomorphological processes (Thomaz; Peretto, 2016). Thus, it is difficult to use a pristine hillslope hydrology approach for modeling the storm-runoff mechanism in a catchment with highly active road networks. These differentiated mechanisms of the hydrological functioning of can alter the natural dynamics of the river basin, thus producing a smaller hydrological response than through infiltration and internal flow just connecting the slope and the river.

Conclusions

Generally, unpaved roads transform the subsurface flow in Hortonian overland flow. The areas of interception of subsurface flow are distributed in different slope sectors. Return flow is observed mainly on the river terrace and wetlands where the interception of the flow occurs in shallow groundwater tables or saturated areas near the drainage network. The pipe flow dominates midslope areas, with one preferred way favoring the passage of the water to be intercepted by road cut embankments. The saturated troughflow is more frequently distributed in the upper slope and is entrenched in the road embankment with water being laterally exfiltrated.

The three types of identified flow display specific properties and function mechanisms. Return flow is the result of exfiltration of soil water and the sum of the intercepted subsurface flow. Pipe flow is the interception that occurs through ducts interconnected in the soil with a single preferential pathway. Finally, saturated troughflow occurs when water is distributed parallel to the road embankment.

Rural roads play a key role in connecting separate areas of the study area, thus altering the natural hydrological response of the catchment. These roads intersect the subsurface flow and redirect it to the river channels, resulting in more rapid hydrological response time compared with subsurface water flow transferred through the soil.

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