EÖTVÖS LORÁND UNIVERSITY-
DEPARTMENT OF GEOPHYSICS AND SPACE SCIENCE

UNIVERSITY OF SÃO PAULO
SÃO CARLOS SCHOOL OF ENGINEERING
ENVIRONMENTAL ENGINEERING

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UNDERSTANDING AND MODELING SOIL EROSION

Budapest/HU
2014

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UNDERSTANDING AND MODELING SOIL EROSION

Graduation Work presented to
São Carlos School of Engineering,
University of São Paulo for
obtaining the title of Environmental
Engineering

Supervisor:
Andrea Raveloson

Budapest/HU
2014

Silva, Arthur Luis Fermiano da
S586u Understanding and Modeling Soil Erosion / Arthur Luis Fermiano da Silva; orientador Andrea Raveloson. São Carlos, 2014.

Monografia (Graduação em Engenharia Ambiental) -- Escola de Engenharia de São Carlos da Universidade de São Paulo, 2014.

1. 3D modeling. 2. soil erosion. 3. photogrammetry. 4. gully erosion. 5. monitoring. 6. Agisoft PhotoScan. 7. voçorocas. 8. Brazil. I. Título.

JUDGEMENT SHEET

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Date of presentation: 28/08/2014

Judging committee: Result:

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Coordinator of the Subject 1800091 – Graduation Work

"I sought my soul, but my soul I could not see. I sought my God, but my God eluded me. I sought my brother and I found all three."

Martin Luther King

ABSTRACT

Silva, A. L. F. **Understanding and Modeling Soil Erosion** / Arthur Luis Fermiano da Silva; Supervisor: Andrea Raveloson. São Carlos School of Engineering / University of São Paulo. Department of Geophysics / Eötvös Loránd University. Budapest, 2014.

In Brazil, climate disasters are usually related to a high population growth rate and a lack of required infrastructure especially in the big cities. The occurrence of urban gully erosion (so called voçorocas) intensifies these problems and leads to economic loss and social issues. The present study aims to understand the erosional processes in Brazil and to apply a technique to model and monitor soil erosion. The method we used was Photogrammetry, which is taking several pictures of an object from different directions and using software as Agisoft PhotoScan to create a 3D model of this object. A field survey was realized in the countryside of Hungary, where different devices were tested to capture the photos, showing that for quick models, a simple smartphone can be used, but for deeper studies and monitoring, more complex equipment are required, e.g. a real time GPS, professional cameras and a powerful hardware.

Keywords: 3D modeling, soil erosion, photogrammetry, gully erosion, monitoring, Agisoft PhotoScan, voçorocas, Brazil.

RESUMO

Silva, A. L. F. **Understanding and Modeling Soil Erosion** / Arthur Luis Fermiano da Silva; Orientadora: Andrea Raveloson. Escola de Engenharia de São Carlos / Universidade de São Paulo. Departamento de Geofísica / Universidade Eötvös Loránd. Budapest, 2014.

No Brasil, desastres climáticos geralmente estão relacionados com a alta taxa de crescimento populacional e a falta de infraestrutura necessária principalmente nas grandes cidades. A ocorrência de voçorocas em áreas urbanas intensifica esses problemas e leva a perdas econômicas e questões sociais. O presente estudo tem como objetivo entender os processos erosivos no Brasil e uma técnica para modelagem e monitoramento de erosão dos solos. O método utilizado foi a Fotogrametria, que se baseia em tirar várias fotos de um objeto de diferentes direções e utilizar programas como Agisoft PhotoScan para criar modelos em 3D do objeto estudado. Uma viagem de campo foi realizada no interior da Hungria, onde foram testados diferentes equipamentos para capturar as imagens, mostrando que para modelos rápidos, um simples smartphone pode ser utilizado, porém para um estudo e monitoramento mais profundo, equipamentos mais sofisticados se fazem necessários, como por exemplo GPS em tempo real, câmeras profissionais e computadores de alta performance.

Palavras-chave: modelagem 3D, erosão de solos, fotogrametria, voçoroca, monitoramento, Agisoft PhotoScan, Brasil.

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1. INTRODUCTION

Brazil is a South American country located in the tropical zone, which makes the climate very rainy during the whole year. It leads the country to have one of the richest biodiversity of the world, but also brings several problems related to soil erosion. The occurrence of urban gullies is nowadays one of the most important environmental issues of the country, that is related to economic and social problems.

The cities do not have the proper planning and required infrastructure for the observed high population growth rate, so thousands of people live in areas with high environmental risk. As a consequence, Rio de Janeiro State suffered in 2011 the biggest climate disaster of the story of the country.

These problems are intensified when in the presence of Brazilian voçorocas. This type of erosion has been studied and verified that they occur specially within the municipality, sometimes very close to occupied houses. It can lead to economic and life quality loss, if not to more serious problems as lives loss. This shows the importance of more studies on this field for a better understanding of the topic.

The erosional processes can be classified according to the shape and other features they develop through time. They can evolve from small rills to large gullies ruled by the increase of runoff and other controlling factors such as land use, soil depletion, intense rainfall, rugged topography, climatic influences and others.

Besides of studying causes of erosional processes, identifying and monitoring them are also great tasks of a high importance in the urban planning. A good method of monitoring gully erosion is Photogrammetry. Software as *Agisoft PhotoScan®* are able to generate 3D models of objects from several photos. By volume measurements, it can tell the soil loss and the effects of gulling downstream. When compared with older models, it can also show the direction of the gulling, which is important when talking about gulling toward houses and urban infrastructures.

A 10-days field survey was realized in the countryside of Hungary to better understand this technic. Different devices were tested to capture the photos, showing that for quick models, a simple smartphone can be used, but for deeper studies and monitoring, more complex equipment are required, e.g. a real time GPS, professional cameras and a powerful hardware.

2. EROSION

DEFINITION

The word *erosion,* with the etymology from the Latin *erodere* meaning “gnaw away” (‘*ex*’ – ‘away’ + ‘*rodere*’ – ‘gnaw’), represents the process or set of processes, which promotes the abrasion of the relief through the weathering, transport and deposition of the soil particles, rocks and fragments by the action of the wind, gravity force, water and ice. This natural process is responsible for the wear of the relief and formation of the plains along hundreds of years, but when accelerated by human forces, it induces an inequality between formation and transportation, triggering economic problems (CAMARGO, 2012).

MAIN TYPES OF EROSION

The erosional processes can occur anywhere in the world surface, and it is mainly caused by the action of wind, gravitational force or, most commonly, by water.

◊ **WIND EROSION**

The wind erosion, usually occurring in areas with low precipitation, is the result of the combination of three environmental conditions: i) the wind is strong enough to mobilize soil particles, ii) the characteristics of the soil make it susceptible to wind erosion (soil texture, organic matter and moisture content) and iii) the surface is mostly devoid of vegetation, stones or snow (BORRELLI et al., 2014). The dynamic transport of sediments by wind action is similar to the transport observed in rivers. Larger soil particles under turbulent action of wind move by saltation, while smaller particles are still in suspension in the air. Once in movement, the particles collide against the soil or rock abrasively, enhancing the erosion process (CAMARGO, 2012).

The wind erosion has always been occurred as a natural process modeling the relief and the landscape, but today, the geomorphic effects of wind are locally accelerated by anthropogenic pressures (e.g. leaving cultivated lands fallow for extended periods of time, overgrazing rangeland pastures and, to a lesser extent, over-harvesting vegetation (BORRELLI et al., 2014).

◊ **GRAVITATIONAL EROSION**

The gravitational erosion corresponds to the movement of larger amount of material from shallow formations and rocks under the gravity force action. This type of erosion is usually associated to the water saturation of the soil that decreases the particle cohesion becoming plastic or liquid (depending on the water content). Erosion by gravity is also known as mass movement processes. They can act very slowly or occur suddenly (CAMARGO, 2012).

Slow mass movement occurs as creeps or solifluction. Creep is the slow and continuous downhill movement of the shallow layers of the soil or decomposed rock above the deeper layers, and it can be observed by the direction of the trees (Figure 1). Solifluction is the flowage of water-saturated soil in areas typically underlain by frozen ground (CAMARGO, 2012).

Figure 1 - Creep erosion observed by the trees. Neszmély, Hungary. Photo: Arthur Fermiano (2014)

Sudden mass movement is of a special interest on the field of slope stability studies and may occur by land detachment or slide, when a portion of the soil detaches from the rest of the massif by i) superficial landslide or slope disruption, when the fast displacement of the landmass slides along the surface and passes by the foot of the slope, or ii) deep landslide, similar to the first but characterized by a sliding curve that passes far from the foot of the slope (CAMARGO, 2012).

◊ Water erosion

Water, in a liquid or solid state, is the main agent responsible for the initiation and triggering of the erosional process in the surface, subsurface and underground observed in the Earth (CAMARGO, 2012).

Water erosion is controlled by climatic characteristics, topography, soil properties, vegetation, and land management. Detachment of soil material is caused by raindrop impact and drag force of running water. Detached particles are transported by overland flow and concentrated flow and deposited when flow velocity decreases (VRIELING, 2006).

In tropical and sub-tropical zones, where high precipitation condition may be observed, the water erosion is the most important cause of the accelerated loss of properties on agricultural lands by reduction of fertility, desertification and increase of recent sedimentation in the water channels (OLIVEIRA; CASTRO, 2005). Although some authors question its impact on global food security, soil erosion creates strong environmental impacts and high economic costs by its effect on agricultural production, infrastructure and water quality (VRIELING, 2006).

In Brazil, many problems with water erosion have been experienced in the last years due to heavy rainy season associated to a not prepared population, without the necessary infrastructure and thousands of people living in area with high environmental risk. In 2011, Rio de Janeiro State suffered its worst environmental catastrophe, considered the biggest climatic disaster of the history of the country. More than 900 hundred people died and around 35 thousand people became homeless. 334 areas were identified as high risk to new landslides. The Figure 2 shows the city of Teresópolis, the most affected of the state.[1]

[1] This information was extracted from the newsletter Veja on 30 July 2014, available on the following link: <http://veja.abril.com.br/noticia/brasil/cidades-brasileiras-ainda-despreparadas-para-a-temporada-das-chuvas>

Figure 2 - Landslide in Teresópolis after heavy rain, Rio de Janeiro, Brazil. Photo: Antonio Lacerda (2011)

Besides the water erosion, temperate and glacial areas are also prone to suffer similar erosional processes mentioned as glacial erosion. The ice implement strong forces against the obstacles present in the terrain, fractioning them into smaller rocks, which help in the abrasion of the surface along their way, which in turn promote its corrosion. The most common features in glacial erosion are grooves and rills, tracked in the soil and rock surface. The cohesion among the soil particles and fragments of rocks are also influenced by the freezing and melting phenomenon of waters in temperate zones. This process increases the susceptibility of this material to be dragged and transported by wind, water, ice or gravity. The snow likewise triggers erosional processes, mainly during defrost periods, but also by snow sliding, which drags downwards the soil layer below the snow mass (CAMARGO, 2012).

Another erosional process of special interest from the economic and environmental point of view in countries with long extension of coastline (e.g. Brazil) is the coastal erosion, caused by the action of the sea waves when hitting the seashore.

EROSIONAL FEATURES

The erosional processes can be classified according to the shape, size, presence of water, ramification and other features they develop through time; they can evolve from small rills to large gullies and more complex systems depending on the increase of runoff.

◊ **SHEET EROSION**

The sheet (or laminar) erosion is the process arising from the diffuse rainfall runoff through the slopes in saturated soil, resulting in the progressive and uniform soil removal. It occurs usually when there is low or absent vegetation and/or obstacles. This erosional feature is not easy to be seen, but can be identified by the emerging of roots, marks in structures or decrease of agricultural productivity (CAMARGO, 2012). This process is mainly caused by runoff in deforested areas where the original cover has been replaced by crops and pasture without conservational practices.

◊ **LINEAR EROSION**

The classification of the linear erosion, especially among the Brazilian authors, is not precise, ranging in dimension, shape of the systems and presence or not of water in the valley.

◊ Rill

Rill erosion starts when runoff concentrates and small fractures in the soil surface appear. It leads to a fast increase in erosion rates as a result of the concentrated higher velocity flows (DESPRATS et al., 2011). This definition is usually the same for the Brazilian authors, although some of them give their own dimensional limits.

◊ Gully

When the erosional processes are not controlled by human actions, the rills usually increase in size and become gullies. The word *gully* has not a defined etymology but it is possibly a variant of the Middle English *golet* ("water channel"), which comes from the Latin word *gluttire*, which means "to gulp down, devour".

In the arid region of the Negev highlands of southern Israel, gully incision erodes alluvial sediments and loess deposited along the valleys. The agricultural fields and the main floral biomass are limited to narrow valleys. The gullies concentrate the runoff into narrow channels, preventing the floodwater from irrigating the whole width of the valley. The change in irrigation efficiency of the valley bottom is reflected in an 80% reduction in biomass and a significant loss in the agricultural potential of the region (VALENTIN; POESEN; LI, 2005).

Gully erosion is usually characterized by the result of the evolution of the rills when the erosional factors are not administered, but other terms and definitions are also commonly found:

- ravine: with translation to Portuguese (*ravina*), this term comes from the French *ravine* originating from the Latin *rapine*, act of robbery, plundering, referring to the result of the rush of water when digging the soil away from the original place. In Brazil, the ravines are usually defined as rills with a 50 cm minimum depth, but without reaching the groundwater surface, with a V shape and no ramification (CAMARGO, 2012). Differently, other authors define the depth between 10 and 50 cm due to the slope stability thresholds (FUREGATTI, 2012).
- ephemeral gully: this term was developed in the 1980s due to the need to distinguish rill erosion from the classical gully erosion (FUREGATTI, 2012).
- voçoroca: the Brazilian authors characterize the voçorocas (or boçorocas) as the largest erosional feature. The U-shaped valley is sometimes characterized by the presence of water, once the groundwater surface was reached. Furegatti (2012) states that "the voçorocas are valleys incised on the soil, sediments or slightly consolidated sedimentary rock, and it might have from decimeters until several meter depth, several tens of meters width and several hundred meters long". They can be presented in the rural areas, but are mostly located within the municipality.
- permanent (or classical) gully: it has the same characteristics as the voçorocas in Brazil. This term is usually used when studied together with ephemeral gully, as a way to differentiate them both.
- lavaka: this term is commonly used in Madagascar, where this specific form of gully erosion have been studied due to its peculiarities and abundance.

GULLY EROSION CONTROLLING FACTORS

Land use, soil depletion, intense rainfall and rugged topography are the most explicit controlling factors of erosional processes. However, less obvious factors have also significant importance, as climatic influences, groundwater flow, past land use and geology (IRELAND; SHARPE; EARGLE, 1939).

◊ **TOPOGRAPHY THRESHOLDS**

Steep slope is usually a threshold for initiating gully erosion due to high runoff, but given climatic conditions, lower slopes can be even worse, once a high volume of water for a longer and more continuous period might intensify erosional processes already started (VALENTIN; POESEN; LI, 2005). Poesen et al. (2003) established that thresholds lines can be represented by a power-type equation ($S = aA^b$) where a critical drainage area (A) is necessary to produce sufficient runoff which will initiate gully erosion in a given slope gradient (S), and also depending on environmental characteristics (constant a and exponent b).

Slopes with a convex profile are more susceptible to the emergence and development of voçorocas, especially those that shows a concave contour, concentrating the runoff in one channel. Concave slopes, either with a concave or convex contour, are less likely prone to the development of linear erosion processes (CAMARGO, 2012).

◊ **SOIL AND LITHOLOGICAL CONTROLS**

The type and magnitude of the erosional processes are deeply connected to the soil type and lithological parameters.

Sandy soil tends to be more susceptible to erosion, as shown in the Figures 3 and 4 (POESEN et al., 2003). On the other hand, soil crusting can delay the initiation of gullies due to their stronger shear strength as compared to non-crusted soils (VALENTIN; POESEN; LI, 2005).

Figure 3 - Ephemeral gully erosion in Vulci, central Italy. hard unweathered bedrock at a depth of ca. 90 cm (POESEN et al., 2003).

Figure 4 - Large (ca. 15–20 m deep and ca. 30–40 m wide) permanent gully which developed in unconsolidated Tertiary sandy sediments, Owerri, South Nigeria (April 1988) (POESEN et al., 2003).

Morais, Bacellar and Sobreira (2004) states in their studies that although the superficial processes related to runoff and land use are decisive, the sub-superficial processes, mineralogy and texture are also important on determining the emergence of ravines and voçorocas, specially related to piping which accelerates this type of erosion.

◊ **LAND USE CHANGE**

Badly planed human interference in catchments has also a significant contribution to the reduction of baseflow in many rivers (specially in Brazil) as proved by Costa and Bacellar (2007) who monitored and compared the hydrological conditions of a preserved and severely degraded catchment. The eroded catchment showed larger stormflow with higher but short-lived peak flows, higher total annual flow and different chemical parameters (indicating lower soil quality from the ecological point of view) compared to the preserved catchment. As a consequence, water quality and availability to downstream users decrease due to the sediment production and elevated nutrient loads in runoff caused by overexploitation of land resources in upper parts of catchment (VALENTIN; POESEN; LI, 2005).

Changes in drainage patterns associated with urbanization can also result gullying and gullies often take place where illegal settlements exist without urban infrastructure, such as sanitation and paved roads (GUERRA et al., 2004). Ide (2009) studied the consequences of land use in the acceleration of the erosional process. The study stated that the evolution of urban gullies in Bauru (São Paulo State) is enhanced by deforestation, soil sealing, illegal dumping of rainwater and wastewater and lack of drainage infrastructure.

In Europe, most gullies were formed during periods of extensive forest clearance and expansion of farmland associated with extreme rainfalls in the 14th century, between the end of the 16th century and the 1730s and during the Little Ice Age at the turn of the 18th and 19th centuries (VALENTIN; POESEN; LI, 2005).

◊ **CLIMATE**

Brazil and other countries situated in tropical and sub-tropical zones have intense rainy seasons with high and intense precipitation for long periods: The infiltration limit is quickly reached starting aggressive flood that in turn decrease the soil stability (CAMARGO, 2012). The same author explains that torrential rain or rainstorm associated with the velocity of the flood form the most aggressive way of water impact to the soil, increasing the erosion rate to the maximum and generating areas prone to the development and rapid evolution of ravines and voçorocas.

PREVENTION AND CONTROL

The most commonly used method to prevent and stop gully formation and growth is to enhance the vegetation cover, whose roots will improve the physical properties of the soil such as its structural stability and infiltrability. To be effective, the last intercepting vegetation layer must be near the soil surface. Intercepted drops by tall trees without undergrowth can be larger and can have higher kinetic energy than non-intercepted drops, favoring soil crusting, runoff generation and gully initiation (VALENTIN; POESEN; LI, 2005). The same authors explain that the success of tree plantings to mitigate gully erosion depends on the stage of gully development and particularly on whether or not mass movement erosion has begun.

As a method for controlling the growth of existing gullies, wood and trash (i.e. weeds removed from cropland) are frequently used by farmers to fill gully erosion and also as a way of disposing this reject (VALENTIN; POESEN; LI, 2005).

In soil erosion studies, an important task is to fingerprint the origin of the sediments in order to identify sources of potential pollution and to develop management strategies to combat soil erosion. The most common technique is to use natural and artificial tracers such as carbon, nitrogen or the radionuclide 137 Cs (VALENTIN; POESEN; LI, 2005).

To limit the risks of gulling by roads, they should be designed in a way that keeps runoff interception, concentration and deviation minimal. Techniques must be used to spread concentrated runoff in space and time and to increase its infiltration instead of directing it straight onto unprotected slopes (VALENTIN; POESEN; LI, 2005).

Unfortunately, most of these conservation strategies are rarely adopted, although their efficacy has been proved. It's not clear for the scientist and policy-makers why they are not accepted, but it seems that these strategies need to be associated with a rapid benefit in terms of land or labor productivity. It happens with the farmers as exampled by Valentin, Poesen and Li (2005) and also in a similar way in the cities in countries with growing population, where the necessity of more habitation is increasing and the land use has been more and more disputed.

3. BRAZIL AND ITS EROSIONAL ISSUES

Brazil is a South American country with almost 200 million inhabitants and the largest area in the Southern Hemisphere. Due to its tropical zone location, it has a very rainy climate, and summing up the above listed other controlling factors, it has significant problems related to soil erosion. The occurrence of urban gullies, the so-called voçorocas, is nowadays one of the most important environmental issue of the country, which is directly related to economic and social problems.

Guerra et al. (2004) studied and monitored voçorocas in São Luís city, which is the capital of Maranhão State with 867.690 inhabitants (IBGE 2000[2]). The area has a dry and a rainy season. The geology constitute of sandstone and the rocks have high porosity and are rather friable, with a high level of laterization. The organic matter content in most cases is low, and the combination of such characteristics make this soil susceptible to high erosion risk, especially where vegetation clearance occurs.

About the land use of São Luís city, Guerra et al. (2004) explains that the region's main vegetation cover was once tropical rainforest but it has been subjected to an intense deforestation process since urban growth started in the 19th century. Nowadays, the main vegetation type is secondary vegetation called Capoeira in Brazil. This type of vegetation cover does not have the same characteristics of the tropical forest, besides of taking several years to grow.

Guerra et al. (2004) identified 17 voçorocas, monitoring 7 of them. Even within a short period (eleven month) some of the studied voçorocas showed rapid retreat with more than one meter in some cases (Figure 5). The authors observed rill formations especially on the head of the voçorocas where the water is flowing towards the voçorocas enhancing erosional processes. Although the monitored period was short, they also observed that the gullying process was more intense where land use and management tend to disturb the environment, especially where the vegetation cover has been completed cut down (Figures 6 and 7).

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[2] IBGE – Brazilian Institute of Geography and Statistics, which promotes demography survey in the country every ten years at least. The survey from 2013 showed a population of 1.053.919 inhabitants, being the state with the highest population growth rate in the Northeast region of Brazil. Data accessed on 31 July 2014 and available on: <http://cidades.ibge.gov.br/xtras/perfil.php?lang=&codmun=211130&search=maranhao|sao-luis>

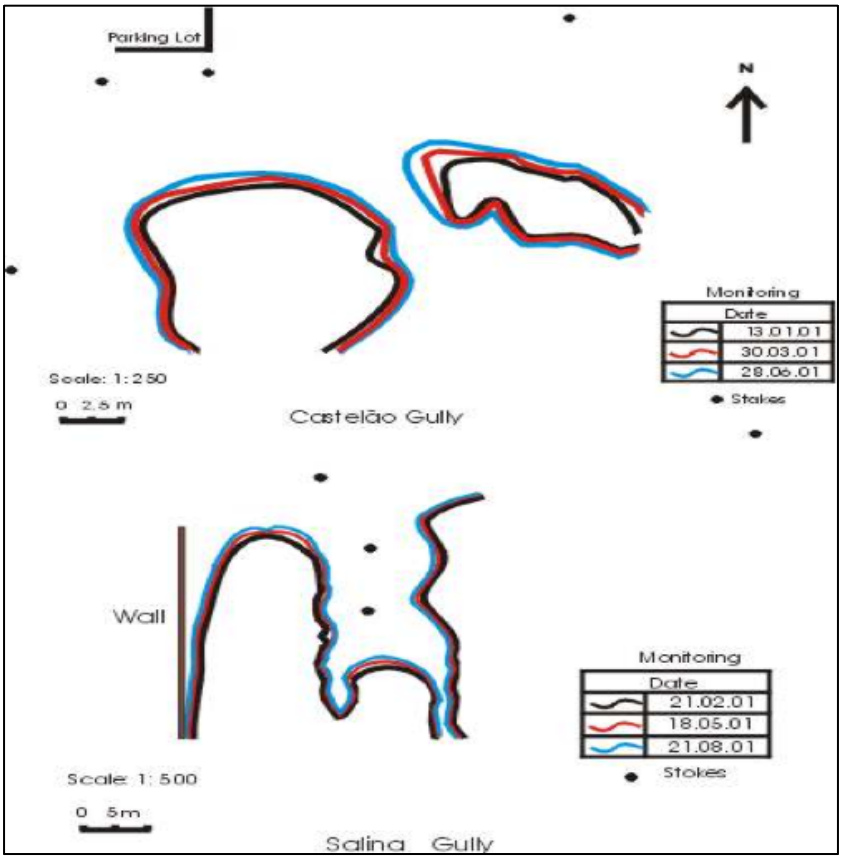

Figure 5 - Monitoring of voçorocas by stakes. São Luís city (Brazil) (GUERRA et al., 2004).


Figure 6 - Voçoroca under monitoring in urban areas. São Luís city (Brazil). The head has retreated 1,5 m towards the transmission energy tower in four months (GUERRA et al., 2004).

Figure 7 - Voçoroca under monitoring in urban areas. São Luís city (Brazil). The head is retreating towards the house, which is at a high risk of collapsing inside the hole (GUERRA et al., 2004).

Santana et al. (2007) studied the relationship between the erosional processes and some factors like pluvial dynamics, erodibility and land use. The studied area is the Araguaia River catchment located in the central-west region of Brazil (Figure 8). The aim was to identify areas where the combination of the erosivity of the rain, the erodibility of the soils and the different land use could help on the identification, characterization and interpretation of the risk areas.

Based on different sources, several thematic maps were developed, combined and studied, resulting in a good method of analyzing erosional processes, once it was possible to identify areas with higher risk of erosion with respect to the interaction between the precipitation, the soil, land use and linear erosive spots. The results showed that the areas with the highest risk of linear erosion are those with more intense land use change. Areas with more conserved natural vegetation showed less risk of erosion, even with higher erosivity and erodibility. The authors explained that this result reflects the importance of planning and applying projects on soil use and management.

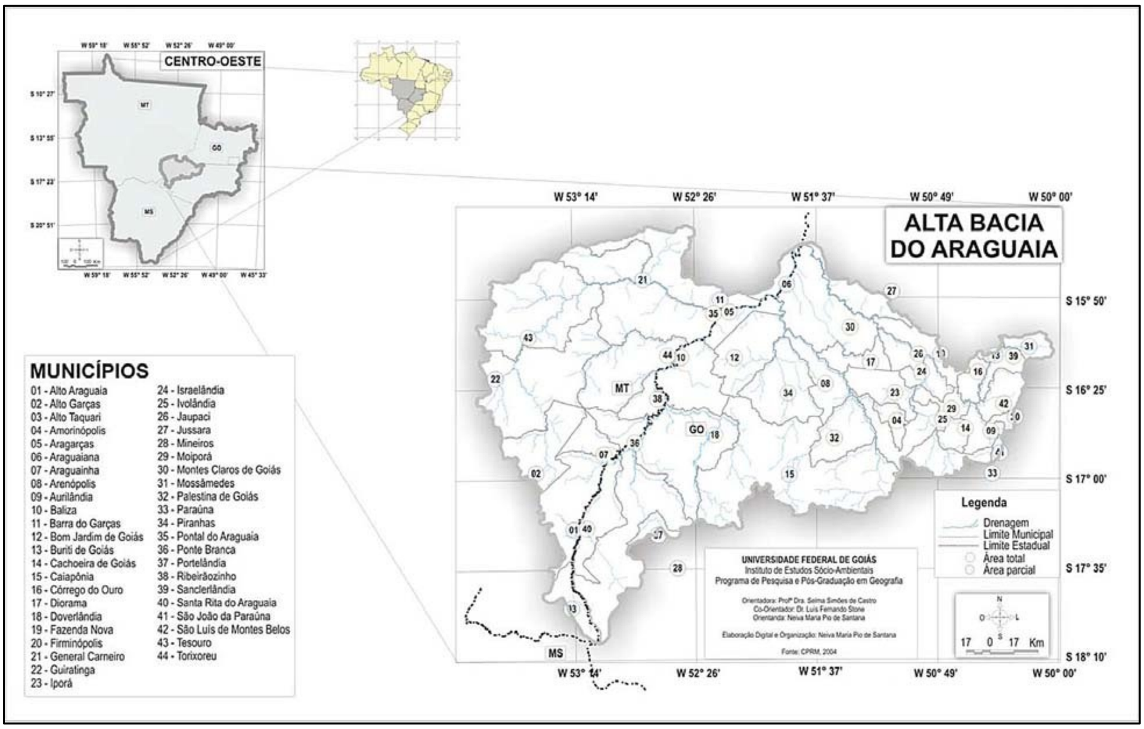

Figure 8 - Studied area of factors that leads to erosional processes. Central-west of Brazil (SANTANA et al., 2007).

As already mentioned, voçorocas in Brazil usually occur in urban areas and often just a few meters from inhabited houses. The reason for that is the accelerated process of urbanization, which usually results in a rapid land parceling. The municipality usually does not have a master plan of the city, and together with the fact that the management and control are ineffective, it is common to see districts being raised in illegal or risk areas.

A city that has suffered this problem is São Carlos (São Paulo State, Figure 9), with 236.457 inhabitants (IBGE 2013[3]), known as the Capital of Technology. It is one of the most important city of the state due to the presence of two prestigious universities (USP and UFSCar) and many national and multinational industries (e.g. Volkswagen, TAM, Electrolux, Tecumseh, Latina and Faber-Castell). Due to its importance and geographic position, the city became an aim for a lot of

[3] IBGE – Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística). Survey realized in 2013. Accessed on 5 August 2014 and available on the following link: <http://cidades.ibge.gov.br/xtras/perfil.php?codmun=354890&search=sao-paulo>

Brazilian students and professionals (it is the South American city with the highest rate of PhD graduated per inhabitant[4]).

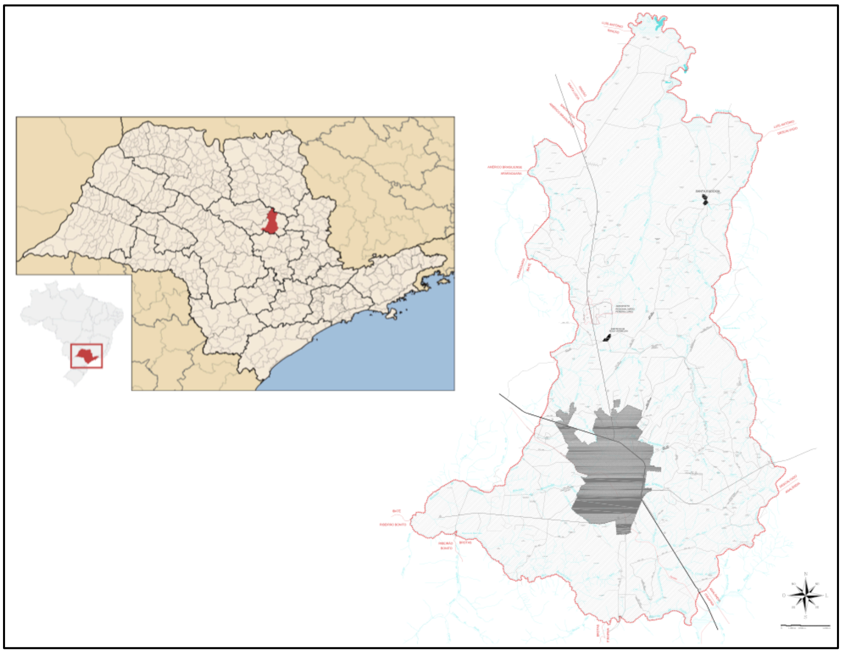

Figure 9 - Geographic position of São Carlos City and urban perimeter (in gray). Adapted from Master Plan of the city and <http://i228.photobucket.com/albums/ee68/Lucas_1989/800px-SaoPaulo_Municip_SaoCarlos-1.png>

On the other hand, the city had several problems related to the fast demographic growth. Many new housing complexes were established specially during the 70s, most of them without the proper planning. These settlements, with especial attention to Cidade Aracy, Antenor Garcia and Presidente Collor, were developed in sensible areas from an environmental point of view. In the Master Plan of the city[5], this area is now part of the Recovery and Controlled Occupation Zone, as it can be seen in the Figure 10.

Pedro and Lorandi (2004), on the attempt to aware the municipality about the erosional issue and its consequences on the economy and quality of life of the population, developed a map with the Natural Potential of Erosion (abbreviated to PNE – Potencial Natural de Erosão). The model followed the international equation

[4] This information was extracted from the newsletter G1 on 5 August 2014, available on the following link:<http://g1.globo.com/sp/sao-carlos-regiao/noticia/2012/04/sao-carlos-primeira-numero-de-doutores-por-habitante-na-america-latina.html>

[5] The Master Plan of São Carlos was established on 25 November 2005 in the Municipal Law Nr 13.691, and it's available on: <http://www.saocarlos.sp.gov.br/index.php/utilidade-publica/plano-diretor.html>

USLE (Universal Soil Loss Equation), which gives a numerical value in ton/ha/year depending on topographic factors, erosivity, erodibility and land use.

Figure 11 clearly shows the effect of the irregular occupation on the erosional processes by the high values of PNE (above 700 ton/ha/year), with a voçoroca arrising in this place (Figure 12). Pedro and Lorandi (2004) also identified other voçorocas and smaller erosional processes within the urban perimeter of the city, which were in accordance with the PNE map.

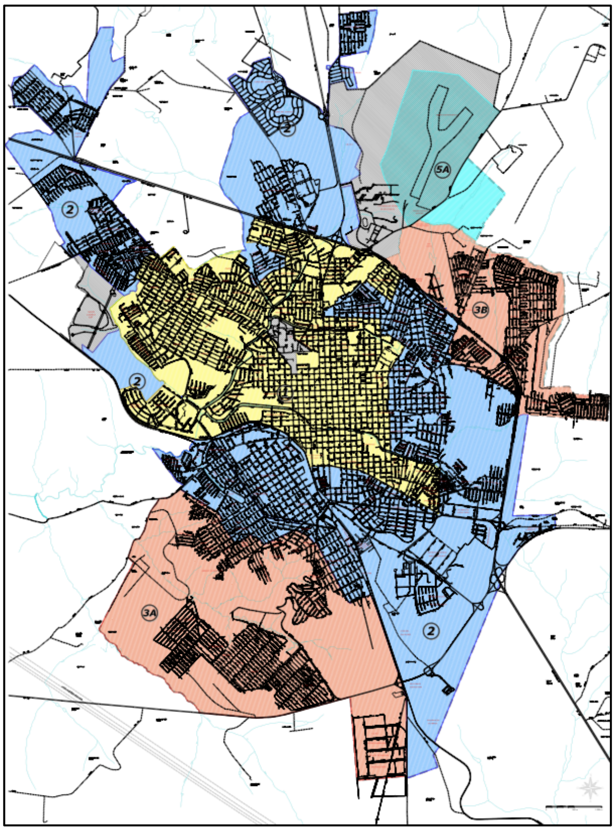

Figure 10 - Recovery and Controlled Occupation Zone shown in orange (3A and 3B). Extracted from the Master Plan of São Carlos City (Brazil). For more detailed map, see Attachment 1

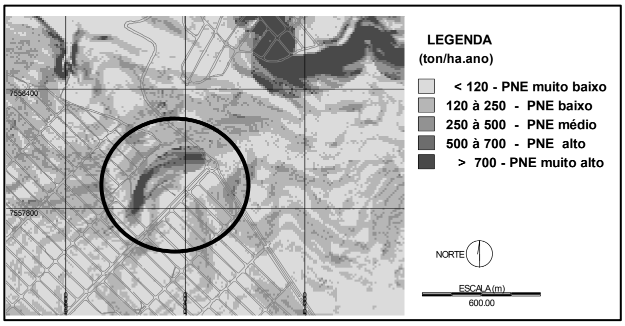

Figure 11 - High values of PNE in the Cidade Aracy distric. São Carlos City (Brazil) (PEDRO; LORANDI, 2004).

Figure 12 - Voçoroca besides occupied houses. São Carlos City (Brazil) (PEDRO; LORANDI, 2004)

Another important environmental problem related to the voçorocas is their filling with trash. Despite of the size of the country, it is very common to have voçorocas being filled with urban trash with the explanation (or excuse) that there is no better place to install landfills, even without a proper environmental assessment of the impact of these landfills. This material is usually coming from civil construction, without any treatment before disposal.

In Jaú (São Paulo State), a voçoroca located close to a residential district has been developed quickly since 2010 and the municipality has been thrown rubbish (including tree trunks, sofas and other furniture) since then, with no improvement observed. Approximately 18000 m^3 of material was disposed between 2011 and 2012 on the attempt to hold the landslides. A geographer who lives on that area said that the municipality never took any action to mitigate the problem.[6]

In Brasília de Minas (Minas Gerais State), the municipality has not taken any action to control a 17 m deep and 80 m width voçoroca (Figure 13), which is developing toward dwellings. People from the community tried to plant trees and improve the local vegetation without any success. In this case, the local secretary of services informed that this voçoroca is known, as well as many other gullies in the region, but since they do not have structure to control all of them, nothing is done.[7]

[6] This information was extracted from the newsletter Comércio de Jahu on 29 July 2014, available on the following link: <http://www.comerciodojahu.com.br/noticia/1307067/Prefeitura+envia+projeto+de+recupera%C3%A7%C3%A3o+a+minist%C3%A9rio>

[7] This information was extracted from the newsletter G1 – Grande Minas (VC no G1 channel) on 29 July 2014, available on the following link: <http://g1.globo.com/mg/grande-minas/vc-no-g1-intertvmg/noticia/2014/07/vocoroca-ameaca-engolir-casas-em-brasilia-de-minas-regiao-norte-de-mg.html>

Figure 13 - Voçoroca developing towards houses, Brasília de Minas (Brazil). Photo: Maicon Rodrigues (2014)

4. PHOTOGRAMMETRY

DESCRIPTION

From the Greek words ('*photo*' – 'light' + '*graphein*' – 'draw' + '*metry*' – 'process of measuring'), photogrammetry is a method for creating 3D model of any static object of different sizes with different accuracy depending on the quality of the collected data. It was defined by the Manual of Photogrammetry (cited by BURNS (1993)) as "the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of electromagnetic radiant energy and other phenomena." Schenk (2005) uses an important definition, saying that it is a method of obtaining information of a surface or object without physical contact with the object, which is an important advantage when dealing with unreachable spots and detailed information are needed.

The process consists in taking several digital photos from the object to be modeled and processing these images through a photogrammetric software, which works on the principle of feature recognition and triangulation. Behrouzi and Li (2012) explains that these programs first recognize the special features in the provided images, then correlate these features in other photographs to create relationships between corresponding features in different images, and finally solve spatial locations of each feature to obtain the geometry of the object.

AGISOFT PHOTOSCAN

Agisoft PhotoScan® is a photogrammetric software developed by *Agisoft*® which allows 3D model generation with an intuitive and user friendly interface for those who are not familiar with the method, but also with important and more complex features for expert users. Although it is a paid software ($179 for the Standard edition and $3499 for the Professional edition), it might be a good option due to its facilities. It can work with up to tens of thousands of photos resulting in an accurate model, but for that, a powerful hardware is required.

With the Standard edition it is possible to reconstruct, model and digitize the chosen objects or scenes, with the following main features:[8]

- Automatic camera calibration
- Automatic tie-point search
- Aerial triangulation and block adjustment
- 3D model generation and export in Triangulated Irregular Network (TIN) formats
- Texture mapping.

In the Professional edition, some important features are included:

- Georeferencing
- Digital Elevation Model (DEM) export
- Orthophoto generation
- Volume and area measurements
- Python scripting, a widely used high-level programming language.

For generating a 3D model with *Agisoft PhotoScan Professional*, the following steps should be taken:

I. Open the software;
II. Add photos (or folder with photos);
III. Align photos: at this stage the software finds the camera position and orientation for each photo and builds a sparse point cloud model. The accuracy (low, medium or high) and pair selection method (using or not geographic coordinates from the photos, when available) should be set. The number of points in the cloud can also be limited. This step might take from a few minutes to several hours to be ready, depending on the number of loaded photos, selected settings and hardware performance;
IV. Build dense cloud (optional): the program might also calculate depth information for each camera and generate a dense cloud for more detailed model. This step might also take a long time;
V. Build mesh: a triangulated mesh is generated in a few seconds;

[8] This information was extracted from the website of the developer on 1 August 2014, available on the following link: <http://www.agisoft.ru>

VI. Build model texture: based on the photos and the selected settings, a texture for the model can be created. Selecting a proper texture mapping mode helps to obtain optimal texture surface and, consequently, better visual quality of the final model.

From this point, some small adjustments might be needed to improve the model (e.g. deleting unwanted areas or close holes). Other important features are also available:

- Different view mode (shaded, solid, wireframe or textured);
- Measure area and volume (this is especially important when modeling gully head retreat);
- Detect markers for further analysis;
- Import or export mash, texture, cameras, markers, masks.

USING PHOTOS FROM DIFFERENT SOURCES

Authors usually recommend using digital cameras with high resolution, but sometimes the researchers are not equipped with these sophisticated cameras during a field survey, but want to have a basic model of an object or scenario either for further analysis or to remember what they have seen.

Based on these principles, and also for a better understanding of the method for further studies of soil erosion, a one week long field survey was realized for a photogrammetry application using different equipment.

The studied area was Süttő village (Komárom-Esztergom county, in Hungary – Figure 14) and surroundings, about 70 km away from Budapest, the capital of the country.

Figure 14 - Studied area. Süttő village (Komárom-Esztergom county, Hungary)

During the survey, different objects were photographed with four equipment, from an iPhone to more sophisticated cameras:

Table 1 - Equipment used during the field survey and their specifications

Device	Resolution	Focal length
iPhone 5	8 megapixels	33 mm equivalent
Compact digital camera Sony model DSC-WX50	16.2 megapixels	35 mm equivalent
Semi professional camera Canon model EOS 600D	18 megapixels	40 mm
Semi professional camera FUJIFILM model FinePix HS10 (bridge)	10.3 megapixels	35 mm equivalent

Three areas were studied in the survey: a loess wall, a pannonian sandstone layer and a sandstone outcrop. During each modeling in *Agisoft PhotoScan*, the same settings were used in order to follow a standard for further comparison:

- Accuracy: medium, which could generate a reasonably good model in an acceptable time;
- Pair selection: disabled, which means that the geographic coordinates were not taken into account;
- A dense cloud was not built, once some models were tested and a significant improvement was not verified;
- Orthophoto mapping mode for the texture, once it creates a more precise result in this sort of analysis.

5. RESULTS

All the models, in a digital format, are in the APPENDIX – CD-ROM, as well as the photos used for modeling.

Loess Wall, Kőpite Hill

One of the studied objects was in Kőpite Hill, a loess wall formed either by erosional processes or by human interference (mining for using sand in the civil construction nearby). The area is visually suffering erosional process (exposed soil), but due to the presence of dense vegetation around to hold the material, it is on its way to stabilize, as it can be seen in the Figure 15.

Figure 15 - Studied object: loess wall. Photo: Andrea Raveloson (2014)

The exposed wall has approximately 6 m width and 3 m height. The lower part is made of whitish loess, and the upper part is hold by the vegetation with plant roots emerging from the darker soil. The higher parcel of organic matter can explain the color of the upper part. For this area we chose to use two devices: the iPhone 5 and the semi professional camera FUJIFILM.

Figure 16 shows the model made with the use of an iPhone. It can be seen that despite of having missing data (white spot) and distorted regions on the edges, the model has significant accuracy and quality, being verified by the presence of a reasonably good texture and shape. Blurred areas were identified in the model (more easily seen in the *Agisoft PhotoScan*), caused by the quality of the images and the effects of the shadows. We could also notice lower accuracy in areas where it was hard to photograph.

The model using photos from the FUJIFILM camera is shown in Figure 17. The result was slightly better than the previous one, once it showed a neat texture in conformity with the shape of the wall. However, missing data were also identified by the presence of a significant white area eastern in image.

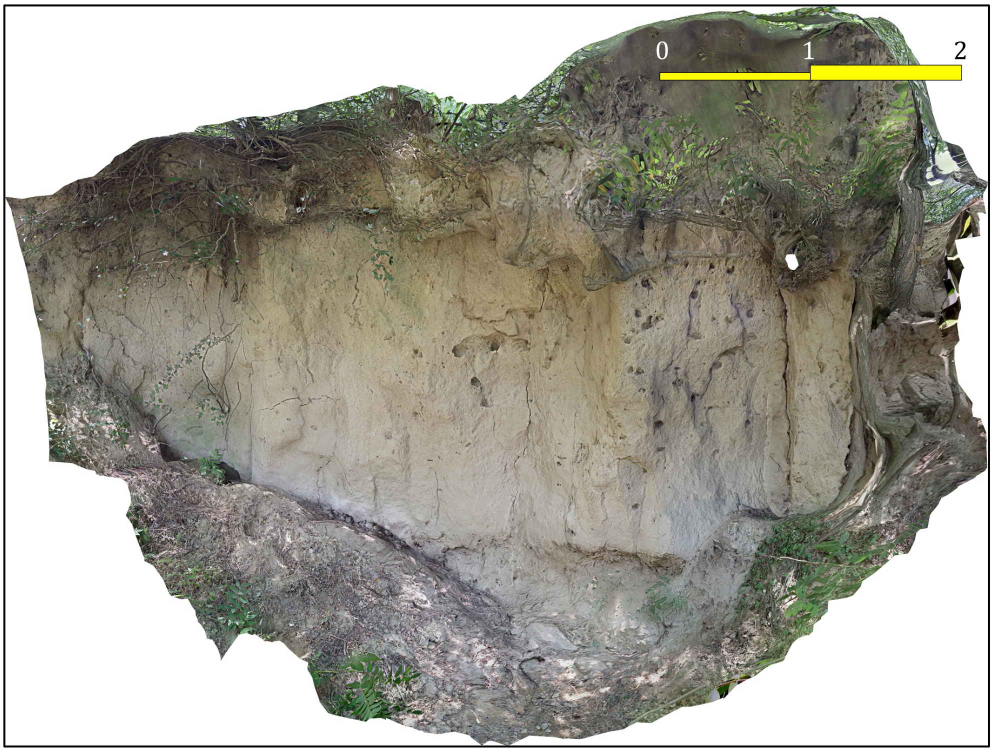

Figure 16 - 3D model from loess wall. Device used: iPhone.

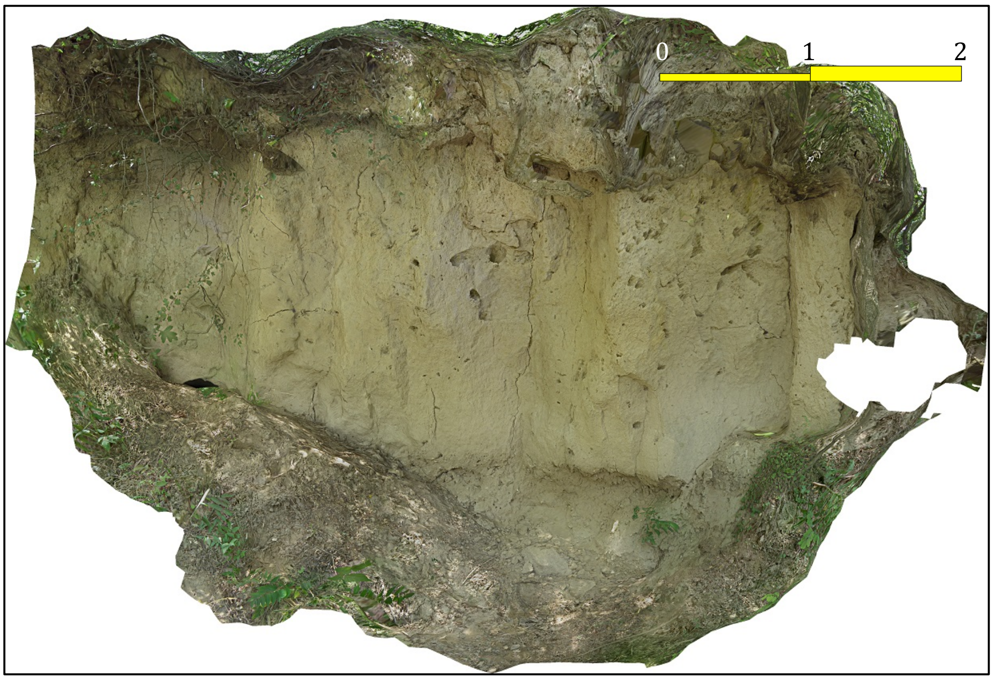

Figure 17 - 3D model from loess wall. Device used: semi professional camera FUJIFILM.

Due to the presence of missing data on both models, we decided to generate a third model combining the photos from both devices. The model (Figure 18) has a significant quality, although some blurred areas are also presented. An interesting about combining the photos from both devices was that though in some part of the model the quality increased greatly some part became worse. In order to avoid this kind of problem pictures should be sorted in the future (so that blurred, dark pictures will not be taken in account by the model).

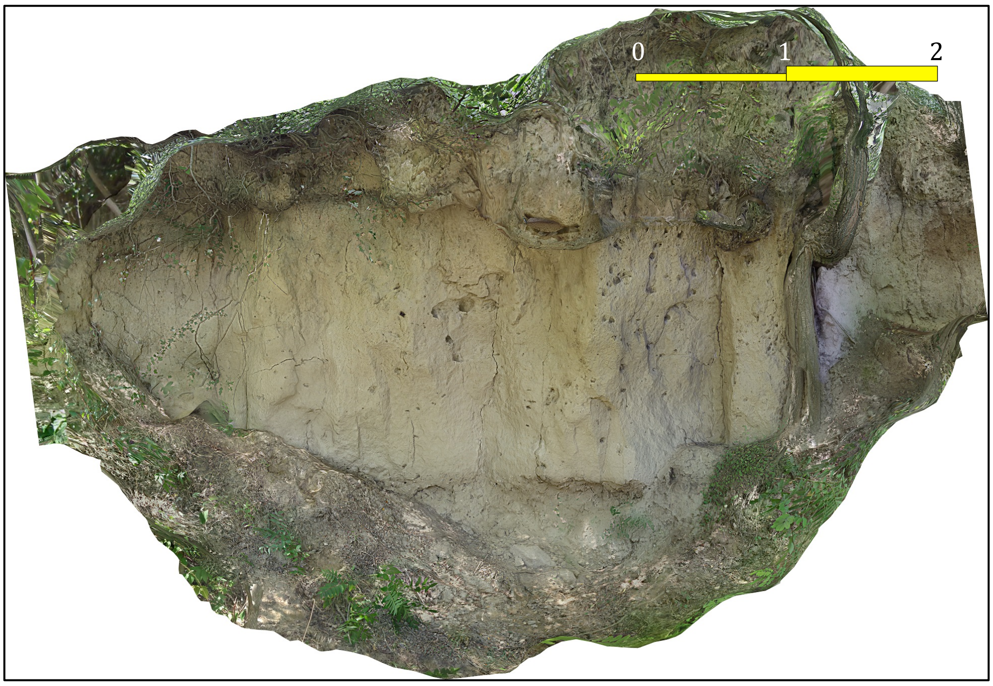

Figure 18 - 3D model from loess wall using photos from two devices: semi professional camera FUJIFILM and iPhone.

Cretaceous Conglomerate, Ivánhalála valley

Another studied object was in Ivánhalála valley, a conglomerate with sandstone immersed in a sandy material, which enhances the susceptibility to erosion. The basement of this conglomerate is a Cretaceous sandstone layer in the lower part of the outcrop (Figure 19).

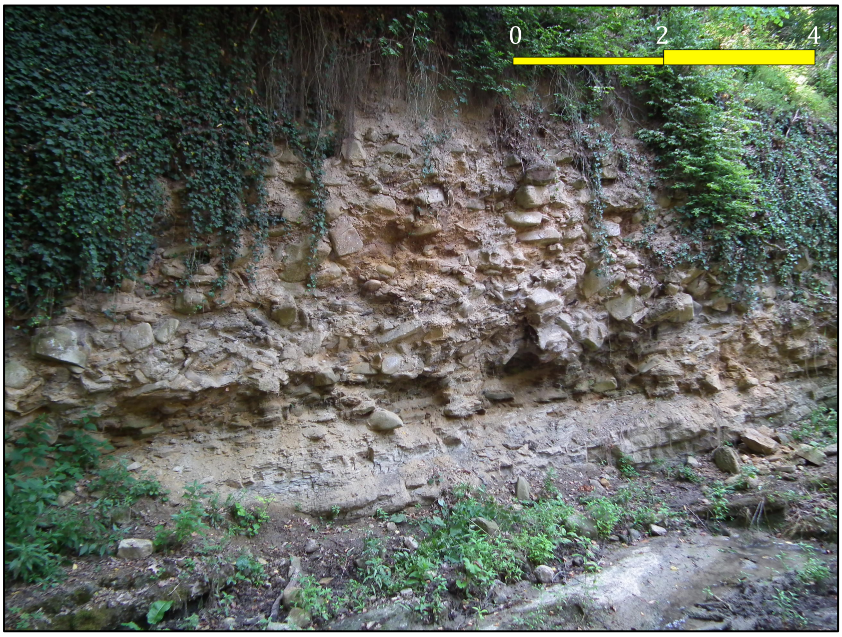

Figure 19 - Studied object: Cretaceous Conglomerate. Photo: Andrea Raveloson (2014)

The exposed area has approximately 8 m width and 4 m height. It is part of a large vegetated and apparently stable wall that follows a stream curse. We used three devices to capture the photos: the iPhone 5 and the two semi professional camera (FUJIFILM and CANON).

The Figures 20, 21 and 22 show the models done with the use of the iPhone, the FUJIFILM camera and the CANON camera, respectively. The three models resulted in reasonably good models with low mean error generated during the photo alignment. The model where the FUJIFILM camera was used showed more details and a slightly better performance on the shape in accordance with the texture, despite of resulting a maximum error of 1.176 pixel (the highest among the three models). The model which resulted in the lowest maximum error (0.916 pixel) was the one that the CANON camera was used.

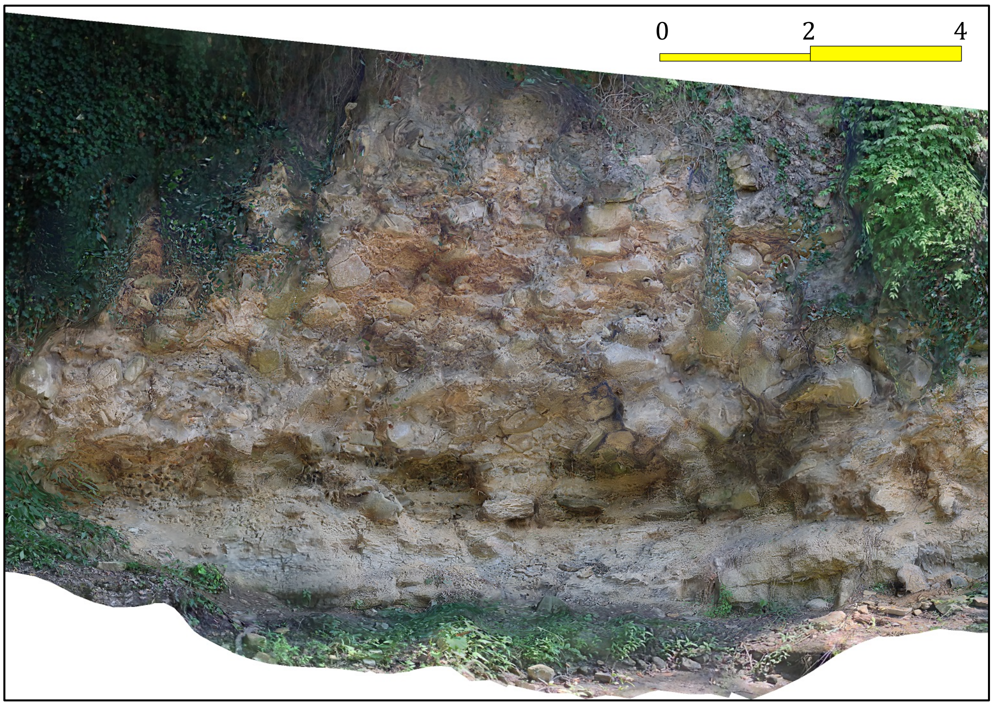

Figure 20 - 3D model from conglomerate. Device used: iPhone.

Figure 21 - 3D model from conglomerate. Device used: FUJIFILM.

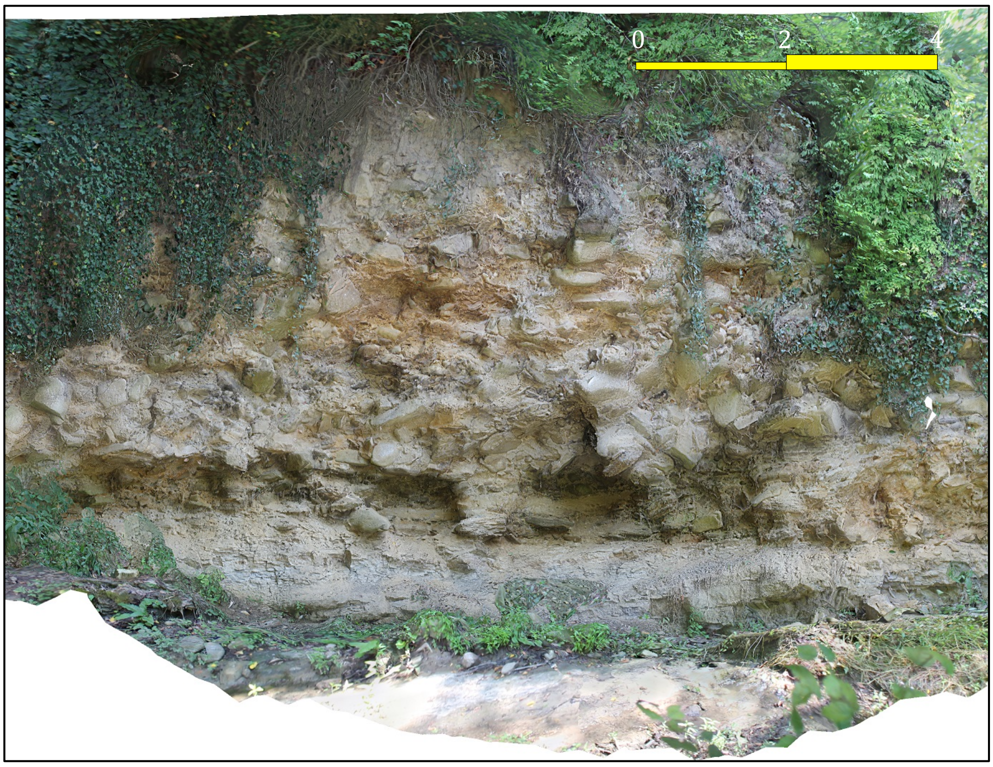

Figure 22 - 3D model from conglomerate. Device used: CANON.

Sandstone Outcrop, Roman mine

The third studied area was a sandstone outcrop with limestone layer, as can be seen in the Figure 23. The area is part of an old Roman mine, and the exposed part has approximately 15 m width and 10 m height in a very steep wall. Even being an ancient mine, the area still shows ongoing erosional processes, once most of its soil is exposed and the scarse vegetation cover is not dense enough to hold the material from erosion.

Figure 23 - Studied object: sandstone outcrop. Photo: Arthur Fermiano (2014)

For this object, two devices were used to capture the photos: the iPhone and the compact camera SONY. Due to technical problems, none of the semi professional cameras were available to be used.

Figure 24 shows that the model using the iPhone did not result well, but at least the limestone layer and other features of the relief can be seen. On the other hand, the model using the camera SONY did not work at all (Figure 25), showing irregularities in the 3D model with unrecognized surfaces and a cluttered texture.

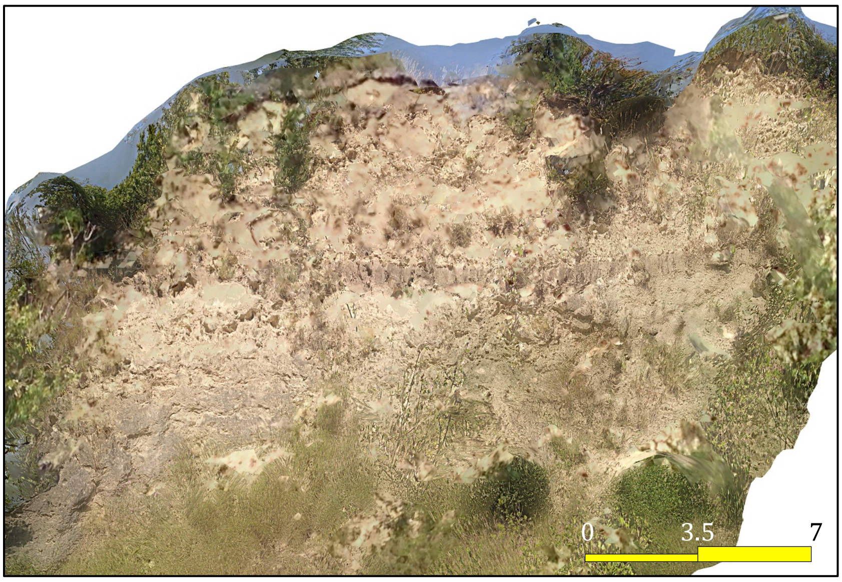

Figure 24 - 3D model of sandstone outcrop. Device used: iPhone.

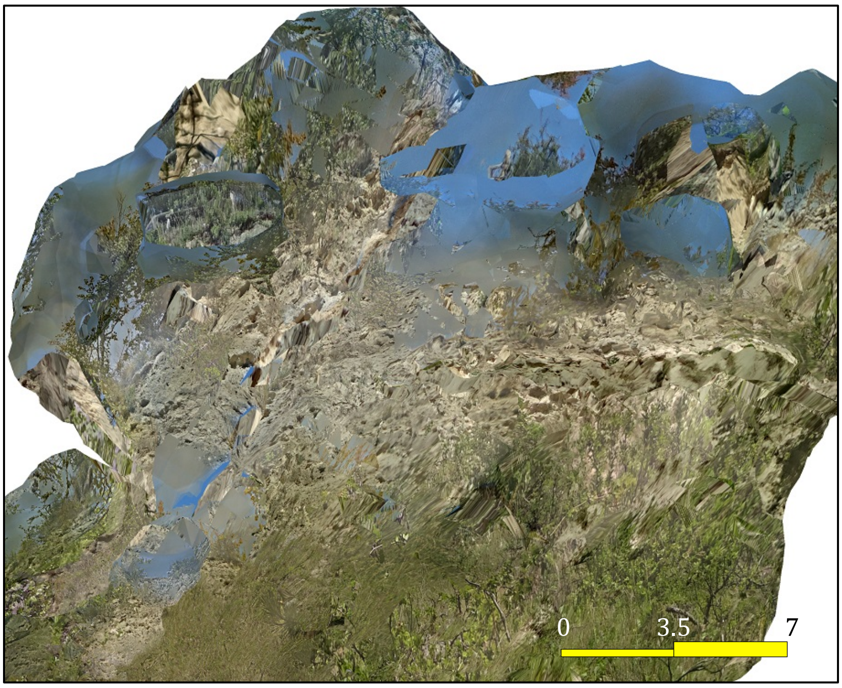

Figure 25 - 3D model from sandstone outcrop. Device used: SONY.

6. USABILITY TO SOIL EROSION CONTROL

It is easily noticeable that photogrammetry can be an efficient tool for recording geological features and allows a better understanding of the objects when the researchers are back from surveys. Nevertheless, it can be also a crucial method to understand and monitor the development of gulling processes.

One of the worst characteristics of gully erosion is its unpredictability. It is very hard to say how much it will erode, and even more difficult, in which direction. In Brazil it is a very important issue, once most of the voçorocas occur in urban areas and it might affect the stability of villages.

This methodology can answer all this questions, if done properly and continuously, once it can tell the exact amount of soil that was lost (by volume measurements) and, when compared with older models, it can show the direction of the gulling.

From the eroded volume, the consequences of gullying downstream, and how these sediments will affect the quality of the environment in the whole catchment can also be better understood.

The erosion rate is another factor that can easily be extracted using this methodology, which is clearly an important factor for any monitoring process especially in Madagascar, where the lavakas are known for their rapid growth during the first years.

7. CONCLUSION

Nowadays the enhancement of soil erosion processes by human actions is one of the most important environmental problems due to its strong connection with economic loss and decrease of life quality. In Brazil, this problem is even worse and may cause loss of lives, once the gulling processes (so called voçorocas) occur within the municipality, very close to villages and inhabited houses.

The photogrammetry turned to be an efficient method to identify and monitor qualitatively and quantitatively erosional processes. Simple devices as smartphones can be used to capture the photos for modeling. An iPhone 5 was used and proved to result in good models with reasonably good accuracy for quick analysis. However, for a more accurate model, in a deeper level of studies and monitoring, more precise (and consequently more expensive) equipment should be used, e.g. real time GPS (for location and headwall retreat studies), high resolution cameras and a powerful hardware for modeling in a plausible time.

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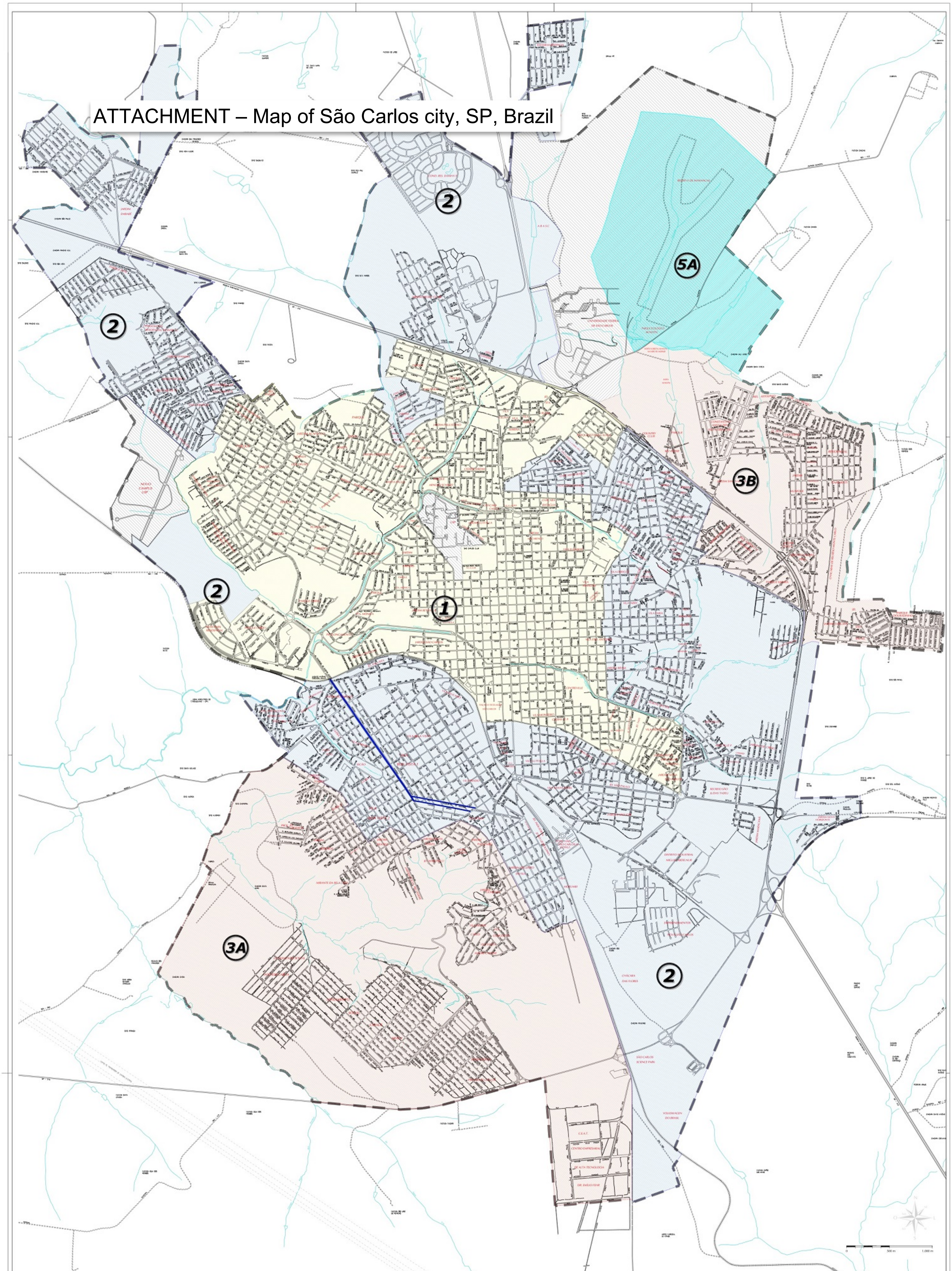
ATTACHMENT – Map of São Carlos city, SP, Brazil



Fontes:
- SMHDU - Secretaria Municipal de Habitação e Desenvolvimento Urbano
- SMOTSP - Secretaria Municipal de Obras, Transportes e Serviços Públicos
- Base Cartográfica Digital Urbana obtida a partir de levantamento aerofotogramétrico realizado em 1998 e fornecida pelo SAAE, com atualizações a partir das cartas do IGC
- IGC - Instituto Geográfico e Cartográfico do Estado de São Paulo

Projeção Universal Transversa de Mercator (Datum horizontal: Sad 69)

Zona 1 - Ocupação Induzida

COEFICIENTES

CA	CO	CP
CAB = 2 CAM = 3,5 CA = 1,4 (uso exclusivamente residencial unifamiliar)	70%	15%

INSTRUMENTOS
- Áreas Especiais de Interesse Histórico, Ambiental e Social
- Operação Urbana Consorciada
- Transferência do Direito de Construir
- Direito de Preempção
- Outorga Onerosa do Direito de Construir
- Uso, Edificação e Parcelamento Compulsórios

CA - Coeficiente de Aproveitamento
CAB - Coeficiente de Aproveitamento Básico
CAM - Coeficiente de Aproveitamento Máximo
CO - Coeficiente de Ocupação
CP - Coeficiente de Permeabilidade
CCV - Coeficiente de Cobertura Vegetal

Zona 2 - Ocupação Condicionada

COEFICIENTES

CA	CO	CP
CAB = 1,4 CAM = 3 (nos eixos definidos nesta lei) CA = 1,4 (uso exclusivamente residencial unifamiliar)	70%	15%

INSTRUMENTOS
- Áreas de Especiais Interesses Histórico, Ambiental, Social e Industrial
- Operação Urbana Consorciada
- Transferência do Direito de Construir
- Direito de Preempção
- Outorga Onerosa do Direito de Construir (eixos específicos): Av. Dr. Tancredo de Almeida Neves, Av. Henrique Gregori, Av. Grécia e Av. Theodureto de Camargo

Zona 3 - Recuperação e Ocupação Controlada

3A COEFICIENTES

CA	CO	CP
CA = 1,4 (Empreendimentos Habitacionais de Interesse Social) CA = 1 (Demais Parcelamentos)	70%	15%

INSTRUMENTOS
- Áreas de Especiais Interesses Ambiental e Social
- Direito de Preempção
- Regularização de Loteamentos Existentes

Bairros Isolados da Zona 3A:
Loteamento Social Cidade Aracy, Jardim Social Presidente Collor, Jardim Social Antenor Garcia

Bairros próximos das Encostas na Zona 3A:
Jardim Medeiros, Prolongamento do Jardim Medeiros, Jardim Beatriz, Mirante da Bela Vista, Jardim Social Belvedere, Jardim Martinelli, Jardim das Rosas, Jardim Santa Tereza, Jardim Pacaembu, Jardim Gonzaga, Vila Monte Carlo, Vila Santa Madre Cabrini, Vila Conceição

3B COEFICIENTES

CA	CO e CP			CCV
	Área:	CO	CP	
CA = 1,4 (Empreendimentos Habitacionais de Interesse Social) CA = 1 (Demais Parcelamentos)	125,00 m²	70%	15%	10%
	125,01 a 300,00 m²	70% a 50%	15% a 30%	
	maior que 300,00 m²	50%	30%	

INSTRUMENTOS
- Áreas Especiais de Interesse Ambiental e Social
- Transferência do Direito de Construir
- Lei Específica das Áreas de Proteção e Recuperação dos Mananciais do Município de São Carlos

Bairros localizados na Zona 3B, bacia de captação do Córrego do Monjolinho:
Parque Residencial Maria Stella Fagá, Parque Douradinho, Jardim São Rafael, Jardim Tangará, Jardim Tangará - prolongamento, Jardim Veneza, Jardim Munique, Residencial Itamarati, Residencial Astolpho Luiz do Prado, Jardim dos Coqueiros, Residencial Américo Alves Margarido, Jardim Santa Maria II, Parque Belvedere, Parque Primavera, Parque Sabará, Chácaras de Recreio Mont Carlo, Santa Maria I (ocupação espontânea)

Legenda
- Zona 1 - Ocupação Induzida
- Zona 2 - Ocupação Condicionada
- Eixos da Zona 2 aptos a receber potencial construtivo por meio de Transferência do Direito de Construir e Outorga Onerosa do Direito de Construir
- Zona 3 - Recuperação e Ocupação Controlada
- Zona 5 - Proteção e Ocupação Restrita (área interna ao perímetro urbano)
- *Campi* Universitários
- Rodovia
- Perímetro Urbano
- Ferrovia
- Córrego

ANEXO 02

Prefeitura Municipal de São Carlos

PLANO DIRETOR DO MUNICÍPIO DE SÃO CARLOS

Zoneamento da Macrozona Urbana e Perímetro Urbano

Escala: 1:12.500 Cada centímetro equivale a 125 metros

Base Cartográfica: ver fontes **Elaboração:** SMHDU **Data:** Outubro de 2005

APPENDIX – Content of CD-ROM

The CD-ROM contains:

- Folder “Loess Wall – Kőpite Hill”: with all the photos and the digital models in the format “.psz”.
- Folder “Cretaceous Conglomerate – Ivánhalála valley”: with all the photos and the digital models in the format “.psz”.
- Folder “Sandstone Outcrop – Roman mine”: with all the photos and the digital models in the format “.psz”.
- ATTACHMENT – Map of São Carlos city, in the format “.pdf”.
- Digital format of the present work, named as “TG – Soil Erosion.pdf”.