A pilot Critical Zone Observatory in an urban setting

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Abstract

The critical zone (CZ) is the heterogeneous surface and shallow subsurface environment, in which energy and mass flows regulate life-sustaining resources, being of great relevance to ecosystem services and socioeconomic activities. Studying the CZ requires a multidisciplinary approach in instrumented locations to quantify interaction mechanisms and trends on its dynamics, at variable temporal and spatial scales. The objective of this work is to present the preliminary results that support the implementation of a pilot Observatory of Critical Zone at EACH-USP, located in the city of São Paulo, an urban environment in a subtropical climate. In this work we show the first geophysical results from this multidisciplinary pilot project.

Introduction

The critical zone (CZ) is the region of the earth's surface that extends from the top of vegetation to the groundwater zone (NRC, 2001). It is a heterogeneous environment in which energy and mass flows reflect the coupling between physical, chemical and biological processes (Anderson et al., 2007), regulating the resources for sustaining life. The term "critical" indicates its relevance to ecosystem services and socioeconomic activities (Banwart et al., 2016; Guo & Lin, 2016).

Studying CZ requires a multidisciplinary approach in instrumented locations and with the ability to operate long enough to quantify interaction mechanisms at varying temporal and spatial scales (Brantley et al., 2016). As shown by figure 1, this integrated study of the critical zone relies on the collaboration of different scientific communities, from hydrogeology, geochemistry, geophysics, to microbiology, ecology and meteorology.

Critical zone observatories (CZO) are connected sites or site collections with no minimum size, defined only by fundamental or locally relevant issues that drive their establishment (Brantley et al., 2017). In addition, these sites serve as information centers for resource management and public education on relevant socio-environmental issues. Currently, the main efforts to develop a network of observatories are mainly focused on the USA, Europe, China and Australia. On the other hand, in South America, this type of multidisciplinary research infrastructure is still scarce.

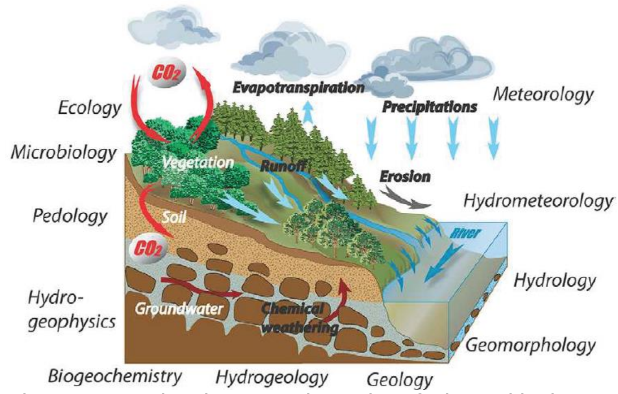

Figure 1 - The integrated study of the critical zone (Gaillardet et al., 2018).

Megacities, such as São Paulo, present numerous socio-environmental problems arising from the patterns of development and transformation of space (Nobre & Young, 2011). Establishing methodologies that allow monitoring contaminated areas has been a growing demand to understand the environmental impacts and evolution of mitigation and/or environmental restoration processes.

Due to the heterogeneity of the critical zone, direct measurements and sampling may not be sufficient to test broader hypotheses. Identification and quantification of CZ processes require the integration of techniques that interpolate and extrapolate information beyond drilling holes (Riebe et al., 2017). Geophysical methods are less invasive, repeatable (time lapse) and have greater spatial coverage and lower cost in comparison with direct measurements (Parsekian et al., 2015). However, when individually used, they can lead to misinterpretations due to the ambiguities associated with indirect methods (Jougnot, 2020).

The objective of this work is to present the preliminary results that support the implementation of a pilot Observatory of Critical Zone at the School of Arts, Sciences and Humanities of the University of São Paulo, east campus (EACH-USP). This sustainable research structure will allow geophysical monitoring to be integrated with hydrogeological and biogeochemical measurements to understand the impacts of seasonal processes in the critical zone, such as droughts and rains, in a contaminated urban environment, in a subtropical climate.

In our proposal, the subsurface environment will be monitored by geophysical methods and analysis of groundwater, soil and associated organic matter, biogenic gases, and microbial content. We will focus on the iron biogeochemical cycle and its links to Earth's climate, soil and water resources. Iron transformations by soil biota have important implications on the carbon and nitrogen cycles. These reactions are governed by soil redox conditions, which are affected by droughts/flooding periods, organic matter content and other environmental perturbations.

Our multidisciplinary approach will enable a better understanding of the feedbacks between biotic/abiotic processes and redox changes in organic-rich sediments. Inspired by existing CZOs networks, we will drive cross-disciplinary understanding of anthropogenic impacts on the CZ. CZOs provide stable research infrastructure for long-term monitoring, and testing of new techniques and instruments, and provide a series of data to feed numerical models and test their predictions. Ultimately, CZOs foster new hypotheses that can only result from systematic and multidisciplinary observations

Methods

EACH-USP (figure 2) has a complex history of contamination by different land uses, such as agriculture, sanitary landfill and sediment deposit area taken from the Tietê river channel (Mendonça et al., 2015a). The campus is also next to the Tietê Ecological Park, an important leisure center in the east of São Paulo.

Figure 2 – Study area localization.

The study is being developed with the approach combination of geophysical methods, meteorological, geochemical and microbial activity parameters, linked to Living Lab EACH (environmental project established in the area). The Living Lab EACH project aims at reducing, mitigating and sequestering greenhouse gasses from wastes and restoring ecosystem services on campus, and will be incorporated into the geophysics analyses.

Geophysical Imaging: The CZO will have an extensive geophysical database, allowing regolith thickness and lithology limits mapping, as well as hydrogeophysical characterization (e.g., porosity, permeability, formation fluid). Several geophysical methods are established for application in this CZO: Electrical Resistivity (ER), Induced Polarization (IP), Electromagnetic Induction (EMI), Ground Penetrating Radar (GPR) and Seismic.

Environmental Magnetism: In the context of environmental magnetism, we also highlight the techniques for measuring the magnetization of acquisition and hysteresis curves, as well as magnetic susceptibility at varying alternating frequencies and temperatures.

Geophysical monitoring: periodic repetition of certain techniques used in the characterization and initial imaging. The database thus obtained will allow the elaborate models of predictability of CZ processes.

Monitoring of biogases and magnetic properties of soils: microbial processes involve gases such as carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and volatile organic compounds (VOCs), which are fundamental for the role of soils in carbon sequestration, nutrient use efficiency and greenhouse gas emissions.

Hydrogeological monitoring: evaluation of variations in water resources in terms of flow and water quality. At this stage, sensors should be equipped in the installed wells and piezometers (water level, specific conductivity), multi-level TDR monitoring and chemical analysis of groundwater.

Meteorological monitoring: evaluation of the hydrometeorological variations, essential for the study of interactions between the atmosphere, vegetation and soils.

CZO Database: The project will allow the construction of an extensive database of various disciplines, which will be continuously fed. The data generated will be organized by the different disciplines included in this pilot stage in addition to the data obtained in conjunction with the Living Lab project. Moreover, the availability of data generated in a virtual environment allows researchers from different areas to integrate with OZC, which will allow the integration of OZC into the network of global observatories, which investigates the resilience to anthropogenic impacts.

Results

The geophysical methods being used in the CZO EACH/USP pilot are the Electrical Resistivity (ER) and Induced Polarization (IP) methods in the time domain along profiles with dipole-dipole arrangement. The equipment employed were the Syscal (IRIS Instruments), programmed for 2s of current injection time and 180 ms of delay-time, a 12 V battery, and stainless steel electrodes with a 5 meter spacing.

Both ER and IP are parameters sensitive to porosity, moisture, salinity, mineralogy, clay content and temperature (Parsekian et al., 2015), but IP, specially at lower frequencies (<100Hz), is also sensitive to variations in grain's textural and structural properties and alterations in the grain-fluid interface (Blondel et al., 2014). These data will guide the location of monitoring wells for soil and water sampling for biogeochemical analysis and application of environmental magnetism techniques.

The first line of geophysical acquisition (figure 3) was chosen due to its importance in the study of local flora development and assimilation of heavy metals, currently underway through the Living Lab EACH project. In addition, traps were also installed at the site for the quantification of stingless bees that work as environmental bioindicators. The Living Lab is a sustainability project aimed at reducing waste, mitigating and sequestering greenhouse gases, restoring ecosystem services on campus. The parameters obtained through this project will also be integrated into geophysical analyses, posteriorly.

Figure 3 – Google map with monitoring line localization (red) on the EACH.

The ER and IP acquisitions were carried out in November 2021 (figures 4a and 5a) and May 2022 (figures 4b and 5b). The sections were generated from the inversion of data acquired in the field, in the RES2DINV software (Iris-instruments) and the color scale was defined considering the maximum and minimum values of resistivity and chargeability for both periods.

In the resistivity profiles (figures 4a,b) the highest values are around 600 ohm.m. In both periods, the sections show a well-marked horizontal contrast of resistivity from 2.0 to 4.0 meters deep. However, from 6.0 meters onwards, two anomalies were identified with resistivity varying concentrically from 72.4 to 207.0 ohm.m. These anomalies at position 45.0 and 75.0 meters are more evident in the May section (figure 4b), while in the November section (figure 4a), resistivity values above 72.4 ohm.m are not very expressive, for the same depth.

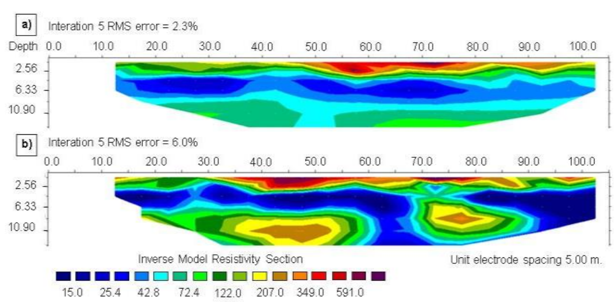

Figure 4 – Resistivity section obtained in (a) November 2021 and (b) May 2022.

The chargeability profiles also show significant anomalies with values greater than 63.40 mV/V above 6 meters of depth, mainly in the May section (figure 5b). However, the portion between 2.0 and 4.0 meters of the profile is more homogeneous in both periods, presenting values below 5.37 mV/V, however, showing a more defined horizontal chargeability contrast in the May section.

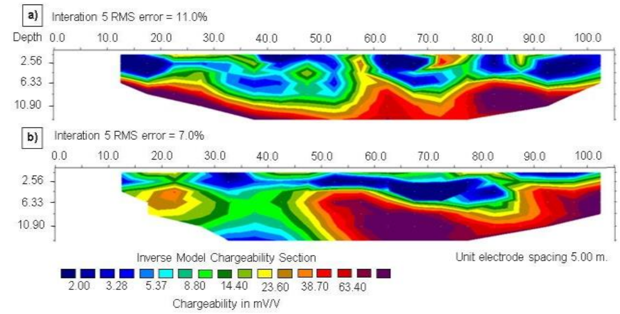

Figure 5 – Chargeability section obtained in (a) November 2021 and (b) May 2022.

Pluviometric data for the region (figure 6), obtained from the CEMADEN website, show a decrease in precipitation values from the month before the geophysical acquisition of May, compared to the month before the acquisition of November. This may have evidenced the anomalies (figures 4b and 5b), which were previously not very expressive (figures 4a and 5a), due to a possible increase in water saturation in the soil. This is considered because, even knowing that the water table is close to 2.0 meters deep and the piezometric surface is relatively flat (Mendonça et al., 2015a), there are considerable ER and IP lateral variations for a place with little heterogeneous geology laterally.

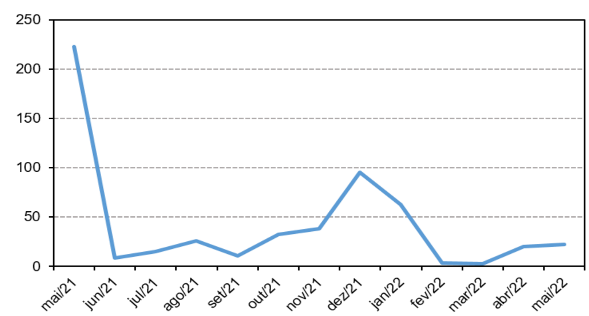

Figure 6 – Precipitation graph from May 2021 to May 2022, at Estação Cangaíba, close to the study area.

Discussions and conclusions

The resistivity and chargeability sections of this work were compared with those obtained by Mendonça et al. (2015a; 2015b). The authors conducted a resistivity study to delineate the distribution of subsurface methane gas at EACH using direct sampling from multilevel monitoring wells and geophysical electrical resistivity tomography data.

The vertical resistivity contrast around 4.0 meters deep, in both sections, is compatible with the contact between anthropogenic deposits (dredged sediments) and quaternary organic sediments (floodplain). The latter are found up to approximately 10 meters deep, with resistivity values below 25 ohm.m predominating. Intermediate resistivity values between 80 and 110 ohm.m were associated with accumulations of methane gas in sandstone or fractured clay lenses. However, here higher values were observed for this anomaly, from 72.4 to 207.0 ohm.m.

Seasonal variations in the ER and IP data were not that expressive in the work by Mendonça et al. (2015b), contrary to what was observed in the present study, mainly in the subsurface. One of the reasons could be the acquisition period. In their case, it was in 2012 (March, May and July) and 2013 (April and June).

Although the resistivity data correspond to those acquired by Mendonça et al. (2015a; b), the same is not valid for chargeability data. In addition, even though it is a close area, as it is a place with a complex history of land use, it is necessary to apply other techniques of direct and indirect analysis, as well as seasonal monitoring, to verify the lateral continuity of what was observed by Mendonça et al. (2015a; b) and study subsurface fluid dynamics.

Both the ER and IP stretches present two significant anomalies, at depth, around 45 and 75 meters, being potential areas for installation of monitoring wells and water and soil sampling for biogeochemical analyses. The installation of the monitoring wells is scheduled for next year.

When evaluating the study area from the perspective of the CZ, we established a resilient research system, which allows us to understand the environment disturbances with or without significant changes in ecosystem services. It is expected, thus, to promote the elaboration of holistic conceptual models of evolution of the critical zone for the area of study, integrating hydrological, geochemical, geomorphic and biological processes, ecosystem services, etc., considering spatial and temporal scales, and provide parameters to predict changes in CZ in response to global or local forces.

Acknowledgements

The authors acknowledge to Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) process 2021/14808-6 and Living Lab EACH Project.

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