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# ENVIRONMENTAL PROBLEMS, HOW GEOPHYSICS CAN HELP YOU! APPLICABILITY OF GEOPHYSICAL METHODS

***Odirlei Neumann and Sandra Garcia Gabas**

Groundwater and Brownfield Laboratory, Faculty of Engineering, Architecture and Urbanism and Geography, Federal University of Mato Grosso do Sul, Campo Grande 79070-900, Brazil

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****Corresponding author:***
***Odirlei Neumann***

**ABSTRACT**

The research features how geophysical methods are used to optimize solutions for different types of environmental problems. To verify the use frequency of these methods today, a wide survey was carried out in recent articles from the scientific journals of the Geophysical Society of three countries: Journal of Environmental & Engeneering Geophysics (JEEG) and Near Surface Geophysics (NSG) and Revista Brasileira de Geofísica (RBGF). The investigation time frame was from the second semester of 2016 until the end of 2019, resulting in an overall total of 448 articles analyzed, and among these, 125 articles related to the environment were selected. After the data tabulation, statistical analyzes were carried out in order to assess which equipment and geophysical methods are bringing innovation to environmental studies. In addition, other factors have been verified, such as the purpose of the surveys, the application places and the methods integration. As a conclusion was reached that the geoelectric methods and the GPR are the methodologies most used; aquifers and contaminated areas are the places of greatest use of geophysics; and the detection of residues and contaminants, studies on geological and reservoir stability, as well as the growing exploitation of underground water resources are the main objectives of geophysics application in contemporary environmental studies. In addition, that most studies do not perform multi-method evaluations, which could result in a great optimization of results.



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## INTRODUCTION

In this work it was verified how geophysics is being used in the search for solutions to the most diverse types of environmental problems. We sought, through statistical analyses, information that could clarify questions about which equipment and geophysical methods are currently being used most for environmental studies globally. In addition to these, other factors were analyzed to obtain relevant information such as the purpose of the surveys, the application sites and the integration of methods. Although geophysics and all its methodological tools are already relatively known by professionals in the area of environment, mainly those who work with contaminated areas (Benyassine *et al*., 2017; Martinelli *et al*., 2018; Rajab *et al*., 2018; Rossi *et al*., 2016; Schoor *et al*., 2017; V. Grünhut and Bongiovanni, 2018), groundwater exploitation(Ikard and Kress, 2016; Koehn *et al*., 2019; Lima and Sato, 2019; Nascimento *et al*., 2017; Ruiz-Aguilar *et al*., 2018; Wynn *et al*., 2016), risk zones (Cueto *et al*., 2018; Lin *et al*., 2019; Pazzi *et al*., 2018; Rasul *et al*., 2018; Ronczka *et al*., 2018)and other areas related to soil and subsoil(Abdullah *et al*., 2019; Casagrande *et al*., 2018; Díaz-Curiel *et al*., 2018; Simms *et al*., 2017), there are still many doubts about how to use these methods and where they could help in solving environmental problems. Therefore, knowing the applicability of these methods and their limitations can be of great value for such professionals to reach conclusions more quickly and at lower costs, since geophysics is usually less costly than the use of direct methods such as wells, trenches and excavations. In many places these methods cannot be used, because unlike geophysics, they are destructive. Geophysical methods use equipment that take readings of physical properties on the surface, so as to determine what is underground, these techniques can be employed in different areas of the environment(Garner and Coffman, 2016; Godio *et al*., 2018; Hivert *et al*., 2017; Legchenko *et al*., 2018; Pasquier *et al*., 2016), such as: Stratification of materials and geological features

(Christensen, 2018; Huntley *et al*., 2019; Karshakov *et al*., 2017); depth of water level; direction of groundwater flow(Aissaoui *et al*., 2019; Ikard and Pease, 2019; Revil *et al*., 2017), leaks(Neto and Elis, 2016; Paria and Gamarra, 2018; Rocha *et al*., 2019; Woodbury *et al*., 2018); detection of ditches, landfills, drums, pipelines(Allroggen *et al*., 2019; Cheung and Lai, 2019), and any metallic object or not; salt intrusions and salinization of soil (Eröss *et al*., 2017; Sarntima *et al*., 2019; Siemon *et al*., 2019; Zucchi *et al*., 2019), delimitation of zones with organic and inorganic contaminants (Abbas *et al*., 2018; Cavallari *et al*., 2018; Moreira *et al*., 2019, 2016; Wang *et al*., 2019; Wemegah *et al*., 2017), among others. The following research presents the mentioned geophysical methods, as well as based on the current norms, seeking to bring to light the current applicability and limitations of each of these.

## MATERIALS AND METHODS

This study analyzed the information collected in the 448 articles published at the following journals: Brazilian Journal of Geophysics (RBGf, 2016), (RBGf, 2017), (RBGf, 2018), (RBGf, 2019). Journal of Environmental & Engineering Geophysics (JEEG, 2016), (JEEG, 2017), (JEEG, 2018), (JEEG, 2019)and Near Surface Geophysics (NSG, 2016), (NSG, 2017), (NSG, 2018), (NSG, 2019) in the time frame of the second half of 2016 until the end of 2019. Seeking to understand the state of the art of national and international geophysical publications in these journals focused on shallow geophysics. To have a database as up-to-date as possible of the quantity and distribution of the various inquiries contained in the publications. And in a second moment we analyzed more deeply the 125 articles of the Environmental area contained in the publications of these journals, so that we have an even more detailed and information rich database of this specific area, which is the object of this review article. And for these publications we analyzed three more topics, being them: the objective of the survey, the geophysical methods used and the place of application of them. As mentioned above, the main objective of this review is to statistically understand how are the various topics possible to withdraw from environmental publications. For this purpose, a general table was created, in which the most relevant information of each article was tabulated, such as title of the article, keywords, authors, pages, institutions, objectives, locations, methods used and area of application.

In Fig. 1, one can see an example except from this general table with information from a publication of one of the journals studied. In this general table we have 10 columns, and the first seven columns have been filled for all the articles, while the last three columns have only been filled for the articles of the Environmental sub-area, focus of this work, these being the ones that were used to make this work. The first column shows the numbering of the article in the general list of the journal; in the second the full title of the scientific article; in the third the name of the authors in the order of title of the publication; in the fourth the main keywords; in the fifth the application subarea; in the sixth the institution to which the main author belongs and in the seventh the numbering of the pages of the article. For the articles of the environmental sub-area, the last three columns were completed, and in the eighth column the main objective of the geophysical survey is presented; in the ninth column, the geophysical methods used in the study were made explicit and in the tenth and last column, the type of place where the surveys were performed was characterized. With this additional data collection of the articles of the environmental sub-area it was intended to demonstrate, as can be seen below in the topic presentation and discussion of the results, with graphical and statistical analyses, how is the state of the art of environmental publications using geophysics, ie where, how and why is using each geophysical method. Based on these data collected and using statistical and graphical analyses, such as: percentage and radar graphs, Pareto diagrams, histograms, end diagrams and quartiles (Boxplot), it was possible to analyze the various information in the General Data Table. In the item Discussion and Results, it is possible to analyze the results found.

**Theory:** Among geophysical methods, some stand out for their applicability in the study of environmental issues, based on the established literature and mainly the international standards ASTM D 6429-99:2006(ASTM, 2006), ASTM D 5753-05:2005 (ASTM, 2005) and NBR 15935/11 - Environmental investigations - Application of geophysical methods (ABNT, 2011). These aim to establish guidelines for the correct choice of geophysical methods for environmental investigations. In these we have the following advice on the use and limitations of each geophysical methodology for each possible environmental problem found. In the following tables we will always see the options of use of each method, where the use is marked as the first option indicates that the method is widely used for this type of work, and when it appears as the second option, is an indication that the method can be used in specific cases and/or as an auxiliary method. The first method to be analyzed is Seismic Refraction. As for its applications, we can see in Table 1 in which situations this method is indicated(Al-Shuhail and Adetunji, 2016; Carrière *et al*., 2018; Q. Chen *et al*., 2019; Dangeard *et al*., 2018; Dias *et al*., 2019). As to its main limitation, we have that this is a method sensitive to vibrations and external noises of the environment, another limitation is its low resolution.

**Table 1. Applicability of Seismic Refraction in Environmental Studies**

| Utilization | First option | Second option |
|---|---|---|
| Stratification of geological materials | X | |
| Depth of bedrock | X | |
| Water Level Depth | | X |
| Fault and fracture identification | | X |

Considering Seismic of Reflection, beyond the problem of the noises we have as limitation, their higher execution time and more complex data processing. Regarding its applications, we can see in Table 2 in which situations this method is indicated (Clare *et al*., 2017; Savini *et al*., 2018; Scottá *et al*., 2019; Simões *et al*., 2019).

**Table 2 - Applicability of Seismic Reflection in Environmental Studies**

| Utilization | First option | Second option |
|---|---|---|
| Stratification of geological materials | X | |
| Depth of bedrock | X | |
| Water Level Depth | | X |
| Fault and fracture identification | X | |

In the case of Electrical Resistivity, using the techniques of Electrical Resistivity Tomography (ERT) and Vertical Electric

Soundings (VES´s), this is likely to interferences such as metal pipes, energized cables and grounding points for various purposes.

We can also mention that another limitation is the physical space required to open the electrodes in the field, because the greater the depth to be investigated, the greater the opening of the arrangement. Another problem is the crimping of the electrodes themselves, these can be hindered by paving for example.

Regarding this last limitation, it is worth noting that for shallow studies, there is already a capacitively-coupled resistivity meter, using equipment type Ohm Mapper, which do not need any electrode crimping, because they work with current injection coils. As for its applications, we can see in Table 3 in which situations this method is indicated(Batista, Juliana Targino Soares, 2019; Bazin *et al*., 2018; Fabien-Ouellet *et al*., 2017; Gama *et al*., 2019; Layek *et al*., 2018; Messias *et al*., 2019; Orlando and Palladini, 2018; Passeri *et al*., 2018; Rossi *et al*., 2016; Woodbury *et al*., 2018).

**Table 3. Applicability of Resistivity Meter in environmental studies**

| Utilization | First option | Second option |
|---|---|---|
| Stratification of geological materials | X | |
| Depth of bedrock | X | |
| Water Level Depth | X | |
| Fault and fracture identification | X | |
| Cavity detection | | X |
| Leakage in dams and containment basins | | X |
| Ditch, Dumping ground and landfill boundaries | X | |
| Saline Intrusion | X | |
| Soil salinization | X | |
| Delimitation of zones with LNAPL | | X |
| Delimitation of zones with DNAPL | | X |
| Delimitation of areas with inorganic contaminants | X | |

Regarding Induced Polarization (IP), this is a method sensitive to undesirable electromagnetic fields, noise related to capacitive and inductive coupling. In order to reduce these noises, the use of non-polarizable electrodes is highly recommended(Keller and Frischknecht, 1966).As for its applications, we can see in Table 4 in which situations this method is indicated (Bucker *et al*., 2017; Gao *et al*., 2017;

**Table 4. Applicability of Induced Polarization in Environmental Studies**

| Utilization | First option | Second option |
|---|---|---|
| Ditch, Dumping ground and landfill boundaries | | X |
| Saline Intrusion | | X |
| Soil salinization | | X |
| Delimitation of zones with LNAPL | | X |
| Delimitation of areas with inorganic contaminants | | X |

Helene *et al*., 2016; Kessouri *et al*., 2019; Sharma *et al*., 2017). The main limitations of the GPR method are the low penetration depth in highly conductive media, and the use of only shielded antennas in environments with high electromagnetic noise levels is recommended(Davis and Annan, 1989). As for its applications, we can see in Table 5 in which situations this method is indicated(Allred *et al*., 2016; Freeland *et al*., 2016; Gundelach, 2018; Parsekian, 2018; Zaremba *et al*., 2016).

**Table 5 - Applicability of the GPR Method in environmental studies**

| Utilization | First option | Second option |
|---|---|---|
| Stratification of geological materials | X | |
| Depth of bedrock | | X |
| Water Level Depth | X | |
| Fault and fracture identification | X | |
| Leakage in dams and containment basins | | X |
| Ditch, Dumping ground and landfill boundaries | X | |
| Saline Intrusion | X | |
| Cavity detection | X | |
| Delimitation of zones with DNAPL | X | |
| Delimitation of zones with LNAPL | X | |
| Delimitation of areas with inorganic contaminants | | X |
| Underground utilities and interference | X | |
| Drums, tanks and metallic objects | X | |
| Drums, tanks and other non-metallic objects | X | |

Consider the Electromagnetic Methods – EM,it has as limitation the susceptibility to interferences of near metallic objects and electromagnetic noises. In the specific case of the TDEM method that operates with large coils, there is still the limitation of free physical space to perform field surveys. Regarding its applications, we can see in Table 6 in which situations this method is indicated (K. Chen *et al*., 2019; Li *et al*., 2019, 2018; Paine and Collins, 2017).

**Table 6. Applicability of electromagnetic methods in environmental studies**

| Utilization | First option | Second option |
|---|---|---|
| Stratification of geological materials | | X |
| Depth of bedrock | | X |
| Water Level Depth | | X |
| Fault and fracture identification | X | |
| Leakage in dams and containment basins | | X |
| Ditch, Dumping ground and landfill boundaries | X | |
| Saline Intrusion | X | |
| Soil salinization | X | |
| Delimitation of zones with DNAPL | | X |
| Delimitation of areas with inorganic contaminants | X | |
| Underground utilities and interference | | X |
| Drums, tanks and metallic objects | X | |

Spontaneous Potential (SP) method is sensitive to interferences of natural telluric currents, to terrain conditions (topography) and cathodic protection currents (Orellana, 1972). As for its applications, we can see in Table 7 in which situations this method is indicated (Abbas *et al*., 2018; Ebrahimzadeh *et al*., 2017; Ikard and Pease, 2019; Revil *et al*., 2017).

**Table 7 - Applicability of Spontaneous Potential in Environmental Studies**

| Utilization | First option | Second option |
|---|---|---|
| Groundwater flow direction | X | |
| Leakage in dams and containment basins | X | |
| Delimitation of areas with inorganic contaminants | | X |

Magnetometry is sensitive to interference from metal objects in the vicinity and suffers from natural changes in the Earth's magnetic field, as well as magnetic storms. As for its applications, we can see in Table 8 in which situations this method is indicated (Doser *et al*., 2019; Huntley *et al*., 2019; Wemegah *et al*., 2017).

| Near Surface Geophysics - City: Amsterdam - Country: Holanda | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Volume: | | 15 | | Issue: | 1 | | Year: | 2017 | |
| Nº. | Title of the article | Author(s) | Keywords | Subarea | Institution | Pg. | Objective | Methods | Place |
| 23 | The 3D Autojuggie: automating acquisition of 3D near-surface seismic reflection data | Brian E. Miller, Steven D. Sloan, Georgios P. Tsoflias, Don W. Steeples | 3D Autojuggie, 3D near-surface, seismic reflection | Equipment | University of Pennsylvania, USA | 3-11 | | | |
| 24 | Facies discrimination with electrical resistivity tomography using a probabilistic methodology: effect of sensitivity and regularisation | Thomas Hermans, James Irving | Electrical resistivity, tomography, probabilistic methodology | Environmental | Stanford University, USA | 13-25 | Hydrogeology | Resistivity | Aquifer |
| 25 | A cost-effective 3D electrical resistivity imaging approach applied to dike investigation | Clara Jodry, Sèrgio Palma Lopes, Yannick Fargier, Philippe Côte, Martin Sanchez | A cost-effective 3D electrical resistivity imaging approach applied to dike investigation | Environmental | Nantes University, França | 27-41 | Hydrology | Resistivity | Dam |
| 26 | VEMI: a flexible interface for 3D tomographic inversion of time- and frequency-domain electrical data in EIDORS | Giorgio De Donno, Ettore Cardarelli | 3D tomographic, inversion, EIDORS | Environmental | University of Rome, Italia | 43-58 | Aquifer contamination | Resistivity | Aquifer |
| 27 | Seasonal saline intrusion monitoring of a shallow coastal aquifer using time-lapse DC resistivity traversing | Eva Sutter, Malcolm Ingham | Saline intrusion, shallow coastal aquifer, resistivity | Environmental | Victoria University of Wellington, Nova Zelandia | 59-73 | Aquifer contamination | Resistivity | Aquifer |
| 28 | Spectral time-domain induced polarisation and magnetic surveying – an efficient tool for characterisation of solid waste deposits in developing countries | David Dotse Wemegah, Gianluca Fiandaca, Esben Auken, Aboagye Menyeh, Sylvester Kojo Danuor | Spectral time-domain, magnetic, waste deposits | Environmental | Kwame Nkrumah University of Science and Technology (KNUST), Gana | 75-84 | Aquifer and soil contamination | Induced Polarization (IP), Magnetic | Dumping ground |

**Fig. 1. Cut out the General Table of the publications**

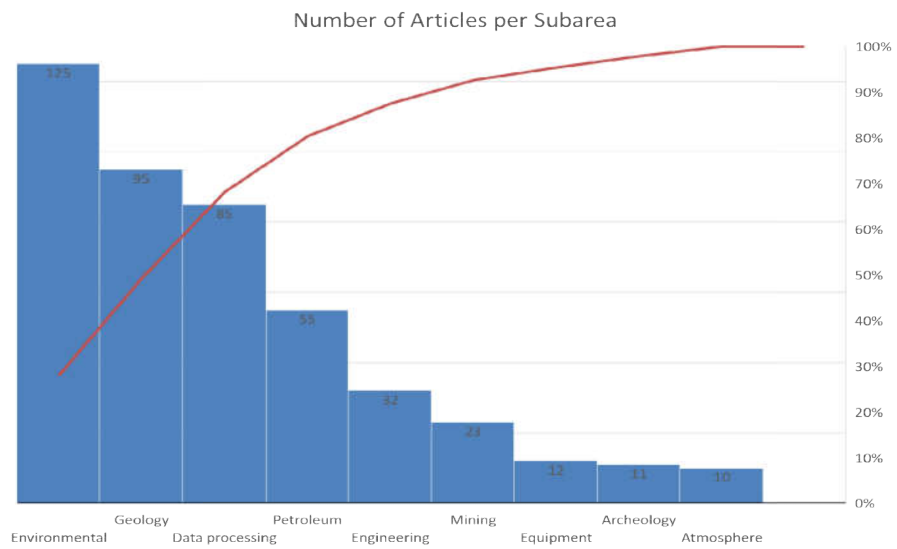


**Fig. 2. Histogram and Pareto Diagram of Subareas.**

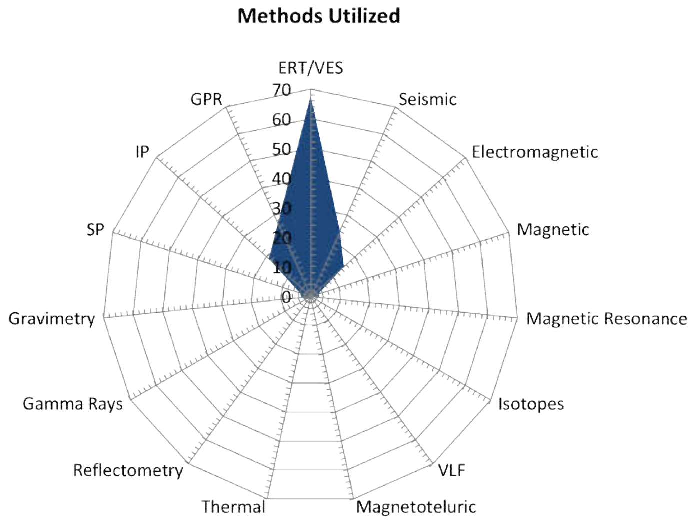


**Fig. 3. Methods most used in geophysical application for environmental studies and their quantities**

**Table 8. Applicability of magnetometry in environmental studies**

| Utilization | First option | Second option |
|---|---|---|
| Fault and fracture identification | | X |
| Underground utilities and interference | | X |
| Drums, tanks and metallic objects | X | |

In the method of Gravimetry, if using the technique of Microgravimetry one has a great sensitivity to vibrations. In addition, the equipment must be perfectly level and with correct altimetry. As for its applications, we can see in Table 9 in which situations this method is indicated (Abdullah *et al.*, 2019; Golebiowski *et al.*, 2016; Mousavi and Ardestani, 2016).

**Table 9. Applicability of Microgravimetry in Environmental Studies**

| Utilization | First option | Second option |
|---|---|---|
| Cavity detection | X | |
| Ditch, Dumping ground and landfill boundaries | | X |
| Drums, tanks and other non-metallic objects | | X |

In addition to these methods, there are still several methods of well geophysics. No details will be given about these in this specific article, as they are not used for environmental applications, which is the main object of this review. With these tables of use and description of the main limitations of each of the geophysical methods most used in environmental issues, we sought to give an overview of their applicability in this area of study.

## RESULTS AND DISCUSSION

Firstly, it is worth highlighting the importance given to the environmental issue in thegeophysical journals analyzed in this study.This relevance becomes evident by analyzing the Histogram and Pareto Diagram of Fig. 2. In this studythe area with the highest number of publications was the environmental area. This type of diagram is ideal to evaluate which items in a given data set have the greatest importance, or which isolated set of items already has a percentage representativeness which if desired to evaluate (Bussab and Morettin, 2012). For the rest of the analyses of this work, which are below, we will take as cut only the 125 articles of the environmental sub-area.

Thus, and evaluating the division of these publications by geophysical method used, we have the result seen in the graphic in Fig. 3, which presents the totality of different types of geophysical methods and techniques that were used, and the amount of times each was applied. Figure 3 presents the large number of different methods that have been applied to environmental studies, a total of 15, thus demonstrating the great possibility of using geophysical tools to help environmental professionals to solve the true mysteries that are frequent in such interdisciplinary work as the environment, mainly in the case of contaminated areas. It can be verified that the Resistivity Meteris the most used geophysical method, more specifically the Electrical Resistivity Tomography(ERT) and the Vertical Electric Soundings (VES´s). Although the techniques of Induced Polarization (IP) and Spontaneous Potential (SP) are part of the geoelectric methods, in this work, as well as in the Brazilian standard, separate the geoelectric methods in their three macro techniques, are: Resistivity Meter, which combines ERT/VES´s; Induced Polarization and Spontaneous Potential, due to its major differences as seen earlier in the literature review on the applicability of Geophysical Methods and also in order to clarify which techniques, specific, what else are being used, enabling greater detail and wealth of information. It is also observed that only the three most used methods account for almost 70% of the cases. And taking the five (5) most used methods among the total of 15 methods and techniques found in the articles, these alone represent 89% of the cases. Thus, demonstrating the great importance of these five methods for environmental studies today. It is worth noting that Resistivity Meter (ERT/VES) is normally used as a complementary methodology to the other methods, which consequently increases its evident prominence. It is important to remember that Geophysics uses indirect methods of investigation of the subsoil, which means there are no measurements collected directly on the object to be studied or detected, but indirect measures made through the equipment that measure the variations in the physical properties of the soil. Due to geophysical ambiguity, which is inherent to these studies as well as to any other using indirect assessment methods and also the great complexity normally involved in underground environmental problems, at least two geophysical methods should always be used(Marans and Ahrentzen, 1987).

In the graphic of Fig. 4 we can analyze exactly the integration of geophysical methods in the same work, which are also separated by periodical.

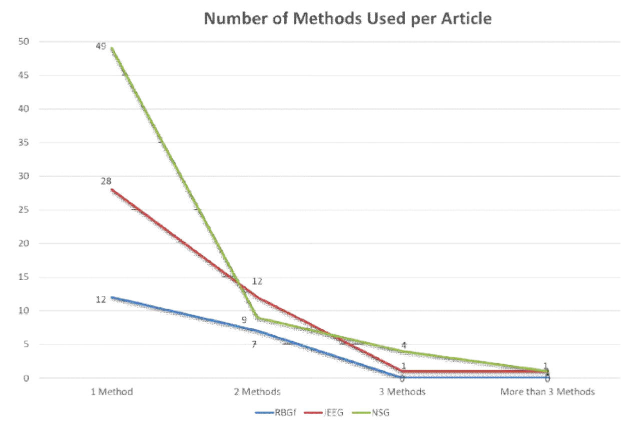


**Fig. 4. Number of geophysical methods used per article**

In Fig. 4 we can verify that unfortunately in 75% of the cases only a single geophysical method is being used in scientific research, and in 95% of the cases only 1 or 2 methods. This implies a possible lack of data and an enormous difficulty in dealing with the aforementioned geophysical ambiguity, thus complicating a correct interpretation and increasing the time to reach a conclusion. Remembering that the geophysical ambiguity is inherent to any inverse problem because they do not have uniqueness of answer as the direct problems. When analyzing the division of articles by purpose of the survey and place of application of the methods, it is noted that most environmental work has taken place with the aim of studying soil and water contamination and for studies of groundwater for exploratory purposes and characterization of aquifers (Figure 5). In Fig. 5 we can see in the Pareto Diagram that there is a great concentration in the two main objectives, ontamination/Waste and Groundwater, and only these two add up 2/3 of the articles.

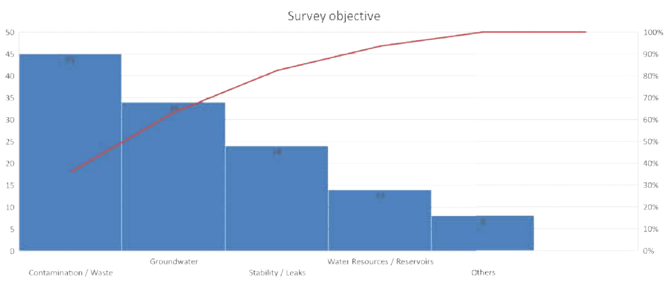


**Fig. 5 - Histogram and Pareto Diagram with Survey Objectives**

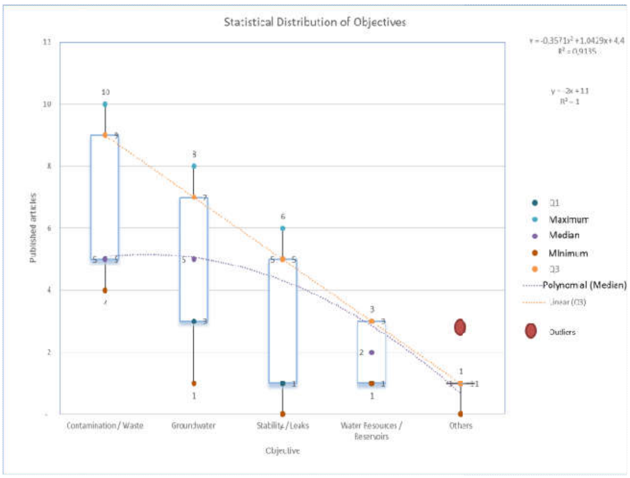


**Fig. 6 - Boxplot diagram of the objective by semester**

In the BoxplotDiagram from Figure 6, we can verify the main statistical information on how the variable number of publications per semester per survey objective is being distributed over time (McGill *et al*., 1978). In this, we can see the asymmetry of the contamination/residues and stability/leakage objectives, as well as the amplitude of each objective to which the variability and standard deviation of the sample are directly and proportionally linked. On the other hand, the Water Resources and the Others objectives show the high predictability of these two data sets. And in the graphic of Fig. 7 it is verified how the division of the articles in the main sites of survey, being evident that the vast majority of the works are linked to aquifers, followed by contaminated areas and works in open field area (Rural)as in Aquatic locations (Dams, Rivers, Sea).

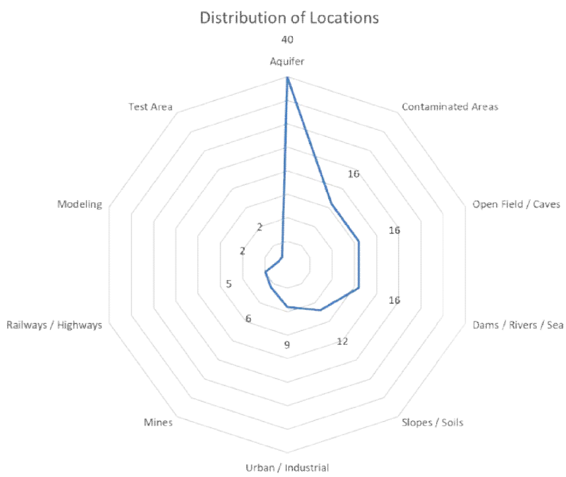


**Fig. 7. Division of articles by Place of survey**

This global importance for aquifers is because it is increasingly seeking to explore the underground water, and for this it is necessary a correct detection of these and their characterization and delimitation. With the decreasing availability of fresh water for consumption, it is inevitable that more and more people will seek to exploit these reserves of major importance for both human consumption, animal desendentation, but also for agriculture and industry.

Great importance has also been attached to contaminated areas because of their consequent impact on public health, as contaminants severely damage the soil and especially groundwater, which as mentioned above is already being so strongly requested in the present day. Due to the enormous financial, environmental and even the great loss of human life, studies of reservoirs/dams and areas at geological risk such as slopes and slopes have become increasingly important, because the destabilization of these areas can provoke enormous tragedies. And geophysics can be a huge help in detecting and monitoring risk areas them in order to prevent or at least mitigate the occurrence of accidents.

## Conclusions

In this article we have some important conclusions, such as the verification of the large numberof geophysical methodologies (16 methods) currently being applied to the environmental area and the great variability of help that these methods can provide. Additionally, the study noted that the existing tools in geophysics is of paramount importance to help environmental professionals to solve their "Mysteries" in environmental issues and problems. With regard to the most used methods in environmental articles, it is evident that Resistivity Meter with ERT/VES´s s is the most used with 39% of publications, that is, more than twice as many articles in relation to the GPR that appears in second place (16%). It is also noteworthy that these two methods plus Seismic (14%) represent almost 70% of the publications. In addition, there aremany different methods used in environmental work, fifteen (15) in total. It is worth mentioning the little integration of geophysical methods in environmental studies, and only 25% of the studies used more than one (1) method and only 5% used more than two (2) methods.

This can hinder a correct final interpretation of the results, or at least delay the solution of it. Another relevant fact is the verification that the need to exploit groundwater, the concern with the contamination of the subsoil and groundwater, together with the mapping and monitoring of areas of environmental risks, such as slopes and dams, are the topics that are in evidence in the current publications of application of geophysical methods in the environmental area, being the aquifers and contaminated areas the most studied actually. Finally we can conclude that ... Yes! Geophysics can and is helping environmental investigations a lot. Today in the labor market we find at least sixteen (16) geophysical methods available and being used for this purpose, and these technologies are always used in order to gain information quality. It is possible to combine gains in surveys scope of coverage, less time and cost in the acquisition, treatment and preparation of conclusive reports, which provide very relevant subsidies to the professionals who are managing environmental investigations. This great relevance is verified, seeing these methods being widely used in studies of contaminated areas, either for detection, evolutionary analysis and characterization of contaminant plumes; location of objects such as tanks, drums and pits with waste; characterization of aquifers and saturated areas; mapping of fracture zones and other geological features for the purpose of exploring groundwater and contaminant flow; geological characterization with a view to landslides, studies on slopes, embankments and underwater environments; mapping of leakage and fragility zones in reservoirs, whether of water or with mining waste, among other various possible applications.

**Declaration of competing interest:** The authors declare that they have no known competingfinancialinterests or personal relationships that could haveappeared to influencethe work reported in this paper.

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