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Sustainable approaches for brownfield revitalisation & rehabilitation: a case in São Paulo

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There is a necessity for sustainable solutions to meet the increasing demand for land in urban development. In this context, brownfields are known to be a viable alternative if characterized and remediated correctly. This study demonstrates the use of two methodologies, TRIAD, and high-resolution site characterization to assess the viability of rehabilitation of the site for new development. Given the conceptual uncertainties, a High-Resolution Site Characterization with the TRIAD approach was conducted to measure the environmental impact and update the conceptual site model of the studied area. The investigation plans were dynamically built with the use of real-time measurement tools. It was possible to measure the spatial distribution and the mass of contaminants still present in the area. Moreover, a more robust conceptual site model was developed to serve as the base for the remediation and rehabilitation strategies. The approach brought measurable financial benefits, an increase in 35% value of the property, as well as the permission to rebuild the area. The study highlights the significance of comprehensive investigations in the effective rehabilitation of impacted areas, while meeting the demands for sustainable urban development by providing a faster and more reliable field investigative campaign, with reduced levels of uncertainty.

Keywords: groundwater/site investigation/sustainable development

1. Introduction

The tools for the management of contaminated sites have evolved throughout the years with the creation and broader adoption of more technological approaches, such as geophysical and direct-push methods (Christy, 1996; McCall *et al*., 2014; McCall *et al*., 2018; Mumford *et al*., 2022; Schulmeister *et al*., 2003; Suthersan *et al*., 2015). Nowadays, the industry has sufficient technology and technical capabilities to properly assess a given site and manage the underlying uncertainty about the environmental impact (ITRC, 2019). For example, as pointed out by the World Health Organization (WHO) in its recent report on the urban redevelopment of contaminated sites, the remediation and revitalisation process of many contaminated sites across Europe were delayed and raised managerial and organisational challenges due to the appearance of unexpected contamination (WHO, 2021). Furthermore, other cases are being revaluated in the USA and Brazil, given the new available technologies and the increasing worry about reducing site uncertainties (Evald, 2018; US EPA, 2016, 2021). In the European context, there are multiple sources for technical support and knowledge, such as the Cabernet Network and the Holistic Management of Brownfield Regeneration. Such projects aim to assess brownfields and provide new insights into the management of these areas.

According to the Revision of World Urbanization Prospects published by the United Nations (UN) in 2018, 55% of the world's population lives in urban centres, and a projected 68% could inhabit these regions by 2050 (UN, 2019). However, urban growth carries an impact on the environment to such an extent that almost all Sustainable Development Goals set by the UN are relatable to the global trend of urban expansion – for example, decent work and economic growth, industry, innovation and infrastructure, sustainable cities and communities, climate action, and life on land (UN, 2014). Thus, with this constant, inevitable urban growth, governments, and the industry have to look for alternatives to support and enable the adoption of feasible and sustainable solutions for the increasing expansion of urban areas without damaging the environment.

The number of sites that can be reutilised, such as in new property developments or even for residential purposes, shows the potential of these areas as a main supply for new urban development. It has been tried out in many areas, however, with limited success. This limited success is mainly due to uncertainties related to possible impacts on human health risks, and it presents challenges for organisations, legal representatives, and technical authorities (Iannone, 1995; Malta-Oliveira *et al*., 2020a; WHO, 2021).

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Challenges posed by the heterogeneity and singularity of sites are pointed out by some studies, as well as the importance of a robust, dynamic approach to site characterisation as the first step in any remediation and redevelopment activity (Brewer *et al*., 2017a; Hadley and Bruce, 2014; Malta-Oliveira *et al*., 2020b; Suthersan *et al*., 2015; WHO, 2021).

The process to investigate contaminated sites is clear and presents specific definitions for each stage and minimum requirements (ASTM, 2020, 2021; CETESB, 2017). However, even by completing the minimum tasks presented by regulations, some contaminated sites are investigated solely with monitoring wells (MWs), a few soil samples, and multiple field campaigns (Brewer *et al*., 2017a; Malta-Oliveira *et al*., 2020b; Suthersan *et al*., 2015), which delays recovery plans and remediation efforts (Malta-Oliveira *et al*., 2020a, 2020b; Suthersan *et al*., 2015; WHO, 2021). This approach usually fails to correctly identify and measure the different phases of contamination and their correct masses. It requires multiple campaigns, is based on point samples, and assumes that the medium is homogeneous and sample points and concentrations are linearly correlated (Brewer *et al*., 2017a; Hadley and Sedman, 1992; Malta-Oliveira *et al*., 2020b; Suthersan *et al*., 2015).

Various studies describe the main challenges in investigating contaminated areas (Brewer *et al*., 2017a, 2017b; Guilbeault *et al*., 2005; Hadley and Sedman, 1992; McCall *et al*., 2014, 2017; Parker *et al*., 2008; Schulmeister *et al*., 2003; Suthersan *et al*., 2015). The common factors that present challenges are the medium's heterogeneity (Brewer *et al*., 2017b; Hadley and Sedman, 1992; Schulmeister *et al*., 2003) and the irregular distribution of contaminants underground, given the medium's complexity (McCall *et al*., 2014; Malta-Oliveira *et al*., 2020b; Suthersan *et al*., 2015). These challenges require a higher level of detail to obtain a more robust conceptual site model (CSM).

A recent review study analysing 25 restoration studies points out that in most situations, the remediation and rehabilitation goals were not met due to the appearance of unexpected contamination in the closing stages of management (WHO, 2021). As noted by Guilbeault *et al*. (2005), in some cases, the mass of contamination is not fully measured or understood. By correlating these findings with other studies presented in this paper, it is possible to point out that the unexpected contamination mentioned by WHO (2021) can be a substance of interest in a given site that was not fully mapped or understood and not truly unexpected as mentioned in the paper.

One possible way to decrease uncertainty and obtain representative data from a site is to use dynamic, high-resolution, and real-time methods, such as geophysical surveys (electrical methods or magnetic methods), as well as direct push technologies, such as the Ultra Violet Optical Screening Tool (UVOST) and membrane Interface Probe (MIP), for example.

By combining the TRIAD method and the high-resolution site characterisation (HRSC) approach, a robust CSM can be dynamically built from the first day of fieldwork until completion, reducing uncertainty to an acceptable level. Thus, the true power of this combination is the ability to properly identify and characterise important zones in a given area.

However, the adoption of the suggested methodologies would enable an adaptive work strategy with real-time analysis of data, facilitating the better identification of these areas. By positioning variable investigative points, knowledge around specific areas of interest can be improved. Implementing an irregularly laid grid ensures that the appropriate effort and resources are allocated to areas requiring a clearer understanding of the position of contamination and its phases (ITRC, 2019; Malta-Oliveira *et al*., 2020b; Suthersan *et al*., 2015; US EPA, 2016).

This approach can be conducted in a qualitative (semi-quantitative) or quantitative manner. Real-time screening tools, such as the MIP system, which analyses vapour from the soil (Christy, 1998; McCall *et al*., 2014), optical image profiler (OIP) (McCall *et al*., 2018), and UVOST (Streitz and Johnson, 2005), which focuses on the detection of light non-aqueous phase liquid (LNAPL), enable dynamic and rapid data collection, covering a larger spatial area within a shorter fieldwork period (ITRC, 2019; Malta-Oliveira *et al*., 2020b; Suthersan *et al*., 2015; US EPA, 2016).

For a quantitative assessment of the contamination level of a site, a common procedure involves collecting a large number of samples to be analysed in a certified laboratory for proper characterisation of contamination and its sources (Brewer *et al*., 2017a, 2017b; Hadley and Sedman, 1992; Suthersan *et al*., 2016). However, studies point out that the number of samples needed to properly quantify and assess a source area is high and could make projects unviable. In such cases, the use of a mobile laboratory is recommended to control costs (Brewer *et al*., 2017a, 2017b; Suthersan *et al*., 2016). Usually, a portable photoionisation detector (PID) is generally used, in first approach of the area, for screening volatile organic compounds (VOCs). This tool is able to read VOCs concentrations' range in hundreds of soil samples per day and eventually could help to support the decision of sampling strategies when used according to method 3815 of US EPA (US EPA, 2007).

However, according to Costanza *et al*. (2000) and Hewitt and Lukash (1997), there are some limitations to only using the portable PID to investigate a site, as it is highly susceptible to interferences from soil water content and differences in lithology, for example. Therefore, it is not the most efficient option to select the samples' location and should be used as a tool to determine the preservation method of the custody chain to be employed as indicated in the method 3815 (US EPA, 2007).

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As portable PID do not assure reproducible VOCs' reading results due to the high water and clay content of the materials and the high cost of obtaining and properly conditioning thousands of samples required to characterise a potentially contaminated area, other options are needed. Therefore, the use of more recent field screening tools, such as MIP, OIP, and UVOST with continuous analysis and results recording almost instantaneously, has emerged as an option for reducing measurement uncertainty by producing a continuous record in a log.

Currently, state-of-the-art site management relies on robust investigation campaigns to provide tailored and individual approaches for each site (ITRC, 2003; McCall *et al*., 2014; Suthersan *et al*., 2015). Moreover, the complexity of the subsurface and the fate and transport of contaminants significantly increase uncertainties and can lead to inefficient site remediation and restoration.

This paper showcases the use of the TRIAD approach combined with HRSC methodologies, applied in a real case of a brownfield that is being revitalised to serve as a residential area in the state of São Paulo, Brazil. At this site, various remediation techniques were not completely effective due to the uncertainties in the CSM, which caused the reappearance of contamination in areas that were previously considered cleaned, and the site was never used.

The aim of this paper is not to compare the current state-of-the-art technology that is available today with the management strategies used at the specific site studied since 2001. Rather, the aim is to showcase that there is a change in management strategies, from the traditional investigation approach to HRSC currently available. Thus, showcasing that traditional investigation approaches, for example, solely relying on MW and soil samples, might not be enough to ensure the effective remediation and restoration of a given site.

2. Site background and management decisions

The site under study was a fuel storage and distribution base that has been subject to investigation since the early 2000s. The area consisted of storage tanks, containing gasoline, diesel, and anhydrous ethanol.

Investigation campaigns were initiated in 2001 and continued until 2016, employing conventional methods, such as soil sampling, occasionally collected manually, and the installation of MW. Figure 1 illustrates the site layout, indicating the presence of the free phase plume and the dissolved benzene plume at the commencement of the new approach.

Based on the available data, the treatment method primarily employed pump and treat strategies, implemented at various locations across the site, as the dissolved plume and LNAPL plume changed over time. However, despite 15 years of remediation efforts, the dissolved plume continued to occupy the same area, even though there was a reduction in the LNAPL plume that was recovered from more permeable layers.

The remediation activities carried out from 2001 to 2016 achieved partial success in containing the migration of the dissolved phase and recovering the mobile fraction of LNAPL at the site. However, the management approach during this period did not sufficiently address the source zones and adsorbed phase, resulting in the persistent size of the dissolved phase plume, potential human health risks, and environmental impacts. Figures 2(a) and 2(b) illustrate the different locations of the known remediation systems. It should be noted that there are more installed pumping wells than documented operational system locations, possibly due to incomplete historical reports regarding the site.

By observing Figures 2(a) and 2(b), it is possible to analyse the shift in positioning in every period. The biggest layout was presented in 2010, having the number of pumping wells decreased in 2011 due to the lack of LNAPL observed in the MW. In 2011, there was also a decrease in reach of the systems, and in 2016 the remediation efforts were focused on the southern zone of the area. However, the LNAPL plume showcased in the figure is from 2016. It is possible to notice that there are LNAPL zones where the previous multi-phase extraction systems were located, displaying that the pump and treat efforts were not fully efficient.

Considering the persistent contamination, an optimisation of the pump and treat methods was implemented in 2016, along with a shift in the management approach of the site through the implementation of HRSC. The HRSC was carried out by application of tools that could gather information on the contaminants and the physical context in which they were occurring, in a centimetric scale using direct sensing tools. This change was first carried out on a pilot scale to assess its effectiveness.

Between 2016 and 2019, the remedial systems remained operational; however, no further investigations were conducted during this period due to site restrictions. Once favourable conditions and the possibility of site reuse emerged, a comprehensive high-resolution campaign was initiated in 2020 to enhance the CSM and develop an improved management strategy for site remediation and restoration. Table 1 summarises the differences in management strategies applied to the site.

3. Material and methods

The CSM of the area had uncertainties regarding the location of the contaminant's centres of mass and the hydrogeological properties that controlled their fate and transport. As the primary sources of contamination were not active in the area, and multiple remediation processes had been applied, the uncertainties of the CSM were due to the heterogeneity of the medium and the distribution of the remaining contaminant mass at the site.

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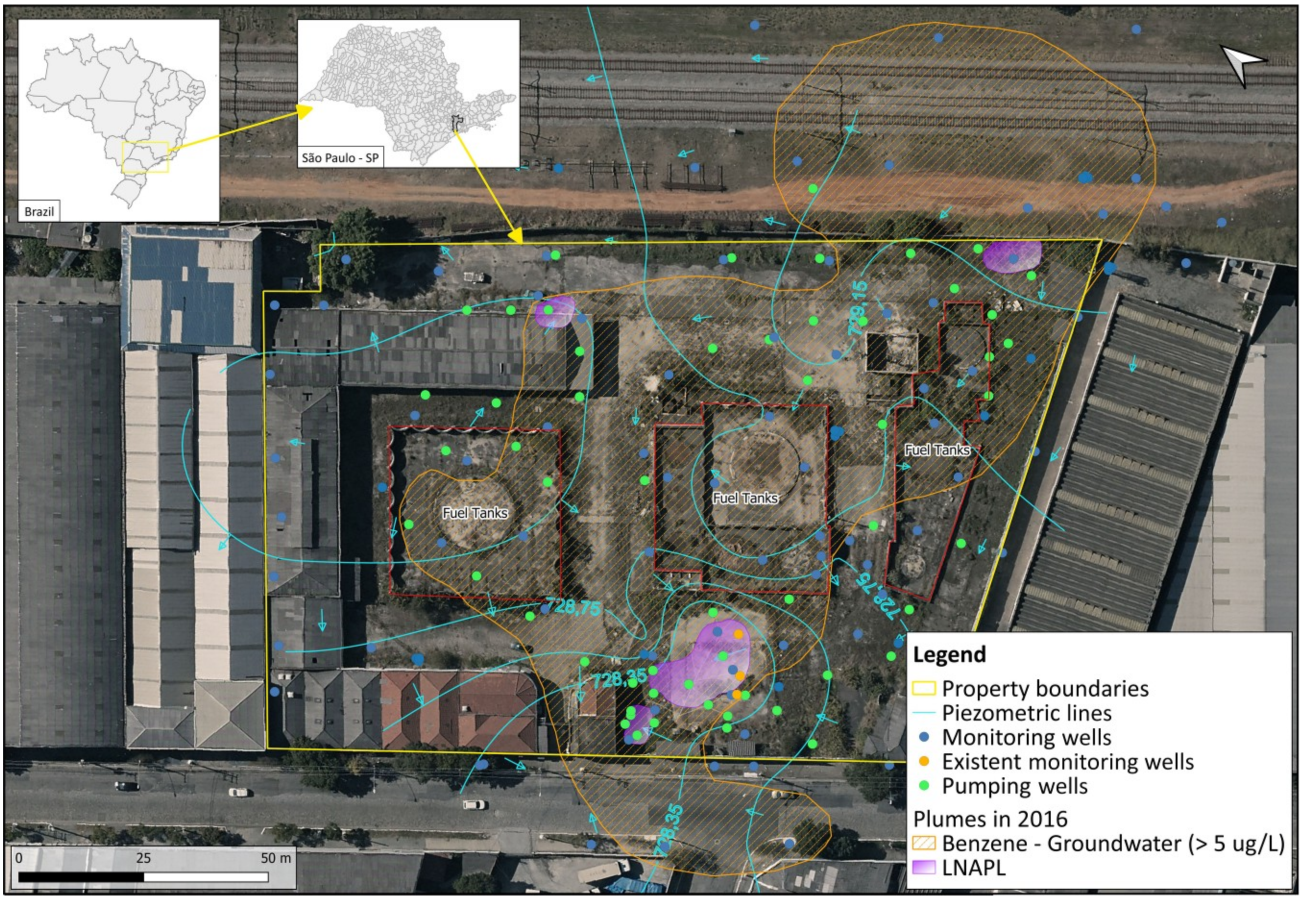

Figure 1. Site location, layout, and the known environmental impact in 2016

The site was a former distribution base for petroleum products with its storage tanks and underground distribution pipes as the main primary source of contamination. Undetected leakages were the main source of infiltration of contaminants in the soil.

The lithology of the area is mostly composed of intercalated beds of alluvial clayey and sandy silts. In this sense, as the visual distinction between clayed and sandy silts is difficult, it was not enough to assess the most permeable layers throughout the site and, therefore, the preferential flow pathways for the distribution and migration of contamination.

Groundwater levels at the site vary around 2.0 m below ground level, ±0.5 m, with the deepest level at 2.7 m in the dry season. The preferential flow direction is quite radial, due to the low hydraulic gradient at the site. However, the regional preferential flow direction is from southwest to northeast, as illustrated in Figure 1, with average hydraulic conductivity at 1.23×10^{-5} cm/s. The groundwater flow rate was previously estimated at 8.5 m/year.

The HRSC and TRIAD approach were applied to develop a more robust CSM. Real-time data acquisition systems were implemented given the nature of the contamination by VOCs and the need to properly characterise the hydraulic properties of the subsurface.

3.1 Data acquisition tools

Three tools were used to characterise the site in high resolution: MIP, OIP, and Hydraulic Profiling Tool (HPT). These tools were selected for their ability to identify and measure hydrocarbons (MIP and OIP) (McCall *et al.*, 2014; McCall *et al.*, 2018) as well as hydrostratigraphic units (McCall, 2011; McCall *et al.*, 2017).

The MIP system utilises a direct push unit to insert a probe into the soil for measuring the presence of VOCs underground (McCall *et al.*, 2014). It heats the soil to a constant temperature of 120°C to volatilise the VOCs present in the subsurface. The volatilised compounds then pass through a semi-permeable membrane and are carried by nitrogen to a gas chromatograph in the field unit above ground (McCall *et al.*, 2014). In cases where the

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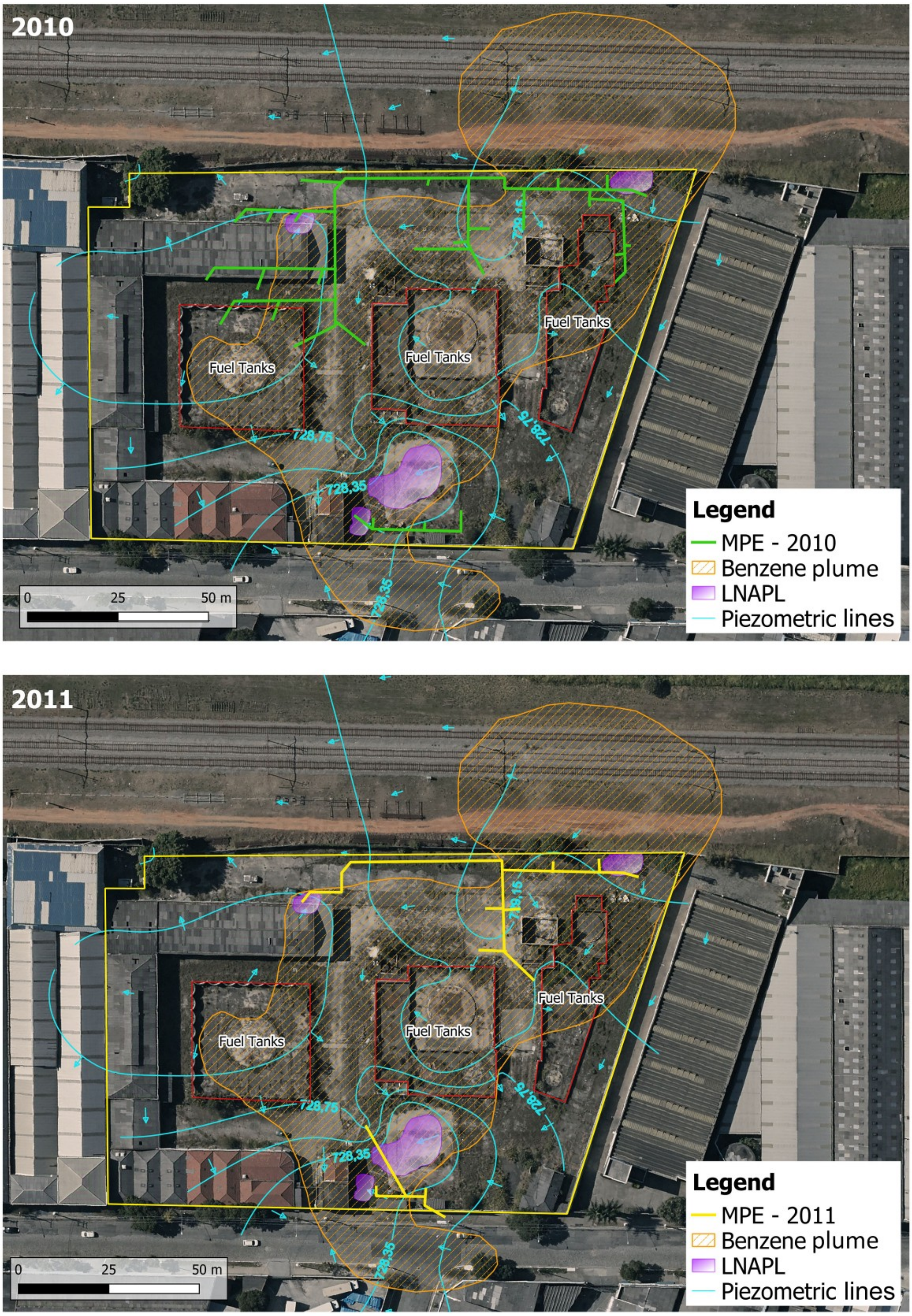

Figure 2. Illustration of the different positions of the pump and treat systems utilised. Data are available from 2010 up to 2016

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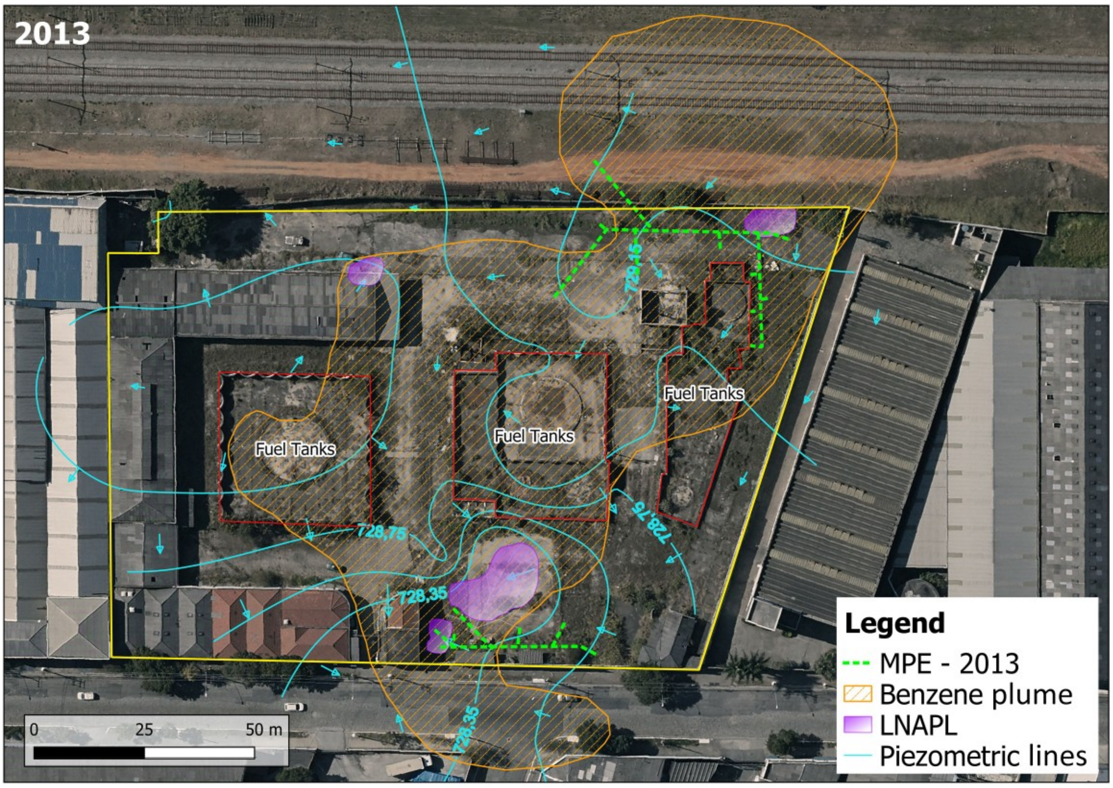

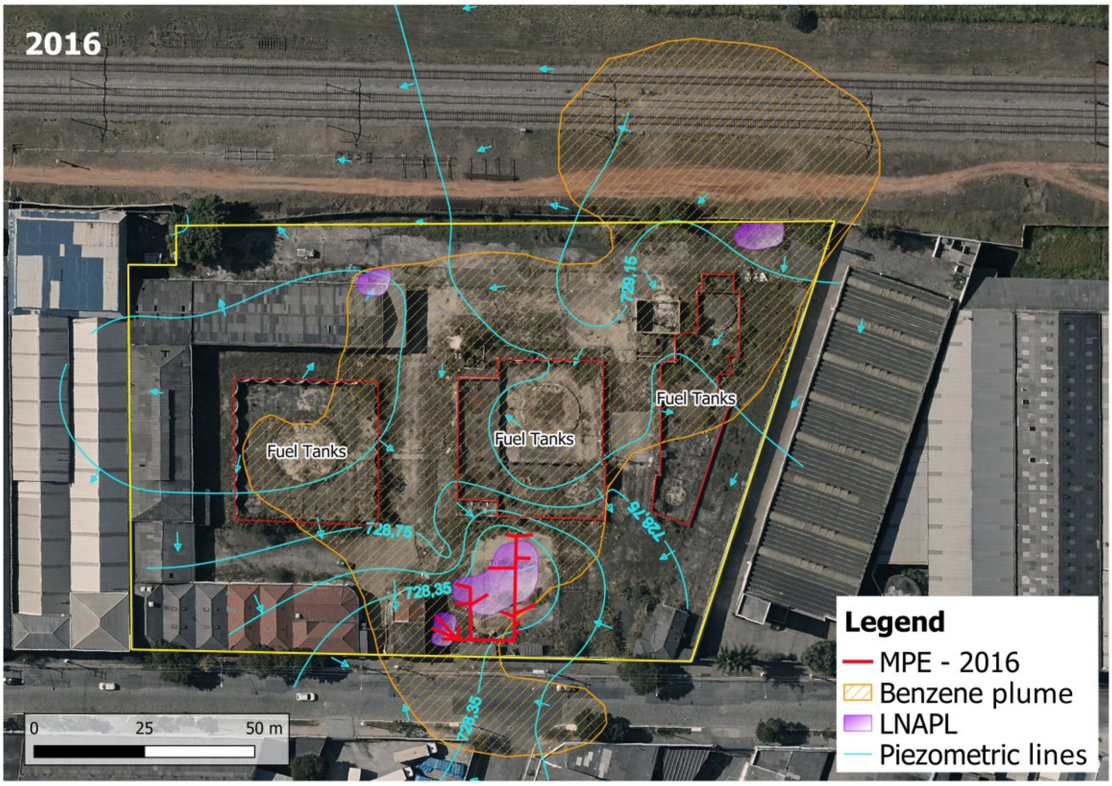

Figure 2. Continued

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Table 1. Summary of management strategies applied to the site since 2011

	2001–2019	2020 onwards
Investigation approach	*Traditional phased approach:* Multiple field campaigns and analysis of laboratory data to define further investigation needs to complete the CSM and define remediation strategies Data density related to the number of samples collected, groundwater samples might be diluted due to the monitoring well placement—not possible to analyse in real time given the wait period for laboratory results to be published Higher uncertainty in the CSM	*HRSC* **+** *TRIAD:* One field campaign for real-time data collection, which allowed the mapping of all contamination phases Subsequent quantification of adsorbed, dissolved, and vapour phases of contamination Data density at the centimetre scale analysed in real time; contaminant mass correctly quantified by guided laboratory samples Creation of a more robust CSM
Remediation approach	Dependent on new field campaigns Focused on LNAPL recovery and removal Did not address mass destruction in source areas Uncertainty about the time frame for completion due to uncertainties on the CSM Contaminant persistence required new investigations campaigns to refine the CSM Mass destruction was less than 10%	Designed after the understanding off all contamination phases described by the more complete CSM Focused on the combination of remedial actions that focused on mass removal and destruction in the source areas Mass destruction higher than 97% Foreseeable finish of the remedial actions and restoration of the site

system's membrane becomes saturated due to the presence of highly concentrated contaminants in the subsurface, additional soil samples were collected to assess their presence.

The OIP system is designed to be used with a direct push penetration method. It utilises an ultraviolet light emitting diode (LED) and a built-in camera to visualise the fluorescence emitted by polyaromatic compounds (McCall *et al*., 2018). The captured fluorescence is then analysed using a pixel-by-pixel filter in the acquisition software, providing a relative indication of the presence of hydrocarbons in the subsurface.

The HPT system is a direct push tool used to characterise the relative permeability of a given unconsolidated formation. It injects water at a constant rate and measures the pressure required to maintain a steady flow (McCall, 2011; McCall *et al*., 2017). In addition, empirical formulas correlating the HPT data to subsurface permeability can be used to estimate the relative permeability (McCall, 2011; McCall *et al*., 2017).

Figure 3 illustrates a log from the main source area, displaying the MIP data with the PID and flame ionisation detector, coupled with the HPT data and electrical conductivity. The figure enables the identification of VOCs in the PID and FID detectors between depths of 2.5 and 3.5 m, where the detection values exceed the baseline.

3.2 HRSC and TRIAD approach

The HRSC methodology aims to reduce uncertainty and accurately assess, both lithology and contaminant distribution (ITRC, 2019; Suthersan *et al*., 2015; US EPA, 2016). However, HRSC does not rely on a single tool or technique; instead, it encourages the combination of multiple approaches to effectively target significant sources and transport zones of contamination in the subsurface. The focus of HRSC is on obtaining the necessary density of data to better characterise the different phases of contamination and their spatial distribution within the lithology.

The TRIAD methodology, introduced by the Interstate Technology and Regulatory Council (ITRC) in the USA in 2003, is based on three fundamental principles: (*a*) systematic project planning, (*b*) dynamic work plans, and (*c*) real-time measurement technologies (ITRC, 2003). These principles emphasise the representativeness of samples, the development of a more robust CSM, and the efficient evaluation of the number of analytical samples required (ITRC, 2003). The TRIAD approach facilitates faster and more reliable decision making by enabling real-time data analysis and involving all stakeholders throughout the process.

The goal of this strategy is to provide site-specific solutions by creating a comprehensive CSM, ensuring technical and legal compliance for all stakeholders involved, including site owners, public institutions, and society during the revitalisation process. Moreover, this approach highlights the sustainability and economic benefits of a thorough characterisation methodology.

In the present study, the OIP and MIP logs were strategically placed in areas with historical evidence of hydrocarbon presence and locations identified as primary sources of contaminants based on the revaluation of the preliminary assessment. In addition, areas with poorly understood contaminant anomalies, such as those with LNAPL and high concentrations of dissolved phase contaminants, were selected.

Following the analysis of data acquired using the MIP and OIP systems, 90 soil samples were collected in key areas to quantify

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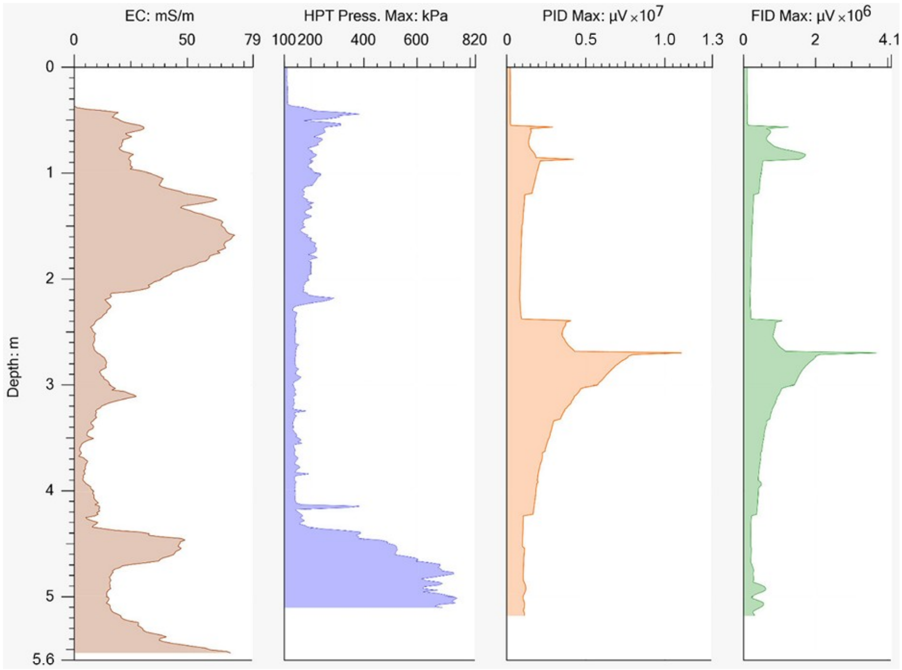

Figure 3. Four visible sensors at display: electrical conductivity (brown), HPT (blue), PID (orange), and FID (green)

the signals identified by both systems. To assess the dissolved phase, 67 water samples were collected from selected MW, and 32 vapour wells were installed in high-priority areas of the site to investigate vapour intrusion. Figure 4 depicts the layout of the logs, groundwater MW, and vapour analysis points.

4. Results

The analysis of data obtained from the MIP and OIP systems facilitated the identification of areas with high concentrations of contaminants in both soil and groundwater. Surprisingly, the contamination levels in the groundwater were found to be up to two orders of magnitude higher than previously estimated. This significant increase in concentration can be attributed to the dissolution of contaminants in other wells, as multiple hydrostratigraphic layers were interconnected by the well screen.

The utilisation of the HPT system played a crucial role in characterising preferential flow paths within the lithology. It successfully identified a 1.5-m-thick sandy layer sandwiched between two less permeable silty-clay facies. This layer acted as a confining zone for the compounds while also providing a pathway for horizontal mobility of the contamination, as illustrated in Figure 5.

It is important to note that the soil layers lack visible distinctiveness, except for the sandy layer, as also highlighted by Guilbeault *et al*. (2005). The silt-dominated layers appeared visually similar across the site. However, the HPT sensor revealed the presence of distinct hydrostratigraphic zones within these silt layers, which influenced the behaviour of the contamination. These hydrogeological units, within the same lithostratigraphic unit, are typically formed due to variations in grain arrangement and potential cementing from finer clay particles, making them indistinguishable through visual and tactile soil descriptions alone. Hence, relying solely on visual stratigraphy descriptions may not be sufficient for adequately assessing the different hydrogeological units that govern the fate and transport of contaminants at a given site.

All sampling locations and media were guided by the semi-quantitative data obtained from the MIP and OIP systems. Soil, groundwater, and vapour, the three affected mediums, were assessed at multiple locations to enable a comprehensive and representative assessment of contaminant mass for a more accurate human health risk assessment.

Figure 4 illustrates the positioning of four MWs, located 3 m apart from each other. MW labelled as 1 through 3 (MW-01, MW-02, and MW-03) were previously installed during past investigation campaigns solely based on the visible lithology description and groundwater table found during installation. All the MWs are 2 in in diameter. MW-01 has 2 m of well screen, place between 1.5 and 3.5 m below ground. MW-02 screen is placed between 2 and 4 m below ground. MW-03 screen is located between 1.75 and 3.75 m below ground. All three wells connect multiple hydrostratigraphic

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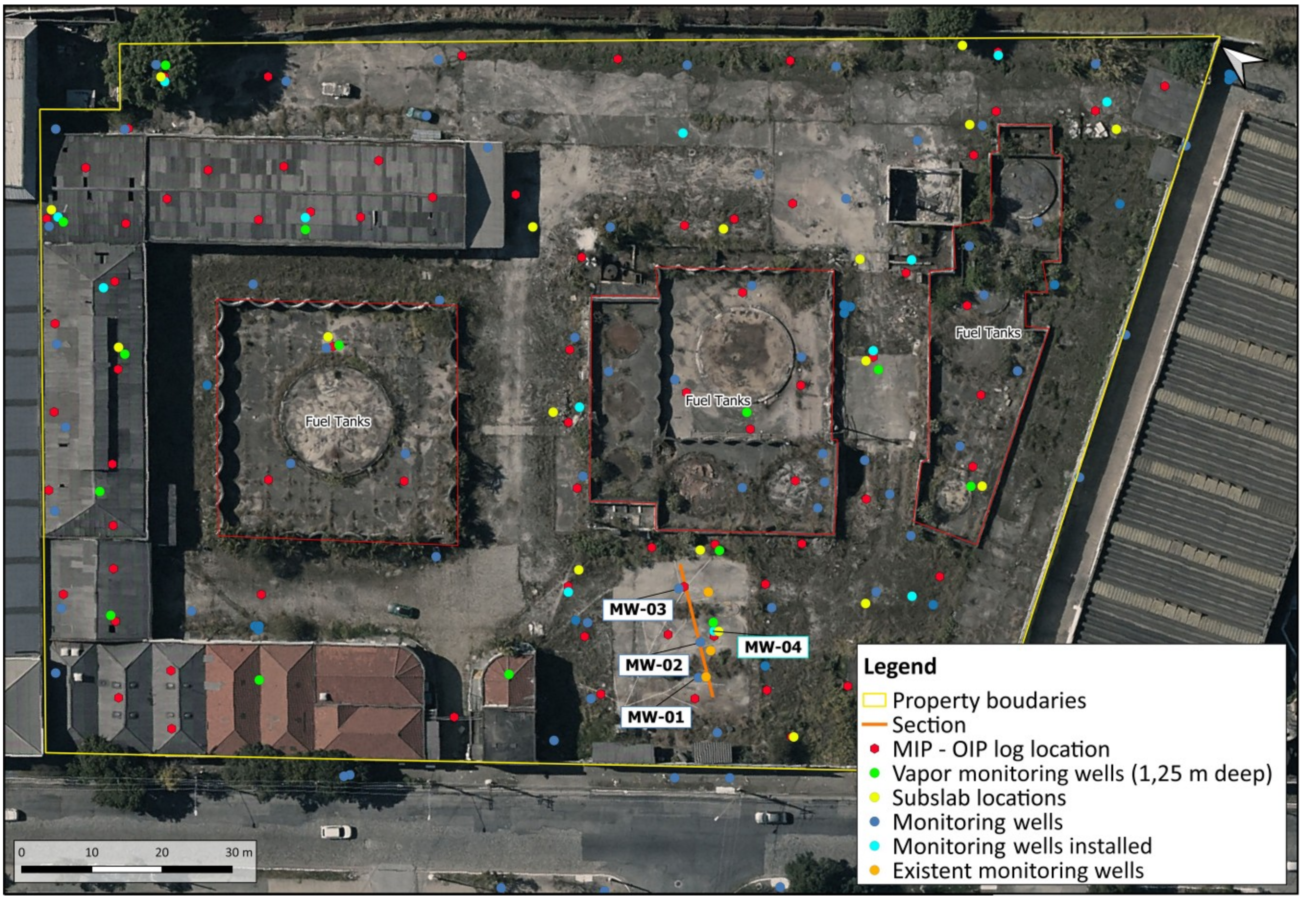

Figure 4. Map displaying the position of the different MIP and OIP logs, MW installed, and the vapour MW across the area

layers and the local preferential flow direction is from northeast to southwest.

MW MW-04 was installed with a shorter screen interval (1 m) completely within the aquifer's flow zone, between 2.5 and 3.5 m, as indicated by the hydraulic profiling sensor described earlier (Figure 5).

As depicted in Figure 5, the benzene concentration in the four closely located wells can be observed. The concentration in MW-04 is 4421.0 μg/l, significantly higher than the 33.6 μg/l found in MW-01, which is less than 5 m away. This discrepancy in concentration, despite the proximity of sampling points, can be attributed to the complex distribution of contaminant mass within the aquifer, as noted by Guilbeault *et al*. (2005).

Figure 6 displays the plumes associated with all phases of contamination, revealing a strong correlation between hotspots and phase locations. The MIP system effectively identified areas with the highest contaminant mass on the site, although it did not detect the extent of the dissolved plume, as this system is not designed for such detection. In addition, it was observed that the groundwater plume exhibited the largest spatial extent compared with the vapour and adsorbed phases. The vapour phase was evaluated using MW located in the hotspots identified by the MIP system. However, it was observed that vapour intrusion risk was only present in areas where hotspots of contamination in the adsorbed phase were also identified.

Upon three-dimensional modelling of contaminant concentration in the soil, the newly calculated soil removal value for treating most of the source zones was 62% smaller than previously known and estimated. The areas where the plumes were mapped are depicted in Figures 6(a) and 6(b).

Despite the relatively shallow groundwater level, 2 m below ground, the generation of vapour was not attributed to contamination in the groundwater but rather to the mass adsorbed in the soil matrix near the source areas. This finding was corroborated by the distribution of contamination across all phases at the site,

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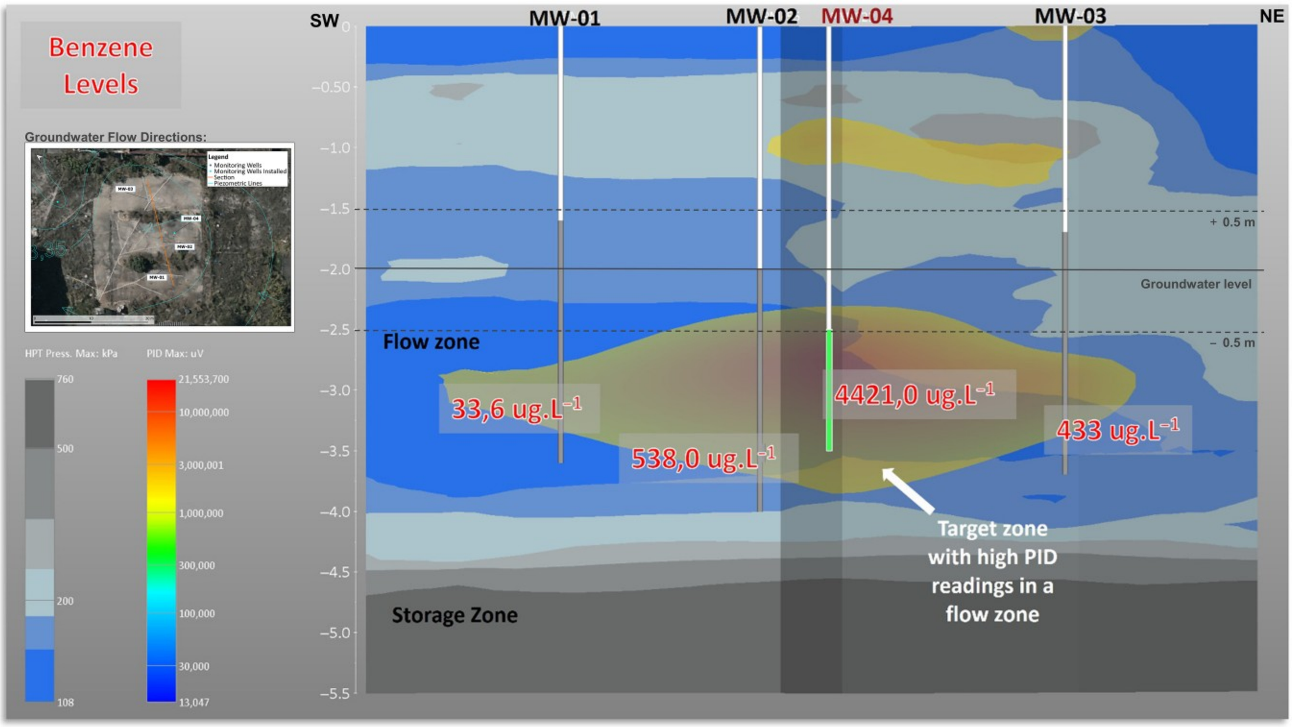

Figure 5. Location of four MW and the benzene concentration in the groundwater sampled from each of them

with most of the mass being adsorbed in the soil matrix. If the initial approach to assess the site had relied solely on vapour screening to identify potential source zones, some areas with elevated concentrations of the dissolved phase would have been overlooked.

The estimation of contamination mass was conducted using Earth Volumetric Studio (EVS), a software by CTech Corporation that is widely recognised as the benchmark software for environmental modelling. The partitioning of contaminant mass was determined as 97.3% adsorbed in the soil, shown by Image 2 of Figure 6, 2.7% dissolved in the groundwater, illustrated by Image 3 of Figure 6, and less than 0.01% as vapour, in Image 4 of Figure 6. The parameters used to quantify the contaminant mass are displayed in Table 2. Therefore, the hotspots of vapour intrusion were more closely associated with the soil hotspots rather than the extent of contamination in the groundwater, since most of the contamination was present in the soil matrix and not yet dissolved in the groundwater.

Following the numerical modelling and identification of different mass values throughout the site, a comprehensive human health risk assessment was conducted in accordance with local state regulatory requirements. It should be noted that conducting a human health risk assessment necessitates quantitative data, such as soil and groundwater samples, as high-resolution systems do not provide quantitative information.

The human health risk assessment was rigorous, considering the correct quantification of mass from soil and groundwater samples guided by the MIP and OIP logs. It identified specific priority areas for remediation activities and areas where monitoring alone was deemed sufficient, considering that most of the mass, which resided in the soil, had been removed or remediated.

As shown in Figure 6, the areas with the highest concentration of contamination are located in a small portion of the site, which aligns with findings from other HRSC cases conducted in Brazil and the USA (Malta-Oliveira *et al.*, 2020a, 2020b; Suthersan *et al.*, 2015). The mass present in the soil contributes to the formation of the dissolved and vapour phases, and unless it is stabilised, remediated, or removed, the presence of these phases will persist due to the low partitioning.

The remedial approach designed for the site was based on several excavation areas strategically located around the centres of mass in the soil. These excavations will facilitate the removal and treatment of over 95% of the contamination mass, thereby creating favourable conditions for the biodegradation of the remaining contaminants in the soil and groundwater. Furthermore, the decrease

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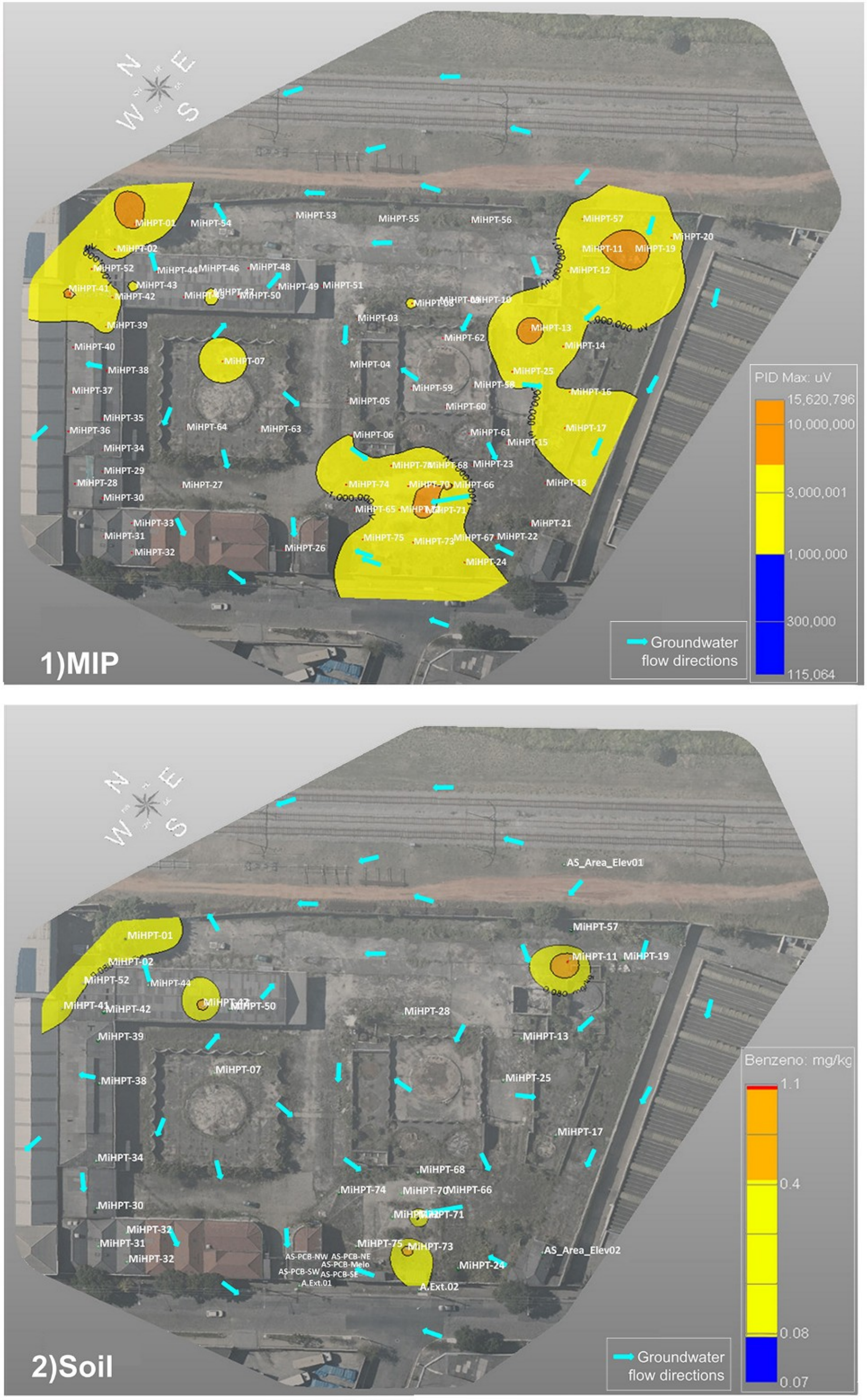

Figure 6. (*1*) Readings from the MIP system; (*2*) benzene concentrations above Brazilian legal standards in soil; (*3*) dissolved benzene above potability standards; (*4*) benzene in the vapour phase

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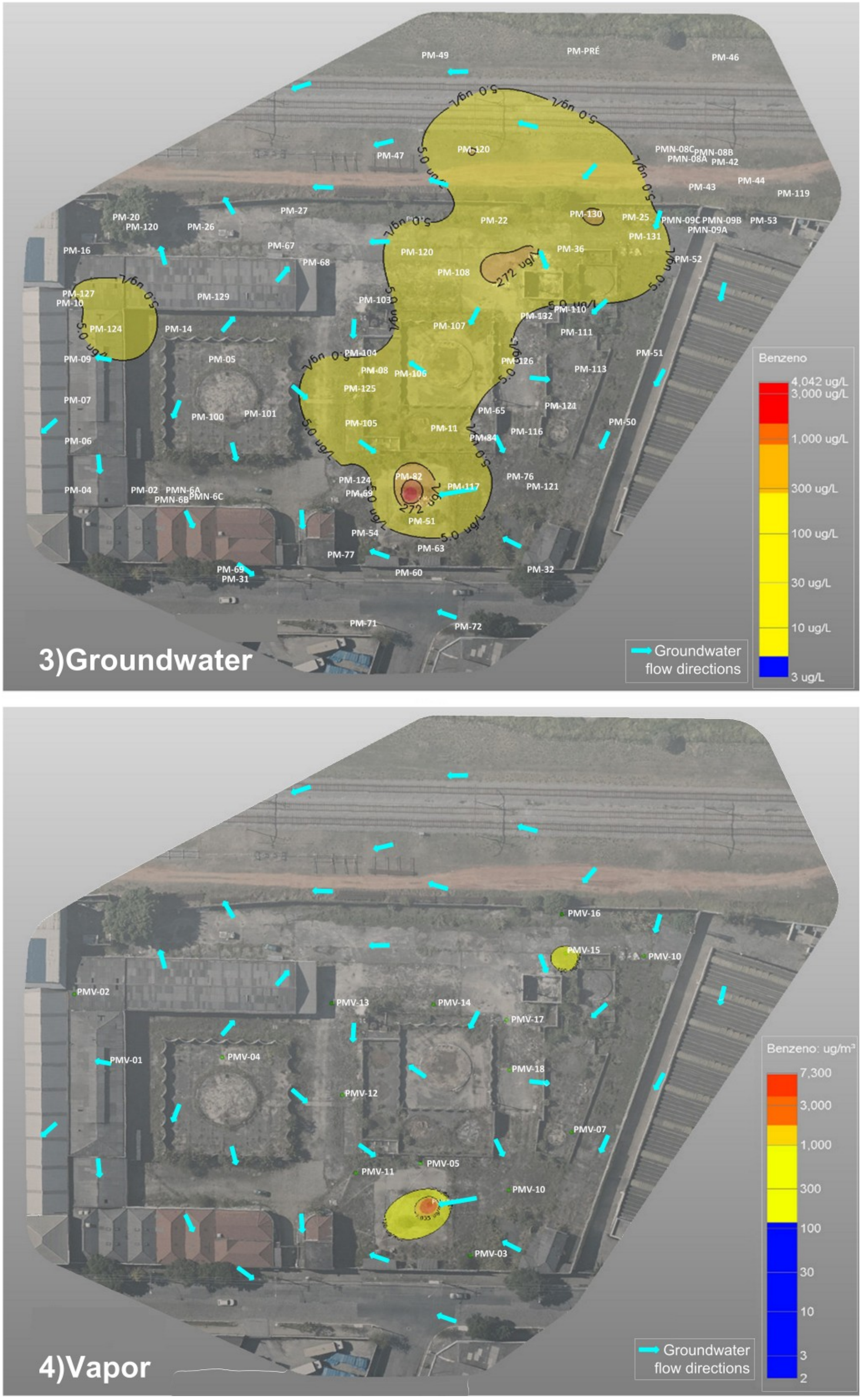

Figure 6. Continued

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Table 2. Parameters for mass estimation

Parameter	Soil	Parameter	Groundwater
Porosity: %	0.39	Porosity: %	0.39
Impacted volume: m^3	7 2489.84	Impacted volume: m^3	1 4491.12
Soil density: g/cm^3	1.17	Chemical density: g/cm^3	0.87
Impacted mass: ton	8 4810.74	Impacted mass: ton	1 4490.7
Average concentration: mg/kg	0.49	Average concentration: μg/l	312.29
Contaminant mass: kg	41.55	Contaminant mass: kg	1.23
Percentage of mass: %	97.3	Percentage of mass: %	2.7

in mass within the source areas will lead to the extinction of the vapour phase.

Previous remediation efforts primarily focused on removing the mobile LNAPL phase, which effectively contained the advancement of the plume. However, these efforts proved ineffective in restoring the site, as they neglected the treatment of the adsorbed phase, which contributes to the presence of other contaminant phases.

Following the implementation of the HRSC and TRIAD approaches, the conclusion of the remediation efforts is now foreseeable and predictable. The predictability of the restoration is attributed to a comprehensive understanding of the contamination extents obtained through the CSM.

The HRSC and TRIAD management approach spanned 3 months and enabled the development of a robust CSM with minimal uncertainties. This enhanced CSM served as the foundation for evaluating remediation strategies aimed at eliminating the soil contamination mass and monitoring the remaining mass as it naturally degrades over time. The goal of achieving a non-toxic condition at the site will be realised through a remediation approach centred on mass removal, destruction, and the natural attenuation of the remaining mass.

5. Discussion

The investigation process of a contaminated site is crucial for an efficient and sustainable restoration process (Iannone, 1995; Malta-Oliveira *et al*., 2020a; Suthersan *et al*., 2015, 2016; WHO, 2021; US EPA, 2021). However, conventional methods such as point samples and MW alone provide limited information about the characteristics of the physical medium and contamination (Brewer *et al*., 2017b, 2017a; Guilbeault *et al*., 2005; ITRC, 2019; Suthersan *et al*., 2015, 2016; US EPA, 2014, 2016). A proper investigation approach can deliver specific results in a shorter period and in a more dynamic, robust way (ITRC, 2019; Suthersan *et al*., 2015), reducing uncertainty and providing precise, reliable data for all stakeholders involved in the decision making process for a given site.

The combination of the TRIAD and HRSC approaches has proven valuable in providing much-needed information about lithology and the current state of storage or flow of the compounds of interest in the area. Achieving overall cost reduction, increased remediation efficiency, and instilling technical and legal confidence can only be accomplished when relevant, density-appropriate data are available and well interpreted (Malta-Oliveira *et al*., 2020a, 2020b; Suthersan *et al*., 2015). This can be achieved through the selection of the correct tools, such as the combined use of the MIP and OIP systems, along with a comprehensive understanding of the behaviour of contamination interacting with the geological features at a specific site.

It is noteworthy that soil and groundwater samples were collected after the identification of the contaminant centres of mass and were a crucial step in quantifying the contamination at the site. However, in this approach, the number of samples that are necessary to conveniently assess a site is reduced. The drilling and sampling are directed to given areas and depths because the positions were previously selected and targeted using the semi-quantitative data from the HRSC systems.

The first management approach for the area involved evaluating the site using samples that were spread across the area but selected without specific criteria. This procedure, coupled with the presence of LNAPL at the site, led to the decision to utilise a pump and treat systems, even though a significant portion of the mass was immobile and trapped in lower permeability zones. The traditional approach failed to provide a reliable timeframe for the area's rehabilitation, ultimately resulting in a 35% depreciation in the site's market value.

As a result of adopting the HRSC management strategy, the option for an appropriate rehabilitation allows to speed up the decisions and the actions. The entire HRSC investigation and proposed remediation plan cost less than 50% of the expenses incurred for site maintenance, previous investigations, and remediation campaigns. Moreover, this approach enables the accurate forecasting of the time required for the complete closure of the remediation process, thanks to the use of a robust CSM. This foreseeable end

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of the environmental management and risk allowed the site owners to market it at a price close to the area's original valuation.

However, current management strategies, which rely on traditionally built CSMs, are unable to predict the end of a rehabilitation process when contamination mass is still present or when passive management strategies are implemented. To establish a reliable timeframe for remediation, it is imperative to base the decision making process for rehabilitating a brownfield on a robust and dynamically built CSM.

There is presently a shift in perspective towards a more holistic approach, deviating from the traditional phased approach (Suthersan *et al*., 2015; WHO, 2021). Phased approaches often fail to consider the overall evolution of fate and transport of contaminants. By transitioning to an integrated approach, as recommended in this paper, and demonstrated by this case study, it becomes possible to forecast the timeframe of the remediation process with greater certainty, based on mass removal or destruction.

6. Conclusion

From a sustainability and social responsibility standpoint, it can be stated that the utilisation of a dynamic HRSC and TRIAD approach, as exemplified in this case study, brings several benefits:

- The environmental impact was assessed more efficiently within a shorter timeframe, considering the appropriate scale in both vertical and horizontal dimensions.
- The adoption of a dynamic HRSC and TRIAD approach resulted in the generation of less residue, as fewer samples were collected and MWs were installed. This reduction in sampling activities contributed to a smaller carbon footprint.
- A comprehensive human health risk assessment could be conducted based on high-density and representative data, ensuring a thorough understanding of potential risks to human well-being.
- The use of a dynamic investigation approach, coupled with real-time data analysis, provided technical and legal assurance to all stakeholders involved. This continuous monitoring and analysis allowed for timely decision making as the investigation progressed.
- A robust CSM was developed, accurately describing and presenting the actual impact of contamination to landowners, legal authorities, facility managers, and the surrounding population. The CSM served as a valuable tool for communication and understanding of the site's conditions.
- By achieving a higher density and completeness of data through the CSM, it becomes possible to establish an achievable timeframe for the full rehabilitation of the site, reducing uncertainty and providing stakeholders with a clearer understanding of the project's timeline.

In summary, brownfields offer a viable solution to the growing demand for urban space. However, their development presents challenges due to uncertainties concerning environmental impacts and human health risks associated with contamination. Therefore, it is crucial to get a sufficient density of data specific to each site to effectively deploy remediation technologies and redevelopment efforts, minimising risks for investors and society at large. Consultants and regulators should prioritise the use of methodologies that provide a dense and dynamic approach to site investigation and restoration.

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