sociedade
& natureza

DOI: 10.14393/SN-v32-2020-49431

Received: 28 June 2019 | Accepted: 28 February 2020

The identification of runoff flows in an area of technogenic relief using hydrological models in GIS

Dener Toledo Mathias[1]
Cenira Maria Lupinacci[2]
João Osvaldo Rodrigues Nunes[3]

Keywords:
Hydrological Modeling
Linear erosion
Geotechnogenesis

Abstract

This article presents the results of mapping the flow routes of surface runoff in an area characterized by profound changes in relief caused by anthropic interventions. We chose the Tucum stream upper basin (Sao Pedro, São Paulo - Brazil) as a case study because it is marked by the advance of urbanization on land with strong susceptibility to erosion, with the presence of linear erosive features (ravines and gullies) and a complex history of interventions seeking to control them. We obtained primary data from a topographic survey in the field and carried out operations to develop a Hydrologically Consistent Digital Elevation Model (HCDEM) in the ArcGIS 10.1 program. Then, the Concentrated Flow Map of the area was elaborated from the modeling using the Multiple Flow algorithm in the ArcView 3.2 program. The results showed that topographic features of detail, especially technogenic terraces, have exercised marked control over the flow routes of surface runoff, contributing to generating erosive advance vectors of the ravines and gullies.

INTRODUCTION

Among the mechanisms involved in morphogenesis, runoff appears as a hydrological agent of great repercussion. In environments under the imperative of hot and humid climate, water discharge from the precipitations sculpts the relief prominently, resulting in a driving force triggering of erosive processes.

Several factors work together to define the runoff patterns in a given landscape. According to Bigarella et al. (1996, p. 890), "climatic conditions, morphometric characteristics, biotic and edaphologic conditions, and anthropic activities" are determinant in the behavior of the surface runoff. The authors also point out that part of the flow will infiltrate the soil, integrating with the subsurface runoff network and that, from the saturation of the soil, it will start to run predominantly on the surface.

Given the beginning of the surface runoff process, the flow will be configured as laminar, in fillets, in sheets, or linear. We attribute the latter to the potential to cause incisions on the ground, especially if the physical conditions previously mentioned contribute to the erosive intensification. This can result in the formation of grooves, ravines, and gullies, which are incised channels at different stages of evolution. Gullies are characteristics of complex dynamics, generated or enhanced by the flow of concentrated linear flow (BIGARELLA et al., 1996; FENDRICH, 1997; GUERRA, 2010).

Regarding the conditioning factors to the erosive trigger, the physical characteristics of the

---

[1] Universidade Federal de Mato Grosso, Cuiabá, MT, Brasil. denertm@yahoo.com.br
[2] Universidade Estadual Paulista "Júlio de Mesquita Filho", Rio Claro, SP, Brasil. cenira.lupinacci@unesp.br
[3] Universidade Estadual Paulista "Júlio de Mesquita Filho", Presidente Prudente, SP, Brasil. joao.o.nunes@unesp.br

landscape stand out, mainly involving geological, pedological, geomorphological attributes, vegetation cover, and climate. The topography is a determining factor in the hydrological behavior of the slopes, since the morphometry reflects the potential energy of the runoff, while the morphography accounts for the distribution/concentration of the flows of this runoff. To the relief is added the anthropic influence, which acts as a catalyst, either through inadequate soil management or through the expansion of urban areas without proper planning (BRYAN, 2000; KIRKBY; BRACKEN, 2009; LIMA, 2003; OLIVEIRA, 2010; POESEN et al., 2003; VALENTIN et al., 2005).

In studies on the dynamics of erosive processes, the generation of digital models that incorporate hydrological information in their matrix, are indispensable. This prerogative is based on the fact that the drainage network consists the element of the physical system in which most of the transport of matter and energy occurs, being decisive in the morphogenetic processes (CHRISTOFOLETTI, 1980).

The surface runoff flows are a fundamental component for the analysis of geomorphological processes. As Coelho (2001, p. 95) points out, “the preferential routes of surface or subsurface flows define the predominant erosive-depositional mechanisms”. In this sense, the identification and mapping of such routes in areas subject to the triggering of linear erosion processes are procedures of great value in the diagnosis of erosive dynamics, as well as in the evolutionary prognosis of features (ASADI et al., 2007; CHAPLOT, 2005; HAIRSINE; ROSE, 1992; QUINN, 1991; PAISANI; OLIVEIRA, 2017; TAROLLI, 2014).

This paper aimed at presenting the mapping of surface runoff routes in an area characterized by the presence of characteristics of technogenic relief. We assumed that the recognition of the preferential surface runoff routes allows the identification of possible vectors of the advancement of linear features, contributing to the evolutionary prognosis of the processes.

STUDY AREA

This study was conducted in the Tucum stream upper basin. It is located in the city of São Pedro, in the central region of the State of São Paulo, Brazil (Figure 1). The area has erosive features occurring on the periphery of the municipality's urban grid.

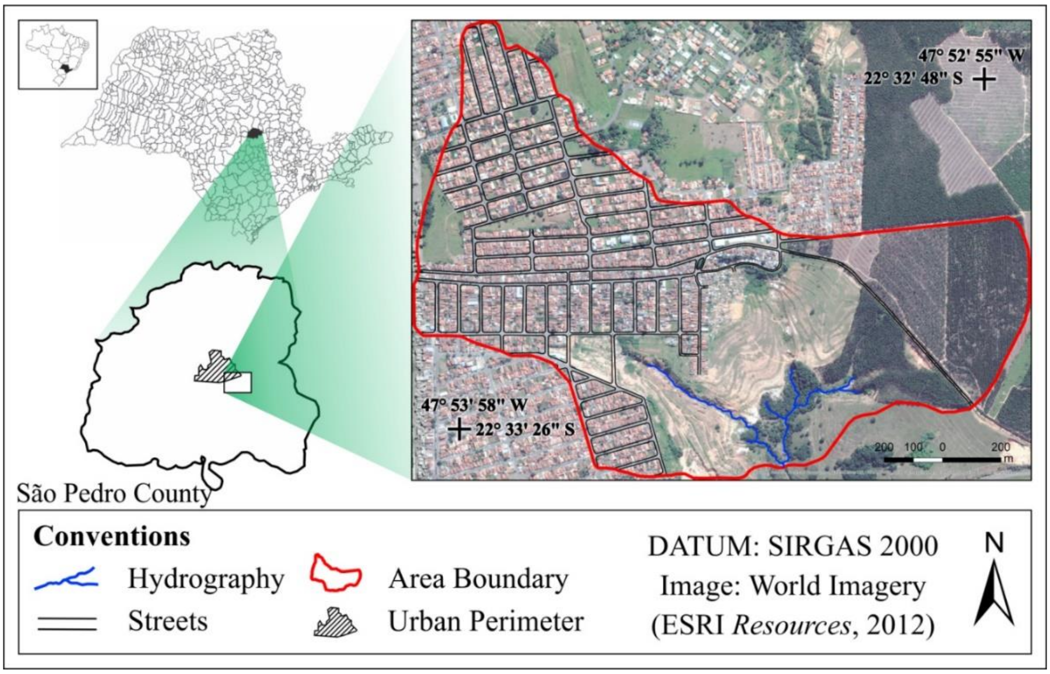
The Tucum stream upper basin is in the morphosculptural compartment of the Peripheral Depression of São Paulo, constituting part of the morphostructure of the Paraná Sedimentary Basin. It has, as a geological framework, sandstones from the Pirambóia and Botucatu formations (dated from the Triassic and Jurassic-Cretaceous, respectively), being the first predominant in the study area (IPT, 1981). There is also the presence of neocenozoic coverings of the Rio Claro Formation, which occur in a modest way covering the interfluves. The lithologies have strong friability, and the soils that developed on them (Argisols and Quartzenic Neossols) have medium to sandy granulometry, being susceptible to erosion (CARPI JUNIOR, 1996; SANCHEZ, 1971). These soils are poor in nutrients, due to the strong leaching typical of these pedological coverings (OLIVEIRA, 1999).

Broad hills and tops with a predominance of tabular form compose the relief in the Tucum stream upper basin. The slopes have a proper ramp length, and they abruptly yield to the banks of rivers where the active erosive dynamics take place. Carpi Junior and Mendes (1992) identify the reliefs of the Tucum stream area as belonging to two geomorphological compartmentalization units: Tabuliform Pieces and Dissected Pieces. The authors note these compartments are the most susceptible to erosive dynamization in the São Pedro region.

Relevant aspects of the area are related to land use and human intervention carried out at different temporal and spatial scales. The advance of urbanization is predominant over areas of past agricultural use, which present degraded pastures, punctuated with patches of exposed soil. The eucalyptus forestry also occurs in restricted sectors. The area was fully occupied by pasturages before the mentioned urbanization processes.

Regarding anthropic interventions, changes produced by works to control erosive processes are observed. These interventions have been carried out since the beginning of urban expansion in the basin, which occurred in the mid-1960s. Level terraces are found in the sectors between the urban network and the river course. Technogenic deposits occur in the erosion headside sectors, showing attempts to obliterate the erosive forms with landfill materials (remobilized soils) and solid urban waste.

Figure 1 - Location of the Tucum stream upper basin.



Organization: Authors, 2019.

Therefore, the physical characteristics of the basin provide conditions for the erosive triggering, which combined with anthropic factors (inadequate land management, advancing urbanization over areas of fragility, and undue deposition of waste), promotes the intensification of erosion processes. Interventions to mitigate the progression of erosive features are inadequate when restricted to burying ravines and gullies and terracing the area (MATHIAS, 2016). Thus, the conditioning imposed by the technogenic features in the hydrological behavior of the area justifies a more detailed study based on the mapping techniques adopted in this work.

MATERIAL AND METHODS

To map the flow routes of the surface runoff in the study area, we adopted processing operations in a GIS environment, using the ArcGIS 10.1 program. Based on the premise that the features of the relief detail are significant in determining the flow routes and, consequently, in the processes acting in areas of erosive susceptibility (characterized by intense anthropic interventions), we carried out a topographic survey to acquire data in level of detail. The equipment used was a Ruide's Total Station, model RTS 825 R3. From the survey carried out in the field, 13648 points were obtained, measured by irradiation from 98 stations, and the resulting area of the polygon was 621491 m².

Data processing was performed using the Autodesk Land 2004 program and resulted in the extraction of a grid of points containing planialtimetric coordinates. The georeferencing of the topographic data took place by two coordinates obtained in the field with precision GPS (model: L1/L2 RTK Leica / GS15 Viva), which we incorporated into the survey at the time of data processing.

In the survey work, we gave special attention to technogenic features, measuring it in detail. In the same way, we raised points along the edges of the erosive forms and in the valley bottoms, to obtain a detailed representation of the incisions and their ramifications.

We transcribed the georeferenced grid of points from the extension generated by Autocad to the shapefile format, to work it in the ArcGIS 10.1 program. Then, we generated a triangular grid TIN (Triangulated Irregular Network), resulting in a Digital Terrain Model (DTM) that enabled us to generate a cartographic base on a scale of 1:500, with 1m of equidistance contour lines.

We based the choice for the triangular grid method on the characteristics of the points mesh, which showed variations in density resulting from a larger sample in sectors of greater morphological complexity, as in the case of the rework forms contained within the erosive incisions. Also, we considered the possibility of making edits about the TIN based on the resampling of data from field observations after the generation of the DTM. We adopted as a premise that only topographic data at the level of detail allows certain phenomena to be judiciously evaluated, as in the case of erosion (TAROLLI, 2014).

From the DTM, we took a series of important steps to refine the data and map the flow routes of the surface runoff. Such steps begun with the identification and enrichment of the drainage network, whose premise was the inclusion of the channels for the concentration of rain flow. According to the guidance contained in an online tutorial offered by ESRI (2013), the Hydrology tool of the Toolbox Spatial Analyst was used, whose algorithms allow the extraction of the drainage network at different hierarchical levels, defined according to the analysis' necessity.

We can summarize the operational sequence adopted in the following steps: a) Fill – filling in the gaps from the design of the digital model; b) Flow Direction – elaboration of a model containing the surface runoff flow directions; c) Flow Accumulation – mapping of the possible concentration channels for the flow of the runoff, based on a multidirectional algorithm (which considers the accumulated flow value in each cell of the model, depending on the preceding cells upstream). We completed the procedure using the Raster Calculator command, from which a file containing the drainage network layout is generated and, using the Stream to Feature command, converted into a shapefile format.

In the next step, a Hydrologically Consistent Digital Elevation Model (HCMDE) was generated, as proposed by Chaves (2002). The procedure uses '*Topo to Raster'* interpolator, that's a component of '*Spatial Analyst*' toolbox, and which considered as the most appropriate for this purpose since it allows to integrate drainage in the interpolation process (GUEDES et al., 2011; RIBEIRO, 2015; VALERIANO, 2004).

Following the procedures contained in ESRI's online tutorial (2013), we interpolated the following features: a) contour lines, with 1-meter equidistance; b) drainage network (including the flow channels generated as already described); c) area boundary, as the bounding polygon of the interpolation. The spatial resolution, inserted as one of the interpolation parameters, was defined after a series of tests, which results for the best accuracy showed to be the one obtained with pixels of 0,5 m on the side (each pixel is equivalent to an area of 0,25 m^2), and therefore the HCDEM is on a 1:1000 scale. The relationship between scale and resolution falls within the values provided for in the Cartographic Accuracy Standard for Digital Cartographic Products (PEC-PCD, in Portuguese), established by the Technical Specification for Geospatial Data Sets Products (ET-PCDG, in Portuguese), according to Decree nº 89.817 (BRASIL, 1984). The topographic data included features of detail, such as erosive forms of rework, which justifies the resolution on a centimeter scale.

The final step comprised an operation aimed to create a map that could represent the preferential flow path of the surface runoff, delimiting the sectors of water dispersion and those of higher concentration. The Flow Accumulation Map is a valuable document for the analyses proposed in this study.

Fontes (2009) explained the procedure adopted to obtain the Flow Accumulated Map, which several studies used (BARBOSA, 2011; MATHIAS, 2011; MORAES et al., 2014). The proposals of Schäuble (2004) are the base of this technique and consists of the numerical calculation of the cells of a digital model, focused on the representation of concentration values per contribution area, that is, we calculated the geometric relationships between the cells of the model to obtain the amount in the area (m^2), that drains for each cell individually.

This technique stands out for appropriating the multiple flow algorithm, developed by Quinn et al. (1991), in which the calculation occurs in various directions. The algorithm is defined based on the flow accumulation index (In), according to Equation 1.

$$In = \ln(\alpha / \tan\beta) \qquad (1)$$

Where: α is the specific catchment area (L^2/L), given by the sum of the upstream contribution area, L is the generic length unit, and tangβ is the slope of the ramp. As explained by Moraes et al. (2014, p. 226), the topographic index In refers to "the tendency of water to accumulate in α; tangβ the term that considers gravitational forces, as an approximate hydraulic gradient". The calculation aims to analyze the flow pathways, determining their direction. Slope values also participate, weighted from the n values of the angles of each grid, from the sum of the orthogonal lengths (QUINN et al., 1991 *apud* MORAES et al., 2014).

The algorithm allows the accumulated slope area of a given cell to be distributed among all directions of the slope, being able to contribute downstream in up to eight possible flow directions. According to Quinn et al. (1991, *apud* MORAES et al., 2014, p. 224), each direction of the downward curve is made "proportionally to the flow path gradient downstream, combined with the length of the ramp and the area drained upstream". As a result, we obtain a map that can be classified according to representative classes to identify trends in runoff concentration.

We adopted the guidelines presented by

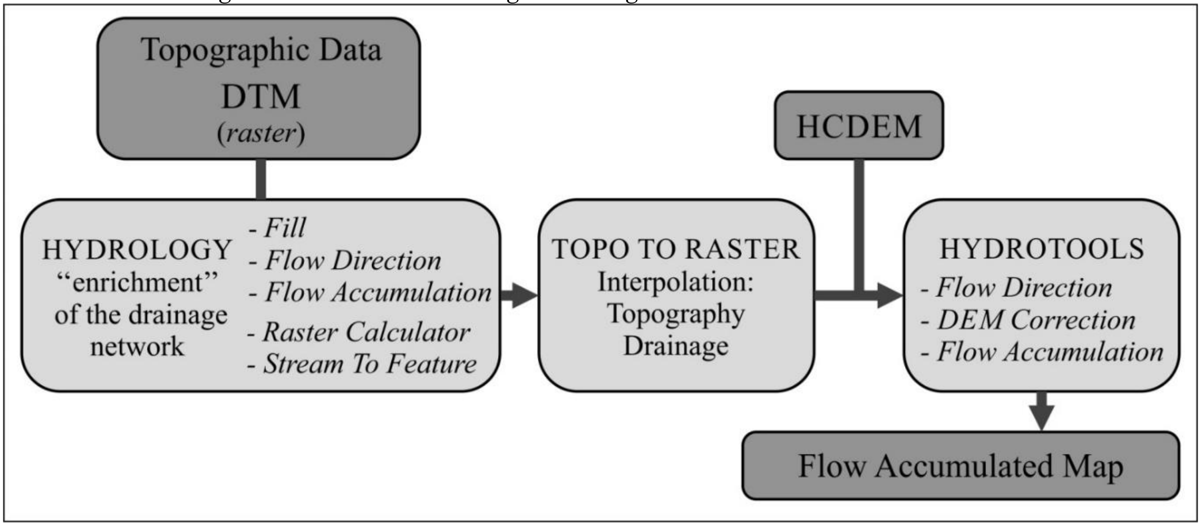
Fontes (2009) to generate the Flow Accumulated Map using the ArcView 3.2 program. The operations to obtain the map uses the Hydrotools tool, which we installed as a complement to the program. The Spatial Analyst extension must also be activated so that the program can read the grid from a raster file.

Having added the file corresponding to the HCDEM, we prepared the surface, in which a grid of flow directions is generated (*Flow Direction*). Then, we operated to correct possible model errors (*DEM Correction*). Finally, within the Hydrology functionality, the Flow Accumulation operation was performed. In this step, the algorithm used is defined, which, in the case of this study, was the MD (*Multiple Flow*), following the propositions of Fontes (2009).

This grid corresponds to the map representing the flow accumulation/dispersion trends. Thus, we exported the map and inserted it in the ArcGIS 10.1 database, whose interface allowed us to reclassify the image at defined intervals. In this study, we defined the intervals on a geometric scale in m² (5, 10, 50, 100, 500, and 1000), because it allows adequate data visualization. Only the last class interval includes the largest values generated by the program (range from 1000 m² to 1761045 m²), in which only the values of the cells corresponding to the layout of the drainage network are contained.

Figure 2 shows the organization chart for generating the Flow Accumulated Map.

Figure 2 - Procedures for generating the Accumulated Flow Chart.



Organization: Authors, 2019.

The fieldwork aimed to recognize features and to investigate and check the data generated, and verify the validity of the final cartographic product. Field activites was carried out between January and March 2015, totalizing 15 days. We based the checking on a visual analysis of both erosive grooves and "pockets" accumulation of sediments in the slope, resulting from transport by surface runoff flows, which corroborated the mapped flow routes.

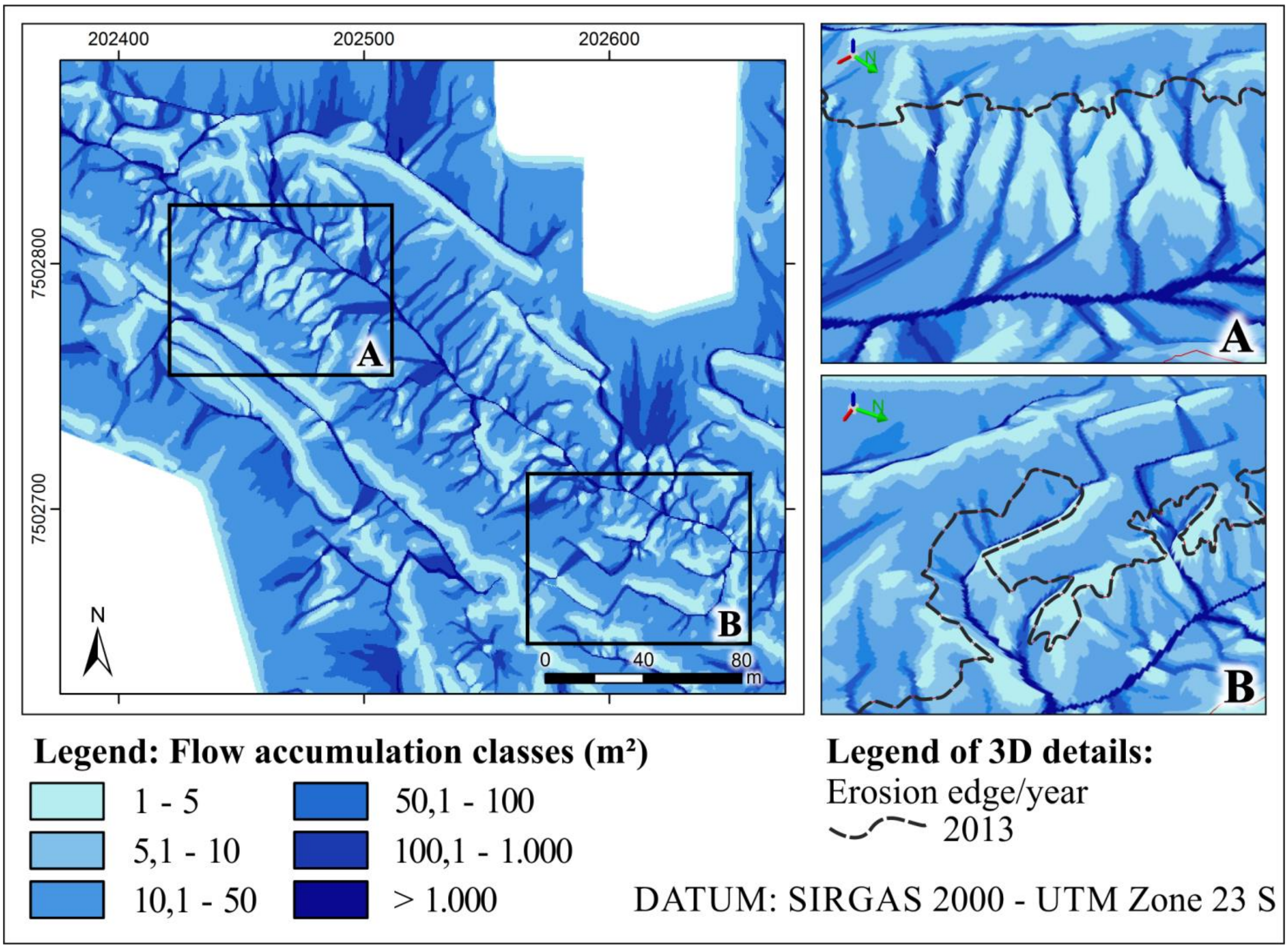
After the generation of the Accumulated Flow Map, a three-dimensional model was elaborated using the ArcScene 10.1 program, from the overlay of the map in raster extension to the MDE. A vector drawing of a line representing the edge of the erosive slope was also inserted. These procedures were carried out to assist the process of analyzing cartographic products, as well as for the composition of the images that illustrate this article.

RESULTS AND ANALYSIS

The analysis of the Flow Accumulated Map of the Tucum stream upper basin shows that the behavior of the surface runoff flow in the periurban slopes obeys the strict control of the topographic features, being conditioned primarily by technogenic terraces. The traces of the concentrated flow are evident as possible vectors of erosive advance, particularly in the edges of the ravines and gullies existing in the area.

Figure 3 shows the section of the Southwest sector of the Flow Accumulated Map of the Tucum stream upper basin, with perspective details generated in the ArcScene 10.1 program.

Figure 3 – SW sector of the study area, with details in 3D visualization (details A and B).



Organization: Authors, 2019.

The presence of a gullet of remarkable dimensions, containing on its slopes a profusion of ramifications in the form of grooves and ravines, characterizes the Southwest sector of the Tucum stream upper basin. The topographic features existing in the slopes bordering that gullet, in particular the technogenic terraces, exercise significant control over the surface runoff flow routes – in some cases, preventing the advance of erosion, and in other cases, contributing to it.

Figure 3 presents three-dimensional images that are representative of two different situations that we can identify from the results. In A it is possible to verify the concentration of linear flows within erosive grooves existing in gully slope. Such flows are contributing to the progression of branches in the feature, although the routes are limited in length, given the existence of an upstream terrace. Thus, despite the profusion of grooves and inter-grooves, we observed that the erosive advance at this point of the slope is less pronounced, according to monitoring carried out by Mathias (2016). The deepening of the grooves is more expressive than its advance upstream. Figure 4A presents the photograph of the slope sector where a large number of groove and ravines occurs.

In detail B (Figure 3) there is a different situation from the previous one. In this case, the presence of terraces potentiates the effects of erosion, as the flow routes are conditioned and concentrated in channels on the reverse of the terraces. When the terrace ruptures (caused by the erosive advance), the flow starts to contribute to the incision of the terrain, creating a ravine that progresses in the direction of the concentrated flow route. The process gains potential due to the unevenness of the embankment at the head of the feature, which is marked by regression alcoves at its base. It is, therefore, an erosive vector identified from the mapping results that allow predicting the spatial evolution of the features. Figure 4B shows a panoramic aerial photograph of the area, with details for the ravines formed.

Figures 4A and 4B – Gully slope with the wide diffusion of erosive grooves and lateral ravines formed after breaking the terrace.

Organization: Authors, 2019.

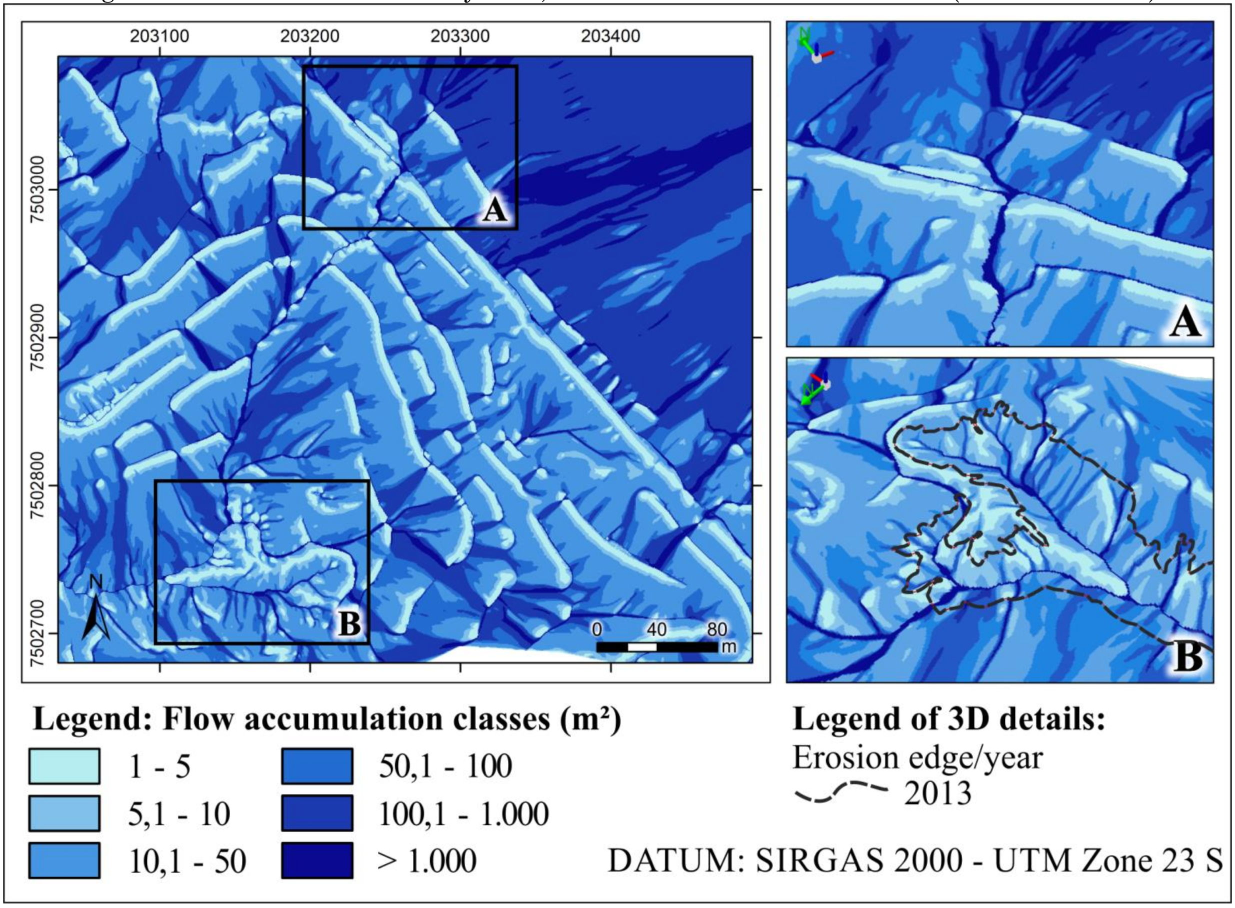
Figure 5 shows the Southeast sector of the Flow Accumulated Map of the Tucum stream upper basin and three-dimensional images of two portions of that land, representative of the characteristics of the runoff flow and associated process. technogenic terraces play a significant role in controlling runoff, producing procedural responses to the erosive dynamics occurring in the area.

The analysis of Figure 5 shows a sharp contrast in the behavior of the surface runoff flow between two portions of the area, bounded by a road that traverses it crosswise. The lands composing the high slope do not have technogenic terraces (upper right corner of the map clipping), while these features marks medium and low slopes.

That road, an unpaved municipal road, is a preferential path to the flow of runoffs in the analyzed sector since there is a terrace on its side. The surface runoff to the lower terrains occurs at a single point (Figure 5A). There is a ravine in the field where the headland is in contact with the road, thus representing a risk factor for the population using this road (Figure 6A).

Unpaved roads, besides being preferential paths for concentrated flow, are susceptible to intense erosive work (for that same reason), mainly due to the conditions imposed on surface materials by the circulation of vehicles (compaction, spraying). According to Thomaz and Ramos-Scharrón (2015), in a study carried out in southern Brazil, erosion in roads produce 17 times more sediments than in areas of agricultural use.

Figure 5 – SE sector of the study area, with details in 3D visualization (details A and B)



Organization: Authors, 2019.

Figure 5B shows a gullet in the low-slope portions of the Southeast sector. Technogenic terraces located in contact with the edges of this gully impose a runoff path, making the concentrated flow end at the head of a branch of the erosive feature. This is one of the most pronounced features of dynamics, as attested in the field. It is a peculiar condition in which structures designed to prevent erosion of the headland causes the intensification of processes in an adjacent area. Figure 6B shows the panoramic aerial photography focusing on the gullet.

Figures 6a and 6b – Head of the ravine in contact with public road and gully in the Southeast sector of the study area

Organization: Authors, 2019.

The analyzes carried out in this study are supported by the considerations of Ternan et al (2013). For the authors, it is evident that the "banks" generated by bench-terracing configure a new and complex condition in surface and subsurface, very different from that found in areas with intact vegetation cover.

Technogenic terraces are, therefore, striking features on the slopes of the Tucum stream upper basin, resulting from past terracing works, carried out as a measure to control erosion processes. The analysis of the Flow Accumulated Map of the study area allowed us to identify such features and to relate them to the surface runoff flow routes. The observations made in the field corroborate the data presented, which proves the efficiency of the referred cartographic document as a useful tool for the diagnosis of processes and the evolutionary prognosis of erosive forms.

FINAL CONSIDERATIONS

The dynamics of linear erosive processes is associated, among other factors, with the potential inherent to the concentrated runoff flow, which we list as one of the agents in the erosion outbreak. The runoff, in turn, is conditioned to the topographic forms of detail, which will determine possible routes of flow concentration as preferential lines to the formation and growth of incisions in the terrain.

In areas characterized by a strong susceptibility to erosion, forms of use and occupation can contribute substantially to the dynamization of processes. In the case of the Tucum stream upper basin, the marked changes brought about by the advance of urbanization are added to the successive unsuccessful interventions to control erosion, either through the obliteration of incisions with burial by the dumping of solid urban waste, as well as by the adoption of engineering methods such as terracing.

In this case, the technogenic forms generated in different cycles of interventions are features that contribute to the increased complexity with which erosive processes occur. This is because they may be controlling the progress of erosion or, under other conditions, allowing its outbreak. Thus, technogenic forms actively regulate the evolution of erosive features, generally responsible for determining the flow routes of the surface runoff.

The approach carried out in this study, based on the elaboration of a cartographic document that maps – through the morphometry of the relief – the concentrated flow routes of the surface runoff, is useful the study of erosive processes, as well as the possible actions of public managers. Therefore, the results obtained in this study contribute with significant subsidies to the possible interventions that can be carried out in the area, aiming to control erosion processes. This work also contributes with an example of the relevance of topographic data in detail, from the construction of a cartographic base suitable to the scenarios of technogenic morphologies.

ACKNOWLEDGMENTS

The authors would like to thank the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for the support granted (Process nº 03745-4).

REFERENCES

ASADI, H.; GHADIRI, H.; ROSE, C. W.; ROUHIPOUR, H. Interrill soil erosion processes and their interaction on low slopes. **Earth Surface Processes and Landforms**, v. 32, n. 5, p. 711-724, 2007. https://doi.org/10.1002/esp.1426

BARBOSA, C. **Planejamento urbano sustentável**: diretrizes de urbanização embasadas nas características geomorfológicas/pedológicas de vertentes. 2010. 123 f. Thesis (Master Degree in Geography). Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Rio Claro, 2011.

BIGARELLA, J. J.; BECKER, R. D.; PASSOS, E. **Estrutura e Origem da Paisagens Tropicais e Subtropicais**. Ed. UFSC. V. 2, 1996. 875 p.

BRASIL. Decreto nº. 89.817, de 20 de junho de 1984. Dispõe sobre as instruções reguladoras das normas técnicas da cartografia nacional. **Diário Oficial da República Federativa do Brasil**, Brasília, 22 de junho de 1984.

BRYAN, R. B. Soil erodibility and processes of water erosion on hillslope. **Geomorphology**, v. 32, n. 3-4, p. 385-415, 2000. https://doi.org/10.1016/S0169-555X(99)00105-1

CARPI JUNIOR, S.; MENDES, I. A. As vertentes do córrego Tucum (São Pedro, SP) e seu significado morfogenético. **Geografia**, Rio Claro, 17(1): 77-90, 1992.

CARPI JUNIOR, S. **Técnicas cartográficas aplicadas à dinâmica da bacia do Ribeirão Araquá – SP**. 1996. 188 f. Thesis (Master Degree in Geography). Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Rio Claro. 1996.

CHAPLOT, V.; GIBOIRE, G.; MARCHAND, P.; VALENTIN, C. Dynamic modelling for linear erosion initiation and development under climate and land-use changes in northern Laos. **Catena**, v. 63, n. 2-3, p. 318-328, 2005. https://doi.org/10.1016/j.catena.2005.06.008

CHAVES, M. de A. **Modelos digitais de elevação hidrologicamente consistentes para a Bacia Amazônica**, 2002. 115 f. Thesis (Doctorate in Forest Sciences). Universidade Federal de Viçosa: UFV, Viçosa, 2002.

CHRISTOFOLETTI, A. **Geomorfologia**, Edgard Blucher, São Paulo, 1980. 188 p.

COELHO, M. C. N. Impactos ambientais em áreas urbanas: teorias, conceitos e métodos de pesquisa. In: GUERRA, A. J. T. **Impactos ambientais urbanos no Brasil**. Rio de Janeiro: Bertrand Brasil, p. 19-45, 2001.

ESRI **ArcGIS Resources**. Version 10.1 Environmental Systems Research Institute, Inc. 2012. Available in: <http://resources.arcgis.com/en/help/main/10.1/>. Accessed: february 13, 2020.

FENDRICH, R.; OBLADEN, N. L.; AISSE, M. M.; GARCIAS, C. M. **Drenagem e controle da erosão urbana**. Curitiba: Champagnat. 4ª ed., 1997, 486 p.

FONTES, N. **Proposta Metodológica para planejamento de sistemas de espaços livres**: Ribeirão Preto – SP. 2009. 193 f. Tese (Doutorado em Geografia). Instituto de Geociências e Ciências Exatas da Universidade Estadual Paulista, Rio Claro, 2009.

GUEDES, H. A. S.; CAPOBIANGO, G. V.; MARTINS, V. S.; SILVA, D. Análise da precisão entre os métodos de interpolação Krigagem Ordinária e Topo to Raster na geração de modelos digitais de elevação. In: XV SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO. **Anais...** SBSR, Curitiba, PR, Brasil, INPE, 2011 p. 4239-4246.

GUERRA, A. J. T. O início do processo erosivo. In: GUERRA, A. J. T. et al (orgs), **Erosão e conservação dos solos**: conceitos, temas e aplicações, 2ª ed. Rio de Janeiro: Bertrand Brasil, 2010. p. 15-55.

HAIRSINE, P. B.; ROSE, C. W. Modeling water erosion due to overland flow using physical principles: 1. Sheet flow. **Water resources research**, v. 28, n. 1, p. 237-243, 1992. https://doi.org/10.1029/91WR02380

INSTITUTO DE PESQUISAS TECNOLÓGICAS DO ESTADO DE SÃO PAULO. 1981. **Mapa geológico do Estado de São Paulo**. V. 01 (texto) e V. 02 (mapa). Escala 1:500.000.

KIRKBY, M. J.; BRACKEN, L. J. Gully processes and gully dynamics. **Earth Surface Processes and Landforms**: The Journal of the British Geomorphological Research Group, v. 34, n. 14, p. 1841-1851, 2009. https://doi.org/10.1002/esp.1866

LIMA, E. R. V. de Erosão do solo: fatores condicionantes e modelagem matemática. **Revista Cadernos do Logepa**, v. 3, n. 1, p. 3-43, 2003.

MATHIAS, D. T. **Propostas de recuperação de áreas peri-urbanas erodidas com base em parâmetros hidrológicos e geomorfológicos**: Córrego Tucunzinho (São Pedro/SP). 2011. 128 f. Thesis (Master Degree in Geography). Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista, Rio Claro, 2011.

_______. **Contribuição metodológica para o diagnóstico da dinâmica erosiva linear e seu prognóstico evolutivo visando subsidiar projetos de recuperação**. 2016. 178 f. Thesis (Doctorate in Geography). Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista, Presidente Prudente, 2016.

MORAES, I. C,; CONCEIÇÃO, F. T.; CUNHA, C. M. L. da; MORUZZI, R. B. Comparação de metodologias na definição de fluxos acumulados a partir de modelos digitais de elevação do terreno aplicado a suscetibilidade de inundações. **Revista Brasileira de Recursos Hídricos**. V. 19, n. 2, p. 223-235, 2014. https://doi.org/10.21168/rbrh.v19n2.p223-235

OLIVEIRA, J. B. Solos do Estado de São Paulo: descrição das classes registradas no mapa pedológico. Campinas, Instituto Agronômico, **Boletim Científico 45**, 1999. 112p.

OLIVEIRA, M. A. T. de. Processos erosivos e preservação de áreas de risco de erosão por voçorocas. In: GUERRA, A. T. J. et al. (Orgs.) **Erosão e conservação dos solos**: conceitos, temas e aplicações. 5ª Ed. Rio de Janeiro: Bertrand Brasil, 2010, p. 58-99.

PAISANI, J. C.; OLIVEIRA, M. A. T. Desenvolvimento de incisão erosiva (voçoroca) descontínua e desconectada da rede hidrográfica em área de cabeceira de drenagem: o caso da Colónia Quero-Quero (Palmeira-PR). **Revista Brasileira de Geociências**, v. 31, n. 1, p. 51-58, 2017. https://doi.org/10.25249/0375-7536.20013115158

POESEN, J.; NACHTERGAELE, J.;

VERSTRAETEN, G.; VELENTIN, C. Gully erosion and environmental change: importance and research needs. **Catena**, v. 50, n. 2-4, p. 91-133, 2003. https://doi.org/10.1016/S0341-8162(02)00143-1

QUINN, P. F. B. J.; BEVEN, K.; CHEVALLIER, P.; PLANCHON, O. Prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. **Hydrological processes**, v. 5, n. 1, 1991, p. 59-79. https://doi.org/10.1002/hyp.3360050106

RIBEIRO, H. J. **Análise da consistência de dados hidrológicos a partir de diferentes modelos digitais de terreno**. 2015. 136 f. Thesis (Master Degree in Environmental Engineering). Universidade Federal de Goiás, Goiânia, 2015.

SANCHEZ, M. C. Contribuição ao conhecimento das bases naturais dos municípios de São Pedro e Charqueada (SP). **Notícia Geomorfológica**: Campinas, Vol. 11 (21), p: 47-60, 1971.

SCHÄUBLE, H. **HydroTools 1.0 for ArcView 3.x**, 2004.Available in: <https://www.terracs.com/wp-content/uploads/2018/05/hydrotools-english.pdf>.Accessed: february 13, 2020.

TAROLLI, P. High-resolution topography for understanding Earth surface processes: Opportunities and challenges. **Geomorphology**, v. 216, p. 295-312, 2014. https://doi.org/10.1016/j.geomorph.2014.03.008

TERNAN, J. L.; WILLIAMS, A. G.; ELMES, A.; FITZJOHN, C. The effectiveness of bench-terracing and afforestation for erosion control on Raña sediments in central Spain. **Land Degradation & Development**, v. 7, n. 4, p. 337-351, 1996. https://doi.org/10.1002/(SICI)1099-145X(199612)7:4<337::AID-LDR238>3.0.CO;2-G

THOMAZ, E. L.; RAMOS-SCHARRÓN, C. E. Rill length and plot-scale effects on the hydrogeomorphologic response of gravelly roadbeds. **Earth Surface Processes and Landforms**, v. 40, n. 15, p. 2041-2048, 2015. https://doi.org/10.1002/esp.3778

VALENTIN, C.; POESEN, J.; LI, Y. Gully erosion: impacts, factors and control. **Catena**, v.63, n. 2-3, p. 132-153, 2005. https://doi.org/10.1016/j.catena.2005.06.001

VALERIANO, M. M. **Modelo digital de elevação com dados SRTM disponíveis para a América do Sul**. São José dos Campos: INPE, 2004, 72p.