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VISUAL INTERPRETATION OF SATELLITE AND AERIAL IMAGES TO IDENTIFY AND STUDY THE EVOLUTION OF INADEQUATE URBAN WASTE DISPOSAL SITES

Camila Camolesi Guimarães [1,*], Alexandre Muselli Barbosa[1,2] and Otávio Coaracy Brasil Gandolfo [1]

[1] *Institute for Technological Research, Av. Prof. Almeida Prado, 532, 05508901, São Paulo, Brazil*
[2] *Departament of Chemical Engineering, University of São Paulo, Av. Prof. Luciano Gualberto, 380, 05508010, São Paulo, Brazil*

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ABSTRACT

One of the main problems Brazil faces in solid waste management is the existence of dumpsites that must be closed. For the shutdown process, an environmental assessment should be performed, which requires knowledge of the history of these sites. This study is often hampered by the lack of past records on the waste disposal activities in these places, especially when they are very old. In this context, the analysis of multitemporal remote sensing images and aerial photographs is an interesting tool for the identification and study of the development of inadequate waste disposal sites. In the present study, these techniques were used to assess former dumps in four municipalities in the state of São Paulo, Brazil. The analysis comprised satellite images and aerial photographs between 1960 and 2010. They enabled the obtainment of information on the progress of activities in the dumps and their surroundings, on how the waste disposal occurred, and on the end of operations and the revegetation process. With geographic information system (GIS) support, information from different data sources was crossed with previous databases, thus allowing the obtainment of greater data structure for a better interpretation of the available information. Thus, the interpretation of multitemporal remote sensing images and aerial photographs allowed a better interpretation of the posterior environmental assessment data through the knowledge of the context in which these were inserted.

1. INTRODUCTION

Proper urban solid waste management represents one of the biggest challenges for Brazilian municipalities. In 2017, the waste generation in Brazil was 78,4 million tons, of which 40,9% was disposed in inadequate sites by more than 60% of Brazilian municipalities (ABRELPE, 2018). This represents approximately 32 million tons of waste disposed in the environment without the necessary structures and control to avoid the contamination of water and soil as well as to protect the surrounding community members' health.

This scenario was even worse from the last century until the first decade of the present century due to the lack of specific regulations towards the topic at the federal level. This means that, in addition to the inadequate sites in operation, there are those used for waste disposal in the past, which still represent possible environmental risks that should be investigated.

There are two classes of inadequate waste disposal sites in Brazil: dumpsites and controlled dumpsites. Dumpsites (or dumps) are the most common, in which waste is simply disposed in surface soil or natural ditches without coverage or soil impermeabilization. The controlled dumpsites (or controlled dumps) have some degree of engineering and management control, such as waste coverage with soil, the construction of ditches or slopes, access control and, less frequently, rainfall, gases and leachate drainage systems.

The Solid Waste National Policy approved in 2010 established that Brazilian municipalities should set goals for the elimination and recovery of dumps and controlled dumps, and the National Solid Waste Plan developed in 2012 set a goal to eliminate all dumps by 2031, promoting the environmentally appropriate final disposal of the waste generated in Brazil.

For the recovery process of these areas, an investigation of soil and water contamination as well as the impacts on human and environmental health must be performed. It is necessary to retrieve the operation history of the dumps,

* Corresponding author:
Camila Camolesi Guimarães
email: camilacg@ipt.br

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obtaining information about the waste distribution and period of disposal, the types of waste disposed, the construction of trenches and slopes, the existence of drainage systems and zones of leachate accumulation, and the use and occupation of the surroundings among others.

However, this investigation is often hampered by the lack of past records in the municipalities and environmental agencies about the inadequate disposal sites, especially when they are very old or have had their operations shut down for a long time. For the dumps that are already closed, the study is also hampered by rapid vegetation growth, making it harder to clearly identify where exactly the waste was disposed. In this context, the utilization of historical aerial photographs and remote sensing images constitutes an interesting tool for the identification and analysis of inadequate waste disposal site evolution, contributing to the process of their correct closure and recovery.

According to the Environmental Agency of São Paulo State (CETESB, 2001), the interpretation of aerial photographs and satellite images for the analysis of waste disposal sites has the advantage of permitting the observation of historical details of their operation, which would not be possible otherwise because of the lack of available documentation. The importance of this analysis is due to the fact that these sites may be used for other activities in the future, presenting risks for human health.

Kuehn & Hoerig (2000) identified the possible uses for remote sensing images and aerial photographs in waste disposal site investigation. The interpretation of these tools permits the study of the chronological development of site operation, including the handling and quantity of dumped waste; the localization of heat sources inside a waste heap; the identification of water seepage at the edges of waste disposal sites; the observation of vegetation succession and vitality; the exploration of the immediate vicinity around a disposal site; the identification of natural and artificial drainage systems; the assessment of surface water conditions; and the identification of previous excavations.

Remote sensing imagery has been largely used by researchers for the identification and mapping of uncontrolled and illegal urban and industrial waste disposal sites. In the 1970s, Garofalo & Wobber (1974) suggested that remote sensing could provide useful solid waste management and planning data. The authors applied aerial photography to estimate waste characteristics and quantities, to study waste disposal site selection and utilization as well as waste collection and transportation, to address environmental impacts of on-site and off-site disposals and to identify waste-generating sources.

Getz et al. (1983) used aerial reconnaissance through a direct aerial search and the photointerpretation of aerial photographs to search for open dumps in the United States. Irvine et al. (1997) made a comparison between historical aerial photography and collected thermal imagery to determine the location of buried industrial waste trenches.

Silvestri & Omri (2008) developed a method for identifying illegal waste disposal sites over large areas using remotely sensed information and a geographic information system (GIS). Glanville and Chang (2015) also mapped illegal disposal through the identification and integration of predictive spatial data in GIS, identifying explanatory variables suitable for predicting its distribution.

More recently, Al-Joburi (2018) used aerial photos, satellite images, digital elevation models and historical land use maps to identify possible subsurface dumpsites in the Kingdom of Bahrain, developing a method to identify, locate and map random dumping sites. Similarly, Massarelli (2018) developed a processing procedure with satellite images applicable to agroecosystems to detect excavation activities and illegal waste disposal in areas that had been heavily disturbed and subjected to continuous change over time.

In Brazil, remote sensing images and aerial photographs have been mainly used to control existing landfills and identify current irregular waste disposal as well as to select suitable areas for the implementation of landfills (Samizava et al., 2008; Coelho, 2017; Carrilho et al., 2018). However, little research has been conducted on the identification and assessment of former dumpsites, as most of them show little evidence of waste disposal or environmental contamination because the sites were usually covered by vegetation in advanced stages of succession.

In his context, as highlighted by Erb et al. (1981), aerial photographs and remote sensing images can be successfully used to inventory waste disposal sites that are presently inactive and have possibly developed other land uses. They are also useful for documenting site boundaries that may have changed through time. The quality of available information as well as the range of dates and scales determine how precisely the history of a site will be reconstructed.

Thus, the objective of the present study was to apply the visual interpretation of satellite images and aerial photographs in the historical analysis of inadequate urban solid waste disposal sites to provide essential information for their investigation and recovery processes and conditions for the elaboration of a robust conceptual site model that reflects the sites' actual environmental conditions.

2. METHODS

The present study assessed former controlled dumpsites in four municipalities in the state of São Paulo, the most populated and richest state in Brazil, which is composed of 645 municipalities. The Urban Solid Waste State Inventory carried out by its environmental agency (CETESB, 2018) shows a generation of approximately 39.890 tons of waste per day. Although 98% of this amount is disposed in adequate sites, such as landfills and composting plants, there are still more than 40 active dumpsites throughout the state.

In addition, as stressed by the environmental agency, the information presented in the inventory refers to the disposal systems currently under operation and does not include the environmental liabilities represented by former and deactivated inadequate waste disposal sites. There are no official data on the number of existing former dumpsites, but it is estimated that almost all the municipalities in the state have once had an active dump in their territories, totaling more than 600 sites. Most of these sites have not been investigated for contamination issues nor have had an established deactivation and recovery plan.

In the present study, four former controlled dumps in the state of São Paulo were analyzed in the municipalities of Capivari, Santana de Parnaíba, Cananéia and Miracatu (Figure 1). The main characteristics of these areas are presented in Table 1. The interpretation of aerial photographs and remote sensing images were part of the contamination investigation and recovery process of these sites, which was carried out between 2014 and 2018.

The municipality of Capivari has approximately 53 000 inhabitants and is located in the east-central region of the state of São Paulo. During the 1990s, Capivari used three dumpsites for waste disposal, one of which, Anicchino was analyzed in the present study.

The utilization of Anicchino dump for municipal solid waste (MSW) disposal started in 1999 and occurred for approximately three years. This dumpsite, which was later transformed into a controlled dump, is 20.000 m^2 in area and located in an agricultural production area. Waste disposal occurred superficially following the features of the terrain along a natural thalweg with a depth of 6 m.

The municipality of Santana de Parnaíba has almost 110,000 inhabitants and is located in the metropolitan region of São Paulo municipality. From the mid-1990s to 2011, an area called Vila Esperança dump was used for irregular MSW disposal and was 65.000 m^2 in area.

Disposal occurred by the slope method, with slope heights varying between 3 m and 15 m.

The municipality of Cananéia is located in the southwestern region of the state and has a population of approximately 12.600 people. Its former controlled dumpsite, Aroeira dump, is located 20 km from the city center and received Cananéia's MSW from the end of the 1980s until 2009. The waste was disposed in man-made trenches of 2 m depth and piles of 3 m height.

The municipality of Miracatu is located in the southwestern region of São Paulo and has 20.790 inhabitants. From the end of the 1980s until 2006, the municipality used a 35.000 m^2 area for waste disposal, Miracatu dump. A natural slope of approximately 10 m was utilized because the site was limited by a mountain on its highest portion and by a river on its lowest portion.

For the historical study of the sites, the corresponding aerial photographs were taken from the database of the Laboratory of Aerophotogeography and Remote Sensing of the Department of Geography in the University of São Paulo as well as from the archives of the Institute for Technological Research; from a survey carried out in 1972 by the Brazilian Coffee Institute; and from specialized private companies. For the visual interpretation process, digital images were obtained from the scanning of the analogic aerial imagery with a 600 dpi.

False color satellite images were obtained in Google Earth® (Quickbird Pan-sharpened images, true color composition, 0,7 m resolution) and for the historical images the "time" tool was used. As the objective of the study is the evaluation of the historical evolution of dumpsites as well as the obtainment of information about irregular waste disposal, the visual interpretation of digital images was considered sufficient to understand the processes of use and management of these sites. For this reason, false color satellite images were chosen instead of original multispectral data. The characteristics of the materials used in the study are shown in Table 2.

All the images were georeferenced using the "georeferencing" tool in Esri® ArcMap™ 10.2.1.3497, applying landmarks identified along the sites as points of similarity. The visual interpretation of the selected images was made tak-

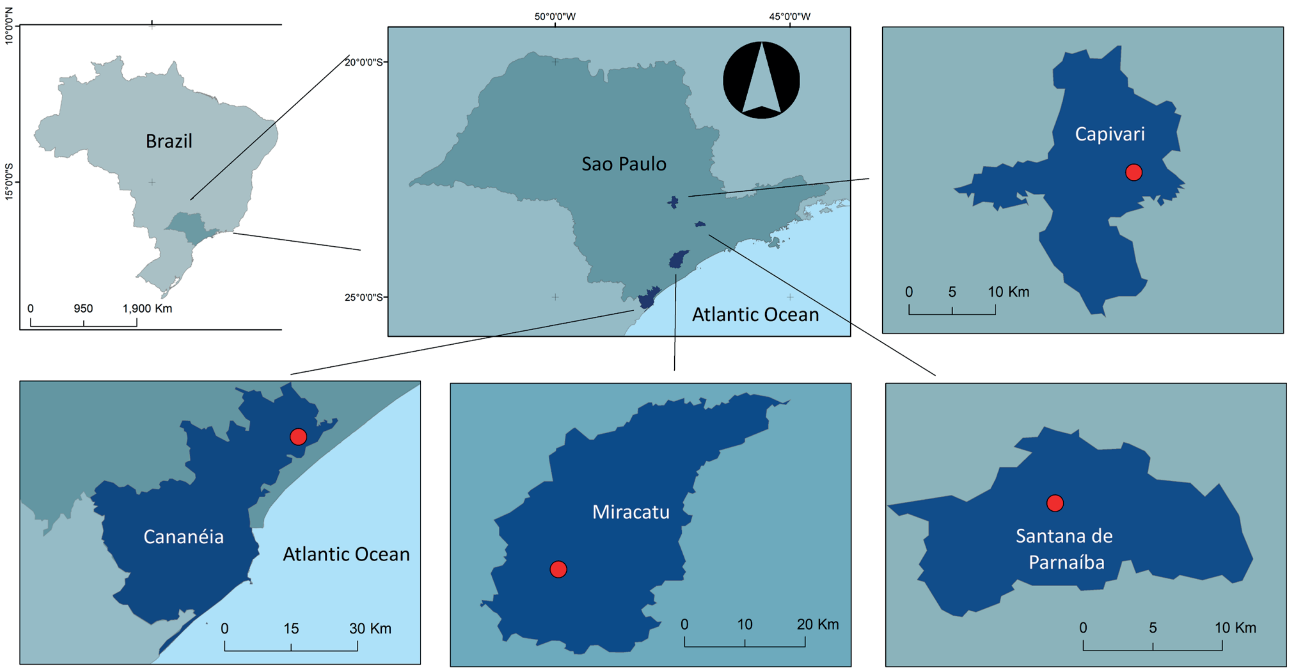

FIGURE 1: Location of the municipalities of Capivari, Santana de Parnaíba, Cananéia and Miracatu in the state of São Paulo, Brazil.

TABLE 1: Main characteristics of the former controlled dumpsites assessed in the study.

Municipality	Area	Duration of use	Waste disposal technique	Type of use of the surroundings
Capivari	20.000 m^2	3 years	Slope method	Agricultural
Santana de Parnaíba	65.000 m^2	15-20 years	Area method	Urban
Cananéia	50.000 m^2	20 years	Combination of area and trench methods	Environmental protection area
Miracatu	35.000 m^2	20 years	Slope method	Environmental protection area with agricultural activities

TABLE 2: Characteristics of the imagery used for the historical analysis of the former controlled dumpsites.

Municipality	Former controlled dumpsite	Year	Resolution (m/pixel)	Source	Original image type
Capivari	Anicchino	1972	1.65	Airborne survey (commercial provider)	Analogic
		2014	0.7	Google Earth ("time" tool)	Digital
Santana de Parnaíba	Vila Esperança	1962	1.2	Airborne survey (Brazilian Coffee Institute)	Analogic
		2002	0.7	Google Earth ("time" tool)	Digital
		2008	0.7	Google Earth ("time" tool)	Digital
		2018	0.7	Google Earth	Digital
Cananéia	Aroeira	1972	2.5	Airborne survey (commercial provider)	Analogic
		1981	1.5	Airborne survey (archives from the Institute for Technological Research)	Analogic
		2012	0.7	Google Earth ("time" tool)	Digital
Miracatu	Estrada do Teagem	1991	1.05	Airborne survey (commercial provider)	Analogic
		2006	0.7	Google Earth ("time" tool)	Digital
		2018	0.05	Drone survey	Digital

ing into consideration the following parameters: use and occupation of the sites and surroundings, vegetation cover and geomorphological characteristics. The photointerpretation process for the evaluation and understanding of the sites geomorphologies was performed by the stereoscopic analysis of aerial photographs, using a Zeiss mirror stereoscope.

Moreover, field evaluations were performed to validate the resulting interpretations, especially regarding the delimitation of the dumpsites limits, using known points (such as water bodies) and a Trimble® Differential Global Positioning System (DGPS), model Pro-XRT and OmniSTAR® correction (error of ± 0,25 cm). The opening of some inspection trenches to confirm the distribution of the waste mass was also performed.

The results were subsequently crossed with other information, such as data from geophysical studies (in the cases of Vila Esperança and Miracatu dumps), thus allowing a better understanding of site evolution and current situation.

The geophysical survey in Vila Esperança dump was performed in 2015. The frequency domain electromagnetics method was used to determine the apparent electrical conductivity of the subsoil, as anomalies could indicate the presence of waste and its byproducts in subsurface. For this, 74 pikets were installed with a spacing of approximately 40 m and georeferenced using a Trimble® DGPS.

The electrical conductivity measurements were performed in every 20 m, using the EM-34 equipment from Geonics Limited, with a space of 20 m between the transmission and reception coil, in both horizontal and vertical dipole mode. Thus, data were obtained by sampling a subsurface volume at two depths: from 0 m to 15 m (in the horizontal dipole model) and from 0 m to 30 m (in the vertical dipole mode).

The results were exported to Golden Software Surfer® 12 for interpolation using the "Griding data" tool (gridding method: kriging), generating contour maps of the electrical conductivity values measured in the field. The results were then incorporated into the site topographic plant provided by the municipality of Santana de Parnaíba.

For the generation of the contour maps, the apparent electrical conductivity was normalized using an established background, according to the following equation, in which $\sigma_{(x,y)}$ is the conductivity measure at the point and σ_{bg} is the stipulated background value:

$$db = 20 \,.\, \log_{10} \sigma_{(x,y)}/\sigma_{bg} \quad (1)$$

In the case of the shallower investigation (0 m to 15 m), the measurements were normalized using a background of 15 mS/m corresponding to the natural values of the ground. For the deeper investigation (0 m a 30 m), the established background was 10 mS/m.

For the geophysical survey in Miracatu dump, the selected method was the electric resistivity, using the dipole-dipole array. The results are expressed in values of electrical resistivity of the studied ground volume. Low electrical resistivity values can indicate the presence of waste and/or its byproducts in the subsurface. The survey was conducted in 2018.

The electric resistivity method employs an artificial source of direct or low frequency current (with intensity I) introduced into the soil by a pair of electrodes. The potential difference (V) that is established in response to this current injection can be measured by two other electrodes located nearby. Thus, the value of apparent electrical resistivity (ρ_a) of the investigated volume is measured by:

$$\rho_a = K \, . \, V / I \quad (2)$$

The geometric factor K, which presents distance dimensions, is defined by the arrangement of the four electrodes. In the dipole-dipole array the space between electrodes was of 5 m and 5 depth levels were investigated. For the investigation 8 lines were defined, 4 longitudinal (L1 = 230 m; L2 = 290 m; L3 = 290 m and L4 = 300 m) and 4 transverse (T1 = 105 m; T2 = 90 m; T3 = 75 m and T4 = 70 m).

The data were interpolated in Golden Software Surfer® 12 using the “kriging” method, generating isovalues maps of apparent electrical resistivity of the surface to a depth of 5 m. The results were incorporated into the site topographic plant provided by the municipality of Miracatu.

For Miracatu dump, the 2018 image was obtained by high resolution photogrammetric survey using a drone Dji®, model Phantom 3, with a flight height of 120 m and acquisition resolution of 0.05 m. The activities comprised the high resolution photographic record with subsequent image processing, obtaining the orthophotos and digital surface model. The image processing was done in PrecisionMapper®, using 103 photos to generate an orthophoto. This allowed the visualization of the site current situation in detail.

3. RESULTS AND DISCUSSION

The historical interpretation of aerial photographs and satellite images enabled the obtainment of several types of information about the use and operation of former dumpsites. In general, four main results were identified: the delimitation of waste distribution; the identification of the waste disposal method; the evaluation of vegetation development and reconstitution; and the assessment of historical use and occupation of the surroundings. These results will be detailed in the following sections.

3.1 Anicchino dump

The historical images of Anicchino dump allowed the delimitation of the waste distribution during its period of operation. Overlapping the obtained images and evaluating the dumpsite evolution, the most significant contributions were obtained by comparing the disposal limit information obtained in the field and delimited in the 2014 image with the geomorphological interpretations based on the 1972 image (Figures 2B and 2A, respectively).

In the 1972 image (Figure 2A), it was possible to identify the delimitation of a natural ditch (yellow line), which resulted from a great erosive process, with an elevation difference between the thalweg base and the top of the terrain. At the base of the thalweg, the delimited drainage and a water spring were also identified (blue line).

Taking advantage of the geomorphological situation of the site, waste was disposed inside the thalweg, pushed to the bottom of the valley. This practice led to the filling of the thalweg, extinguishing the natural relief differences, which cannot currently be perceived at the site. In this way, the interpretations lead to the conclusion that the waste disposal process was carried out through dumping and scattering, taking advantage of the site’s natural characteristics.

However, during field observations in the area delimitated for Anicchino dump, large amounts of vegetation cover that developed on the waste mass were identified (Figure

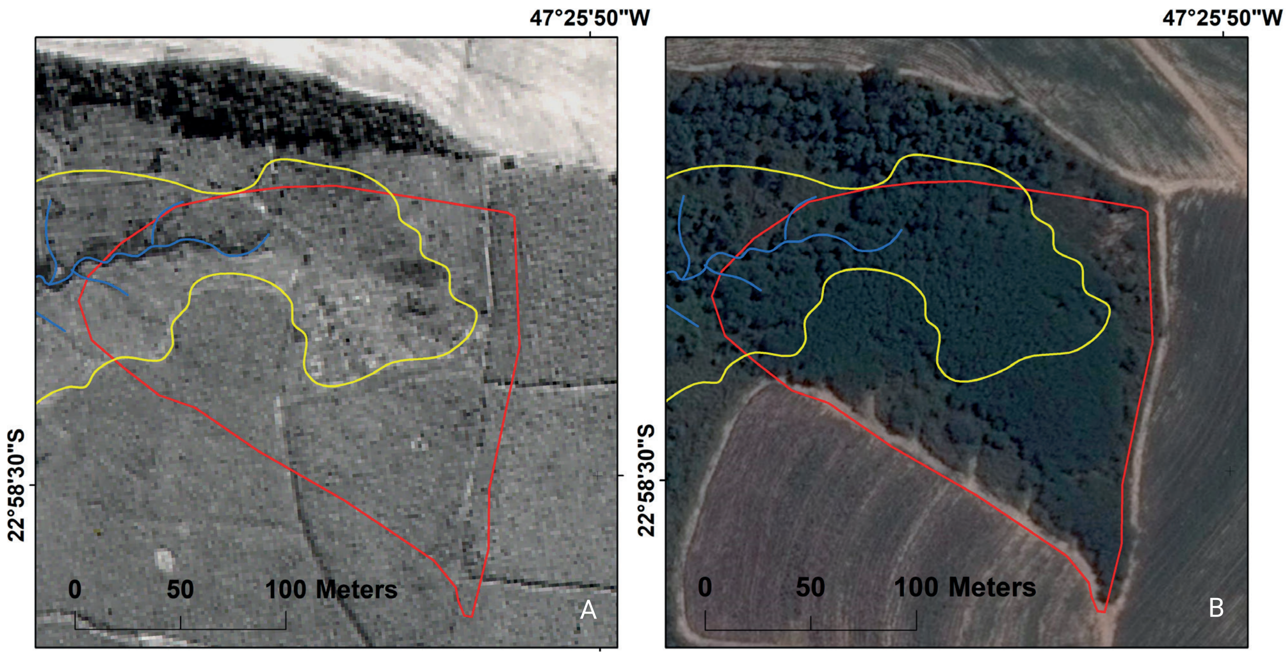

FIGURE 2: Analysis of Anicchino’s 1972 aerial photograph (A) and the 2014 satellite image (B).

3). The vegetation was primarily composed of Leucaena leucocephala with trees approximately 10 m in height. The surroundings were occupied by sugarcane plantations (Saccharum ssp), which are very common in that region.

Kuehn & Hoerig (2000) classify anomalies in vegetation as indicative of the presence of anthropogenic components in a landscape, and they can be easily identified through the study of aerial photographs and remote sensing images. The authors consider vegetation as a good indicator of the presence of hazardous substances in soil, which can cause alterations in its morphological characteristics.

Regarding Anicchino dump, the presence of waste in the subsurface was indicated by the natural development of an exotic species generally used in forest recovery processes because of its high dispersion capacity. In this way, the high available organic matter content favored the growth of this leguminous species, which is capable of forming dense vegetated masses and advancing into adjacent areas (Costa & Durigan, 2010).

Considering this information, when analyzing the 2014 image (Figure 3B), updated limits of waste disposal along the site were generated (red line) in addition to the one identified in the 1972 image. In this case, as in the study developed by Erb et al. (1981), little evidence of thalweg filling can be found in the site currently or in the most recent images. Alternatively, if only the 1972 image was considered, the extension of the waste mass, as indicated by the development of a specific type of vegetation, would not be fully understood.

In this way, the sole analysis of the site's most recent satellite image as well as field inspections would not permit the real delimitation of the waste distribution, which was obtained by the interpretation of historical imagery together with the geomorphological characteristics of the site. In addition, the field inspections and analysis of more recent images permitted updating the site limits based on the correlation between the waste distribution and vegetation cover.

3.2 Vila Esperança dump

Analyzing the historical imagery between 1962 and 2018, it was possible to observe the evolution of Vila Esperança dump. In 1962 (Figure 4A), the site (perimeter defined by the red line) was not yet under operation, as it was partially covered by a secondary forest. In 2002 (Figure 4B), it is possible to observe soil movements and the presence of waste disposed in the surface soil without coverage.

In the 2008 image (Figure 4C), the excavation of the borrow pit is evident (northern portion of the site) as well as the construction of slopes and the tanks for leachate storage. It should be noted that in 2008, it is no longer possible to identify the surface waste present in the 2002 image, which was already covered in this stage of the dump operation. Both in 2002 and 2008, it is possible to observe the presence and growth of irregular occupations in the surroundings of Vila Esperança dump, which was principally carried out by waste pickers that collected recyclables and used the materials as their means of subsistence.

Finally, in 2018 (Figure 4D), approximately seven years after the end of the dump operation, the removal of the irregular occupations is observed as well as the high level of vegetation recovery on and around the waste mass. During the field inspections, it was not possible to identify clear evidence of waste disposal in the surface soil, which was

FIGURE 3: Vegetation cover identified on the waste mass.

identified in the 2002 image, and only its distribution on the slopes was evident.

Geophysical techniques are also important tools in the study of former inadequate waste disposal sites as they allow the estimation of waste distribution from the results of conductivity or resistivity anomalies. As a noninvasive technique, geophysical surveys reduce the need to open trenches to confirm waste distribution, which may affect the current stability condition of a site.

For this site, geophysical studies were carried out using the frequency domain electromagnetics method with the results obtained in electrical conductivity scales measured in the subsoil for depths of 0 to 15 m (Figure 5, left) and 15 to 30 m (Figure 5, right). The identified conductivity anomalies can be correlated with the presence of waste and/or leachate.

At depths of 0 to 15 m, the identified conductivity anomalies were restricted mainly to the slope base, where the main mass of waste was concentrated. However, at depths of 15 to 30 m, several electrical anomalies were detected outside the waste mass. Although some of them followed the water flow direction, indicating the movement of leachate through the dump, others were contrary to the flow direction, and there was no clear explanation for this. When combining the geophysical data with the topography, the dump adequation project and the satellite image of 2008,

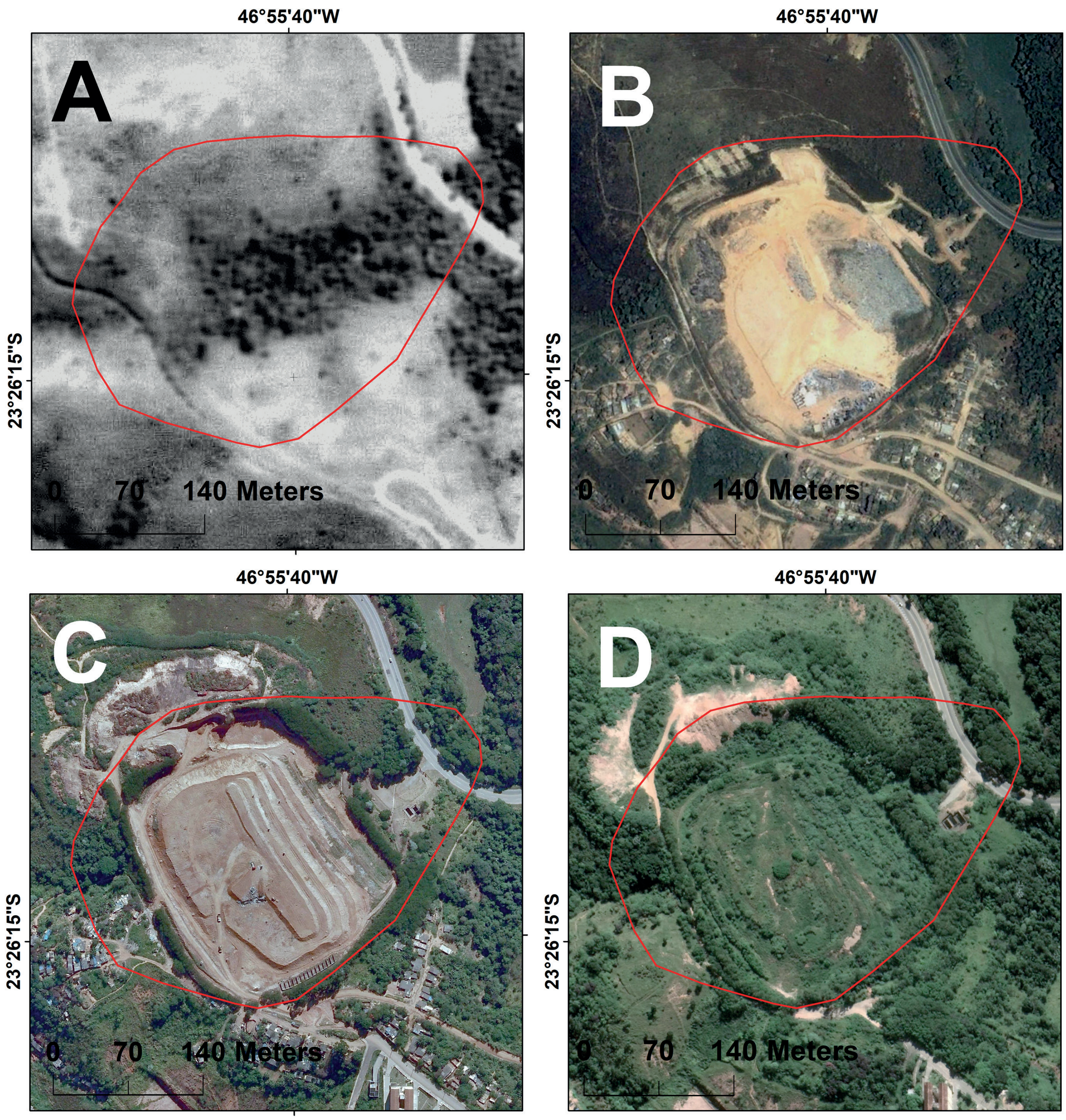

FIGURE 4: Historical analysis of Vila Esperança dump with images from 1962 (A), 2002 (B), 2008 (C) and 2018 (D).

it was possible to interpret the anomalies in a consistent way.

The main anomalies outside the principal waste mass were divided into regions (Figure 5B). In region 1 (green dotted line), it is possible to observe the overlapping of electrical anomalies with one of the former irregular occupation areas. As this area was not served by sewage collection, all the domestic sewage was released and infiltrated into the soil, altering its electrical characteristics. These discharges occurred approximately ten years ago, but their impacts could still be identified through the electric behavior of the soil.

Region 2 (orange dotted line) presents a small anomaly, which can be explained by the infiltration of leachate into the soil. As the dump is located in a water parting region, even though it is on one side of the slope, the leachate reaches a portion of the water table that flows to the opposite side, which was evidenced in the electrical results.

In the northern part of the site (region 3, the pink dotted line), it is possible to identify an area provisionally used for waste disposal that did not appear in the official dump registries, but in the satellite image of 2008, it was possible to observe the area excavation and preparation to receive the waste disposal. Later, these materials were covered with soil, and there is no record of the period or quantity of waste disposed.

Finally, region 4 (the blue dotted line) presents the behavior of leachate coming from the waste mass, which follows the distribution of the drainage systems installed in the site, showing a leakage of liquids from the drains directed to the leachate ponds.

In this case, the remote sensing images were valuable because they could be used to reconstruct the chronology of change of the waste disposal site (Lyon, 1987). Without the historical study of satellite images, it would neither be possible to correctly interpret the geophysical anomalies detected nor to identify the areas where the waste was disposed in the surface, of which there is little current evidence in the area.

3.3 Aroeira dump

During the environmental studies for closure and recovery of former controlled dumpsites, one of the necessary activities is the evaluation of the use and occupation of the surroundings, which provides information on possible influences on the area of interest.

During the interpretation of aerial photographs and satellite images, a large occurrence of vegetation suppression was identified. In the 1972 (Figure 6A) image, it is possible to verify several suppression polygons with an estimated area of 112.000 m^2. In the 1981 image (Figure 6B), a great recovery of the vegetation was observed, with a reduction in the impacted area. The calculated area in 1981 was 57 000 m^2, showing a reduction of 49% in dimension compared to 1972, which represents a vegetation regeneration rate of 6 000 m^2/year.

A portion of the impacted area was opportunistically used for the installation of Aroeira dump, whose activities began in the 1980s and ended in 2009. The site received MSW in this period as well as a large volume of fishing waste, an economic activity of great relevance for the city.

In 1984, the Cananéia-Iguape-Peruíbe Environmental Protection Area was created, in which Aroeira dump was inserted. This contributed to a reduction in anthropogenic activities and to the complete regeneration of the suppression areas. In the 2012 image (Figure 6C), the whole area is already regenerated, and it is visible only by the difference in color tonality.

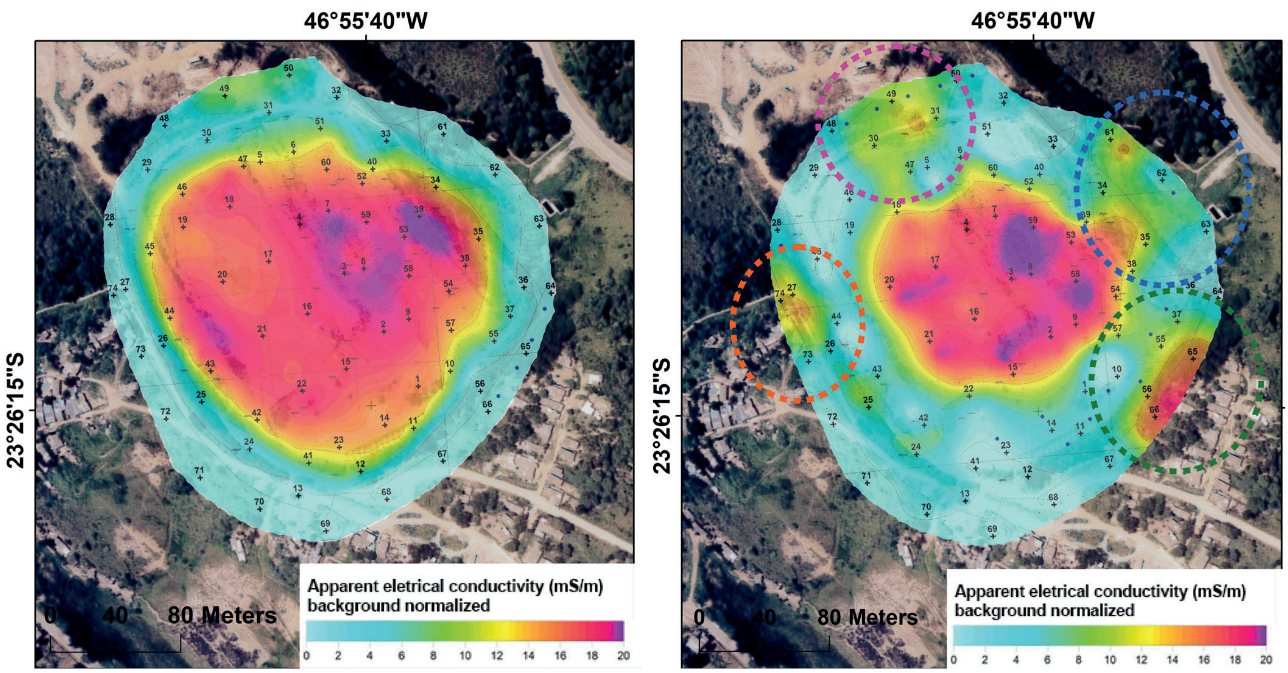

FIGURE 5: Results of the geophysical survey in Vila Esperança dump with electrical conductivity anomalies identified at depths ranging from 0 to 15 m (left) and 15 to 30 m (right)

In the historical study of Aroeira dump, the potential of vegetation resilience and regeneration in the Atlantic forest was evidenced. In less than 40 years, a 112 000 m^2 area was naturally regenerated as the sole result of anthropogenic activity restriction.

The results are also corroborated by the soil and groundwater physical-chemical parameters analysis, which did not show any value above the limits established by the environmental agencies (CETESB in Brazil and USEPA in the United States of America). This shows that even after 20 years of irregular waste disposal, natural attenuation processes were able to facilitate the environmental regeneration of the site.

3.4 Miracatu dump

During the field inspection of Miracatu dump (the pink line in Figure 7), it was observed that the waste was disposed in a natural slope formed between the road level (yellow line) and the river located in the southern portion of the site. The former controlled dump operation was carried out by depositing, compacting and covering the waste with soil, resulting in layers built from the slope base up to the level of the road, surpassing it by approximately 1 m.

Currently, it is possible to clearly identify the waste disposal in the western portion of the site, as shown in the 2006 image (Figure 7B). However, there were no registries of waste disposal in the eastern portion, as seen in the 1991 image (Figure 7A), which occurred during the initial period of Miracatu dump operation.

As a result of this lack of knowledge, in this area, agricultural activities are currently developed with the cultivation of bananas and some vegetables. In this way, the historical analysis of the imagery permitted the precise delimitation of the waste distribution in the former controlled dump, subsidizing the next stages of its environmental evaluation.

In the 2018 image, which was obtained via a drone (Figure 7C), the vegetation reconstitution of a large area in the dump surface is observed, including the development of arboreous species. Despite this fact, the presence of waste can still be evidenced by the lower exuberance and vegetation growth compared to the surroundings, especially in the areas closer to the river.

In Miracatu dump, geophysical studies were also carried out using the electrical resistivity method. The results were expressed in electrical resistivity scales in the subsoil (Figure 8). The areas with a lower resistivity and, consequently, a higher electrical conductivity were associated

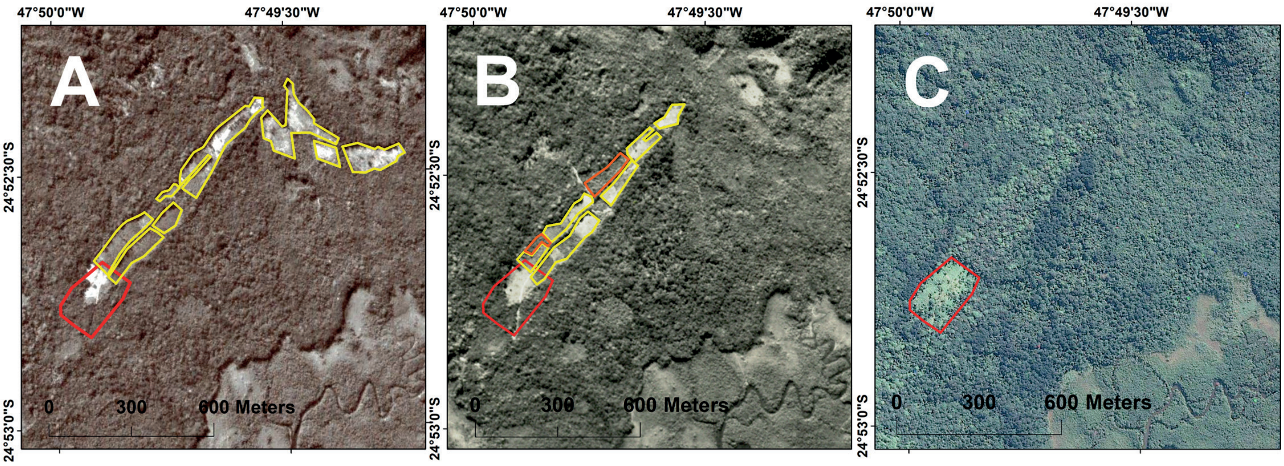

FIGURE 6: Analysis of vegetation suppression and reconstitution in the surroundings of Aroeira dump in 1972 (A), 1981 (B) and 2012 (C).

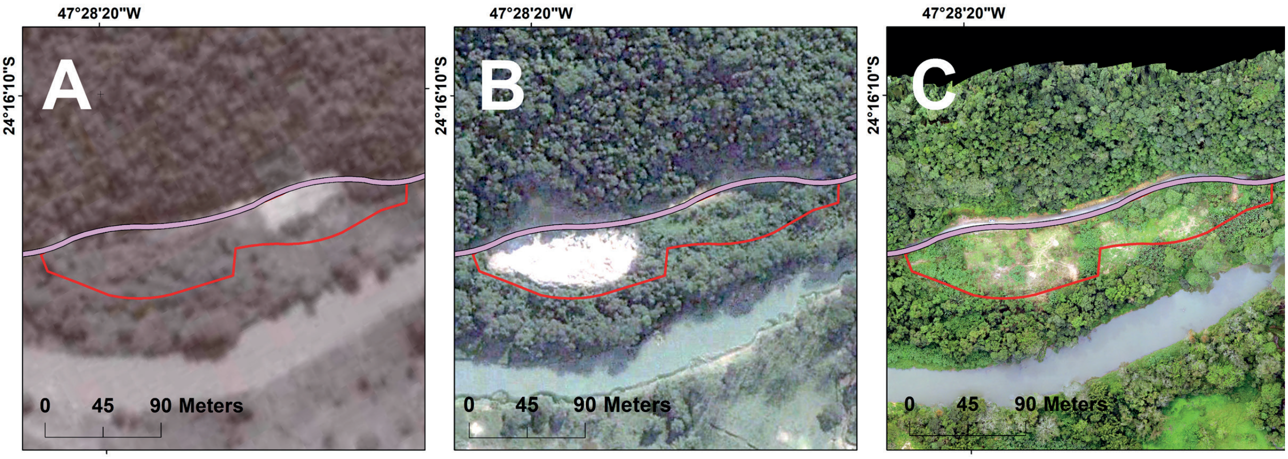

FIGURE 7: Historical analysis of Miracatu dump in 1991 (A), 2006 (B) and 2018 (C).

with the presence of waste and/or leachate. The results indicated a high correlation between the waste disposal areas delimited by the historical evaluation of aerial photographs and satellite images and the low resistivity zones identified at a depth of 4 to 5 m in the subsurface.

Therefore, as in the case of Vila Esperança dump, the comparison of the information obtained in the imagery study with the geophysical results allowed a more detailed and precise delimitation of the waste distribution throughout the former controlled dump. This is essential for planning the next steps of environmental assessment, such as setting the distribution of monitoring wells for the evaluation of soils and groundwater quality, thus optimizing and subsidizing the former dumps' recovery processes.

4. CONCLUSIONS

The visual interpretation of aerial photographs and satellite images for identifying and assessing the evolution of inadequate waste disposal sites has been shown as an excellent tool, principally in areas with a lack of past records. The application allows for retrieving the operation histories of former dumpsites and helps create an adequate investigation model that suits each particular situation.

Information from different databases, which has been generated in recent studies, can be crossed with previous databases, thus allowing the obtainment of greater data structure for a better interpretation of the available information. For the obtainment of current and historical imagery, this paper sought to suggest a methodology that can be widely applied in terms of database availability, with the use of high quality materials from free and open sources. This could be particularly interesting for municipalities that lack the technical and financial resources for investigating inadequate waste disposal sites.

In addition, field inspections and activities are also essential during this process, as good data interpretation also depends on the knowledge of a site and its particularities, allowing, in this way, the obtainment of robust results and contributing to the advancement of dumpsites recovery processes.

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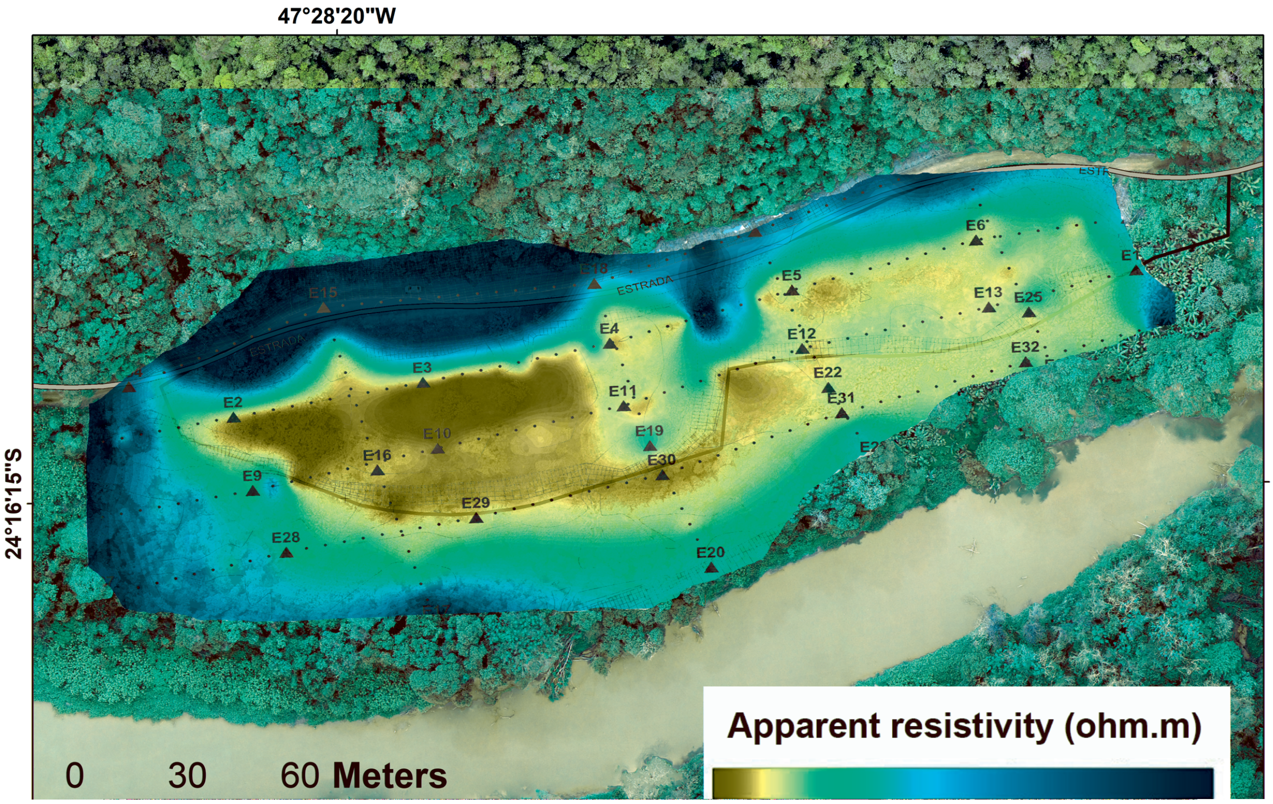

FIGURE 8: Geophysical results in Miracatu dump expressed in scales of electrical resistivity in the subsoil.

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