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Climate-Resilient and Sustainable Soil Remediation: Hydrocycloning for Metal Removal in Flood-Prone Brazilian Region

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Abstract

Soil contamination by heavy metals from industrial and mining activities poses a significant global threat to both environmental and human health, particularly in brownfields—abandoned or underutilized industrial areas that frequently accumulate pollutants. Climate change exacerbates this issue by intensifying extreme events such as floods, which can enhance contaminant mobility and compromise the reliability of conventional remediation methods. This study evaluated the in situ application of a sustainable soil washing technique based on hydrocycloning at a contaminated site in Canoas (Porto Alegre, Brazil), a flood-prone area heavily impacted by the 2024 climate disaster. The method physically separates heavy metals by concentrating them into a fine, high-contamination fraction for controlled disposal. Approximately 3019 m^3 of soil was treated, recovering 93.4% of the material (coarse and fine sand) for potential reuse and isolating only 6.6% (200 m^3) as hazardous waste. Chemical analyses confirmed that the recovered fractions complied with regulatory limits for heavy metals, while contaminants were effectively retained in the sludge and safely disposed of through landfills. During the April–May 2024 flood events, although the site was inundated, no significant erosion of the backfilled material was registered. The results support hydrocycloning-based soil washing as a robust and climate-resilient approach to adaptive remediation in contaminated environments.

Keywords: sustainable remediation; heavy metals; hydrocycloning-based soil washing; resilience; climate change

Academic Editor: Francesco Ferella

Received: 11 August 2025
Revised: 4 September 2025
Accepted: 12 September 2025
Published: 14 October 2025

Citation: Sillos, M.; da Silva, P.F.; Suhogusoff, A.; Brito, G. Climate-Resilient and Sustainable Soil Remediation: Hydrocycloning for Metal Removal in Flood-Prone Brazilian Region. *Sustainability* **2025**, *17*, 9083. https://doi.org/10.3390/su17209083

1. Introduction

Soil contamination by metals has become a significant global environmental issue, primarily driven by anthropogenic activities such as mining, industrial operations, and other productive processes that generate metal-rich effluents [1,2]. These practices contribute to the accumulation of potentially toxic elements (PTEs) within the soil matrix, thereby posing substantial risks to environmental quality, ecological functionality, and public health [1,3]. This challenge is particularly pronounced in previously urbanized or industrialized sites, commonly referred to as brownfield sites, where soil and groundwater contamination is widespread and demands tailored, site-specific, and technically robust remediation strategies [4].

In parallel with this scenario, the impacts of climate change have become increasingly pronounced and well-documented, as highlighted by the IPCC [5]. The frequency and intensity of extreme weather events, such as severe storms, torrential rainfall, intense heat waves, recurring wildfires, and prolonged droughts, have noticeably increased. Additionally, long-term systemic changes, including sea level rise, the retreat of snow and ice cover, ocean acidification, warming of aquatic systems, and persistent freshwater scarcity, pose significant threats to both ecosystems and human populations' safety [6].

Within this context, climate change presents additional complexities in the management of contaminated sites. At brownfields containing hazardous substances, extreme weather events can compromise the effectiveness of remediation efforts by altering the toxicity of contaminants and exposure pathways, as well as enhancing the mobility and dispersion of pollutants. This situation necessitates increased rigor in long-term monitoring and management practices.

Parameters such as elevated temperature, shifts in redox potential, and variations in pH can drive biogeochemical processes that promote the release of contaminants, due to changes in metal speciation and the destabilization of containment phases, including oxides, hydroxides, and colloids, among others [7,8]. Similarly, the growing frequency and severity of flood events may facilitate the transport of contaminants and compromise the integrity of implemented remediation measures [9].

Thus, the need for remediation strategies that incorporate resilience to climate change has become increasingly critical. In 2009, the Sustainable Remediation Forum, Inc. (SURF) (Newark, NJ, USA) introduced the concept of sustainable remediation as the process of removing, reducing, or containing contaminants in soil, groundwater, and other affected media in a manner that is technically robust, environmentally responsible, socially beneficial, and economically viable throughout the entire life cycle of a project [10].

As a key approach to enhancing the long-term benefits of brownfield redevelopment, sustainable remediation advocates the adoption of innovative technologies that reduce environmental impacts, optimize the use of natural resources, and integrate broader social and economic considerations [4]. To support informed decision-making regarding the selection of optimal treatment technologies and the associated costs, analytical tools such as those developed by Gurdon et al. [11] prove particularly valuable. Among the most promising approaches are phytoremediation [12], natural attenuation [2], and in situ chemical treatments using various amendments such as nanomaterials [13], limestone and bone powder [14], modified biochar [15], and surfactants [16]. Additionally, soil washing methods, sometimes enhanced with substances like humic acids [17] or amino acid ionic liquid [18], are also highly effective [11,19]. Soil washing using hydrocycloning is a highly effective method for the long-term removal of heavy metals from contaminated soil [20,21]. This technique combines physical and chemical separation processes to isolate contaminants and concentrate them into significantly reduced volumes, thereby facilitating their management and disposal.

In this context, the present study, conducted within the framework of a PhD research project, examines the application of hydrocycloning-based soil washing, implemented in 2019/2020 in a flood-prone area of Porto Alegre, Brazil, to demonstrate its efficiency and feasibility as a resilient remediation strategy to address climate-related challenges.

2. Materials and Methods

2.1. Materials

2.1.1. Characterization of the Study Area

The study area is in the central region of the municipality of Canoas, in the state of Rio Grande do Sul, Brazil (Figure 1), located in the Metropolitan Region of Porto Alegre and bordered by water bodies—Jacuí River (to the Southwest) and Sinos River (to the West).

It is located within a fluvial plain, characterized by predominantly flat to gently undulating terrain, typical of meandering river environments. The drainage network is dense and well-developed, reflecting the low slope and high soil saturation throughout the year. Surface deposits consist of sandy–silty–clayey sediments interbedded with gravel, rounded pebbles, and plant remains [22], indicating successive fluvial sedimentation events during periods of flood and ebb. The low average elevation of the area, estimated at approximately 10 m, contributes significantly to its high vulnerability to flooding, especially during extreme rainfall events.

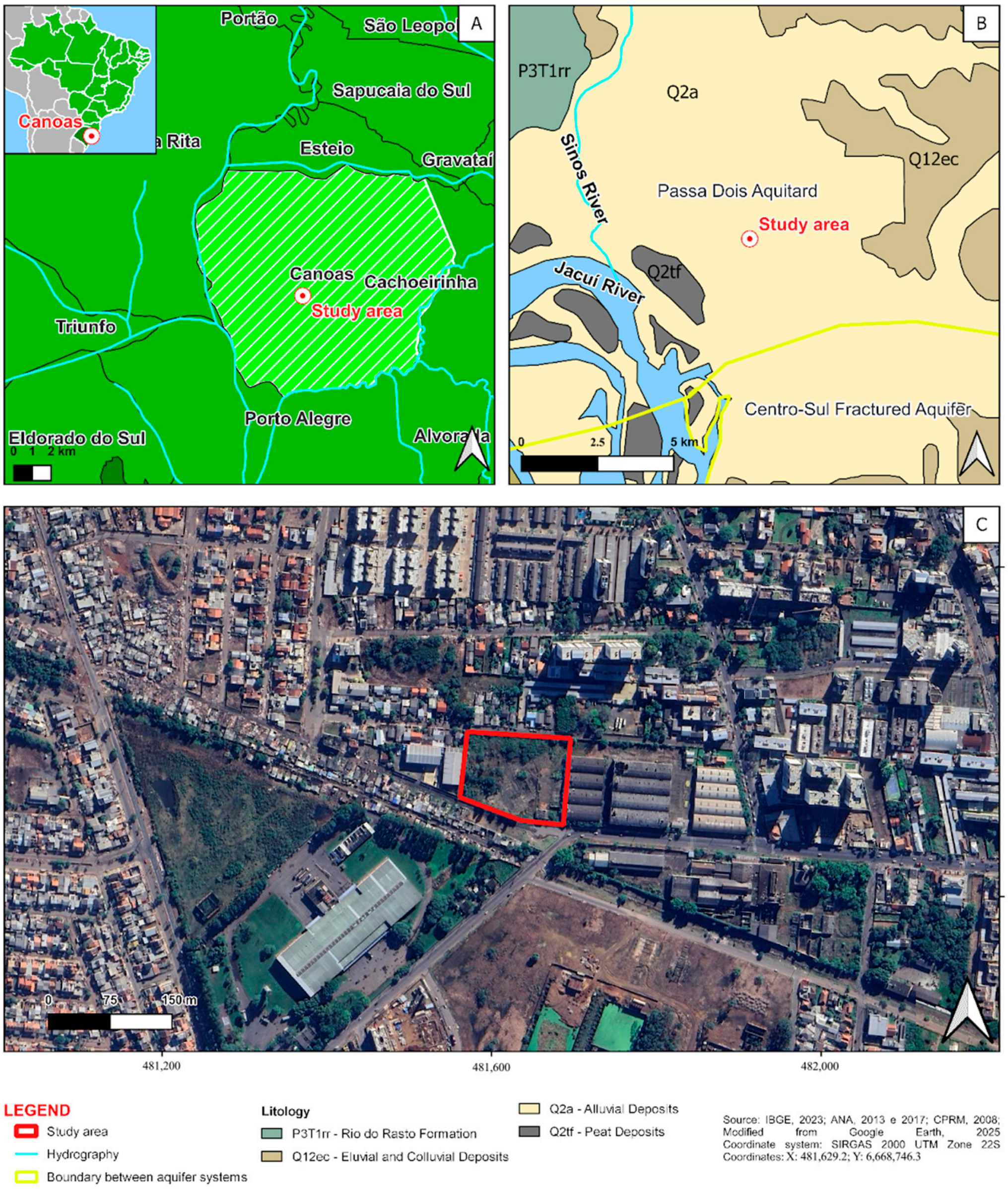

Figure 1. (**A**) Location of the study area (adapted from [23]); (**B**) geological map of the surroundings of the study area (adapted from [24,25]); (**C**) satellite image showing land use and land cover in the surroundings of the study area (adapted from [26]).

Canoas covers a territorial area of 130,774 km^2 (Figure 1A) and has an estimated population of 347,657 inhabitants, making it the third most populous city in the state of Rio Grande do Sul, after Porto Alegre and Caxias do Sul [27]. The municipality of Canoas has significant industrial activity.

The total area of the study site (Figure 1C) is 11,300 m^2 and lies within an industrial complex that has been in continuous operation for over 80 years. Historically, the site activity was the manufacturing of glass bottles, and it also contains an irregular landfill of industrial waste, with high concentrations of arsenic (As), chromium (Cr), BPF—a low-melting-point hydrocarbon oil, and glass [28]. Currently, the surrounding region is undergoing urban expansion and is being gradually occupied by vulnerable communities (informal settlements).

According to [29], the outcropping geology of the study area consists mainly of arkosic sands, which comprise the Alluvial Deposits of the Jacuí River. The main hydrostratigraphic unit present is the Passa Dois Aquiclude, composed of fine sedimentary rocks that contain water but have extremely low permeability. Additionally, during site investigation works, a landfill was identified between 0 m and 2 m deep; from 1 m to 10 m, alluvial soil composed of silty clay was observed; below 10 m, weathered gneiss was detected, which constitutes the local basement.

2.1.2. Environmental Characterization

Before the implementation of remediation procedures in the northern portion of the site, a comprehensive site investigation was conducted, encompassing preliminary, confirmatory, and detailed assessment stages. The sampling process, conducted in accordance with the guidelines of ITRC [30], employed the Incremental Sampling Method (ISM). In this approach, the number of increments and the sample mass were determined by the degree of small- and large-scale heterogeneity of contamination within the decision unit, the chemical characteristics of the contaminants, the type and physical properties of the waste, and the mechanisms of contaminant release. For the present evaluation of treatment effectiveness in the recovered soil materials, between 30 and 50 increments were collected, as deemed appropriate. All sampling and analytical procedures adhered to the applicable quality assurance standards, including the use of spikes, duplicates, and chain of custody (COC) protocols for QA/QC. Analytical determinations were performed in agreement with the USEPA Method 6010C method [31].

These investigations confirmed the presence of contamination primarily by heavy metals and arsenic (metalloid)—the potential toxic elements (PTEs) with concentrations exceeding environmental reference values. Based on risk assessment to human health, specific remediation actions were defined and executed to eliminate direct exposure risks through dermal contact, ingestion, and leaching pathways, focusing on industrial use [32]. Site general treated soil data sent to treatment is shown in Table 1.

The analytical results demonstrated that the raw (untreated) soil presented concentrations exceeding the intervention values for industrial land use defined by the CONAMA Resolution n.º 420/2009 [33] for antimony (43 mg/kg), arsenic (230 mg/kg), cadmium (17.1 mg/kg), and lead (461 mg/kg). These levels indicated a significant environmental liability, posing potential risks to human health and the environment, particularly through dermal contact or accidental ingestion of contaminated soil.

Table 1. Concentrations of PTEs detected and comparison with CONAMA Resolution n. 420/2009 [33] intervention values.

Parameter	Unit	Raw Material (ISM)		CONAMA 420/2009
		Sample 1	Sample 2	SSTL
Antimony	$mg \cdot kg^{-1}$	43	22	10
Arsenic	$mg \cdot kg^{-1}$	120	230	55
Barium	$mg \cdot kg^{-1}$	76	140	500
Cadmium	$mg \cdot kg^{-1}$	16	17	8
Lead	$mg \cdot kg^{-1}$	461	396	300
Cobalt	$mg \cdot kg^{-1}$	13	12	65
Cooper	$mg \cdot kg^{-1}$	90	69	400
Chromium	$mg \cdot kg^{-1}$	65	83	300
Chromium VI	$mg \cdot kg^{-1}$	<1	<1	-
Mercury	$mg \cdot kg^{-1}$	4	2	36
Molybdenum	$mg \cdot kg^{-1}$	2	2	100
Nickel	$mg \cdot kg^{-1}$	20	19	100
Silver	$mg \cdot kg^{-1}$	17	14	50
Selenium	$mg \cdot kg^{-1}$	3	<1	-
Zinc	$mg \cdot kg^{-1}$	244	151	1000

ISM—Incremental Sampling Method; SSTL—site screening target level.

The development of an intervention plan in Brazil follows the technical standards established by the Brazilian Association of Technical Standards [34,35]. These standards establish the methodological framework for the design of rehabilitation plans for contaminated areas, encompassing the definition of intervention measures, the development of a conceptual site model, the preparation of a comprehensive technical report, and the evaluation of the toxicological risks to human health. However, standards specifically addressing environmental and ecotoxicological risk assessment have not yet been issued in Brazil.

The total area was divided into 43 excavation cells, from which approximately 6498 m^3 of soil were removed between January 2018 and August 2019. The excavated material included construction debris, which was sent to a licensed landfill, and contaminated soils that underwent treatment using two different techniques: biopiles (720 m^3) and soil washing through the hydrocycloning system (3019 m^3).

To ensure the quality of the remediation, post-intervention soil sampling campaigns were conducted beneath operational areas. Analytical results confirmed that contaminant concentrations in the treated zones did not exceed the applicable environmental thresholds, thereby demonstrating the effectiveness of the intervention [28]. No additional environmental and ecotoxicological investigation were required by the national environmental agency.

2.1.3. Flood Susceptibility of the Region: The Case of Rio Grande Do Sul in 2024

Between April and May 2024, the state of Rio Grande do Sul, in Brazil, experienced one of the most severe climate disasters in its recent history. Within the living memory of inhabitants alive in 2024, this event was unprecedented. Intense and persistent rainfall affected several regions of the state, causing rivers to overflow, urban infrastructure to collapse, and interruptions to essential services, resulting in major social and economic impacts. The municipality of Canoas was one of the area's most severely affected, with water levels exceeding 1.5 m [36].

The study area is in a zone classified as having medium flood risk, situated on the floodplain of the Sinos River. Although a polder-type flood defense system protects the region, it was affected by the 2024 flood event (Figure 2A), during which the Sinos River exceeded the height of the Mathias Velho polder dike, eroded the structure, and flooded the entire protected area [37].

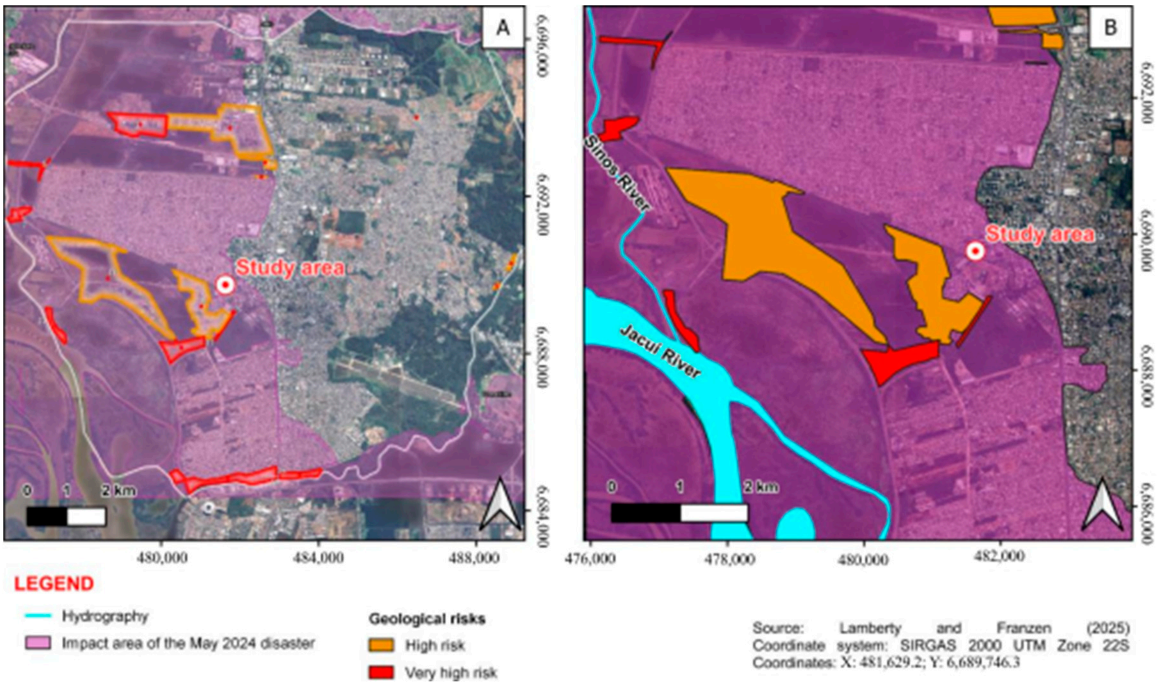

Figure 2. (**A**) Area of the municipality of Canoas affected by the May 2024 flood, and (**B**) Detailed view of the disaster area showing geological flood risk classification (adapted from [36]).

Near the study area, to the southwest, there are zones classified as high and very high flood risk areas (Figure 2B). These areas show signs of instability and a high potential for damage, with a medium to high frequency of flood occurrence. This situation is exacerbated by the expansion of residential settlements on the floodplain of the Sinos River, a naturally flat region that is prone to slow and gradual flooding due to the river's fluvial dynamics [37].

Rainfall data from the period between 20 April and 20 May 2024, recorded by the Porto Alegre meteorological station [37], indicates a cumulative precipitation volume of 520 mm, with a daily average of 16.77 mm. The peak rainfall events occurred on 30 April (99.1 mm), 1 May (60.5 mm), and 2 May (99 mm), revealing episodes of extreme rainfall over a short period (Figure 3). These volumes far exceeded the region's natural and urban drainage capacity and caused the overflow of several water bodies, including the Jacuí River.

The area was completely flooded, highlighting the site's vulnerability to extreme weather events. Aerial images taken before and during the event show the dramatic transformation of the landscape, with the advancing waters submerging previously dry land The estimated flooded area reached 53 km^2, underscoring the magnitude of the event (Figure 4). The rising water levels, in addition to damaging buildings and infrastructure, posed a direct threat to the health of surrounding populations, most of whom live in socially vulnerable conditions with limited access to mitigation and recovery resources.

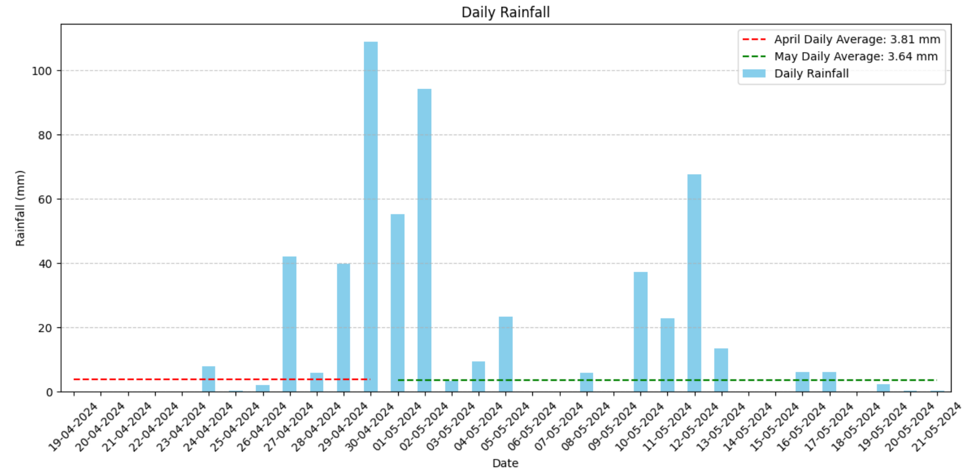

Figure 3. Average daily precipitation [37] in Canoas (Brazil) during the 2024 extreme flood event.

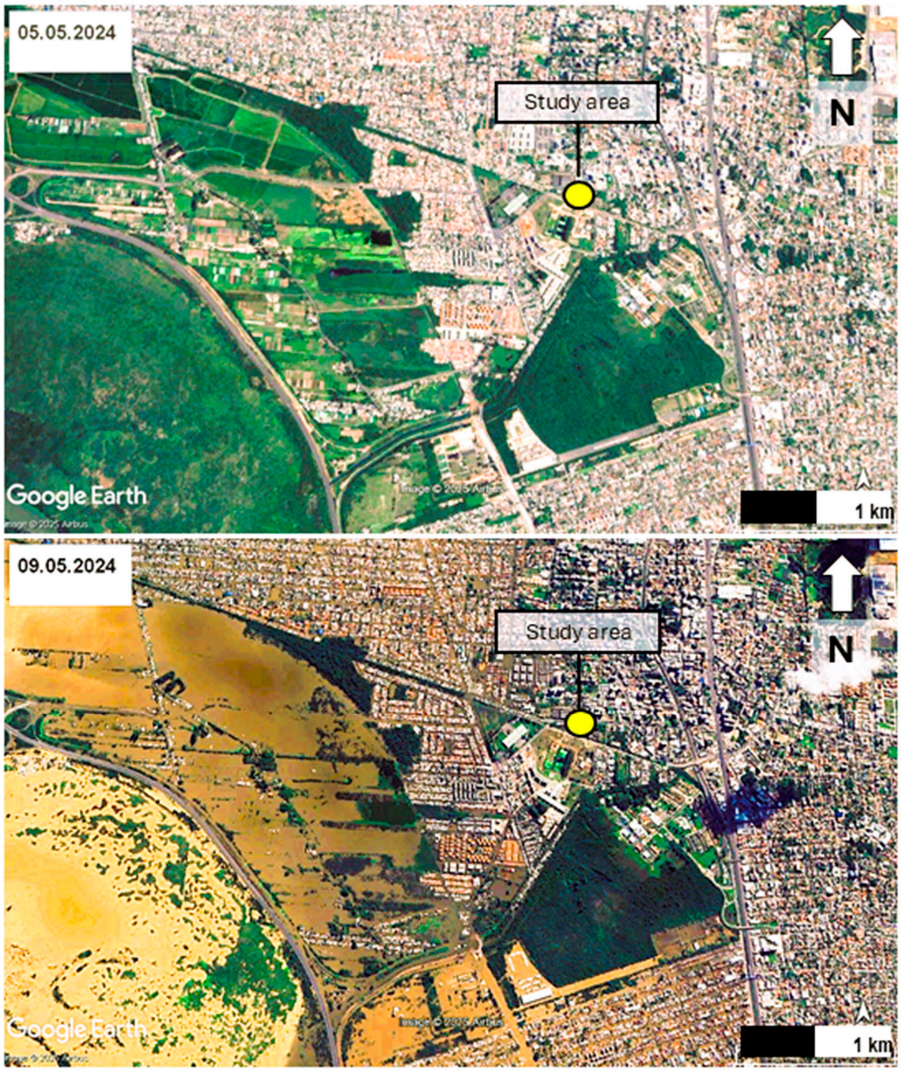

Figure 4. Aerial image [38] of the Canoas and Porto Alegre region (Brazil). (**Top**): aerial image from 5 May 2024; (**Bottom**): aerial image from 9 May 2024, showing the area completely submerged after the overflow of the Jacuí River.

Before the flood event, a soil washing remediation system using hydrocyclone technology had been implemented in the study area.

To support the analysis of land use history, a visual synthesis of the site's environmental evolution between 2016 and 2025 was developed (Figure 5), incorporating environmental impacts from the 2024 flood event. This series of images enables the observation of land use and land cover changes, the outcomes of the remediation intervention, including the reestablishment of vegetative cover (notably tree growth) in a formerly contaminated area, and the effects of flooding on the remediated site.

(**a**) 13 June 2016: Study area prior to remediation—impermeable soil with concrete cover and sparse vegetation.

(**b**) 13 September 2018: Excavation in progress—surface soil exposed after concrete removal, with some rainwater visible (in dark orange).

(**c**) 13 June 2019: Backfilling with clean soil processed through hydrocycloning.

(**d**) 13 June 2020: Vegetation cover starts to regenerate in the treated area.

(**e**) 13 June 2023: Tree growth as an environmental quality indicator.

(**f**) 5 May 2024: Before the extreme flooding event affected the site and its surroundings.

(**g**) 9 May 2024: During the extreme flooding event at the site, before reaching the peak stage.

(**h**) 9 May 2025: Stabilization of native vegetation.

Figure 5. Environmental history of the area between 2016 and 2025: (**a**) 2016—initial waste disposal; (**b**) 2018—beginning of environmental intervention; (**c**) 2019—excavation and separation of soil fractions; (**d**) 2020—installation and operation of the hydrocycloning system; (**e**) 2023—monitoring of the remediated area; (**f**) 2024—before the flood; (**g**) 2024—after the extreme event, site completely flooded; (**h**) 2025—gradual recovery of the remediated area.

2.2. Methods

2.2.1. Selection of Remediation Techniques

As part of the preliminary evaluation of potential remediation strategies, the development of a conceptual model is essential. This model defines the condition of the contaminated area, identifying the sources of contamination, the physicochemical properties of the contaminants, and their transport and exposure pathways. It also includes a comparative analysis of suitable remediation technologies, assessing their respective advantages and limitations to identify the most adequate option.

The intervention plan must also incorporate sustainability criteria that go beyond technical effectiveness. These include waste management practices, the scope and timing of environmental monitoring, stakeholder engagement, particularly with communities affected by toxicological risks, and the definition of compliance points for monitoring performance.

Considering the intensifying global impacts of climate change, the selection of resilient remediation strategies has become a critical requirement. Table 2 presents a comparative assessment of the alternative techniques for the remediation of the PTEs. Among the evaluated options, the soil washing process was selected as the most suitable due to its capacity to deliver conclusive and robust post-remediation outcomes.

Table 2. Comparison of the characteristics of the main remediation techniques.

Technique	Treated Metals?	Remediation Time	Waste Generation	Relative Cost	Soil Reuse	Technical Complexity	Environmental Impact	Sustainable	Reference
Soil washing	Yes	Short	Medium	Medium–High	Yes	Medium	Low	Yes	[11]
Natural attenuation	Yes	Very Long	Minimal	Low	Yes	Low	Low	Yes	[2]
Bioremediation	No	Long	Low	Low	Yes	Medium	Low	Yes	[2]
Land farming (Soil Biotreatment)	No	Long	Medium	Low	Partial	Medium	Medium	Partially	[2]
Dig and dump	Yes	Short	High	High	No	Low	High	No	[4]
Soil/Residue encapsulation	Yes	Short	Does not treat, only isolates	Medium–High	No	Medium	High	No	[12]
Excavation	Yes	Short	High	High	No	Low	High	No	[39]
Incineration	No	Short	High	Very High	No	High	Very High	No	[40]

Technology's ability to reduce contaminants of concern (COCs) and to concentrate waste into a smaller volume for safe disposal was a decisive factor in its selection. The estimated gross cost of soil washing using the hydrocyclone method in Brazil is approximately USD 75 per cubic meter (m^3), whereas the average cost of excavation and disposal in a hazardous waste landfill is around USD 150/m^3, which is nearly twice as high.

By contrast, alternative approaches, such as off-site disposal of all excavated material in landfills or in situ encapsulation with clay covers, were considered less favorable and less sustainable when evaluated against factors including energy consumption of excavation machinery, costs and risks associated with hazardous waste transport, expenses related to clay import, and requirements for water and energy management. These options either posed greater environmental impacts or lacked resilience to future flooding events, an essential factor for ensuring long-term site stability.

2.2.2. Soil Washing System Using Hydrocycloning

Contaminants present in contaminated soil can be distributed in various ways, such as being retained in pores, adsorbed or absorbed by solid particles, or even accumulated around them. Figure 6 illustrates these different forms of occurrence.

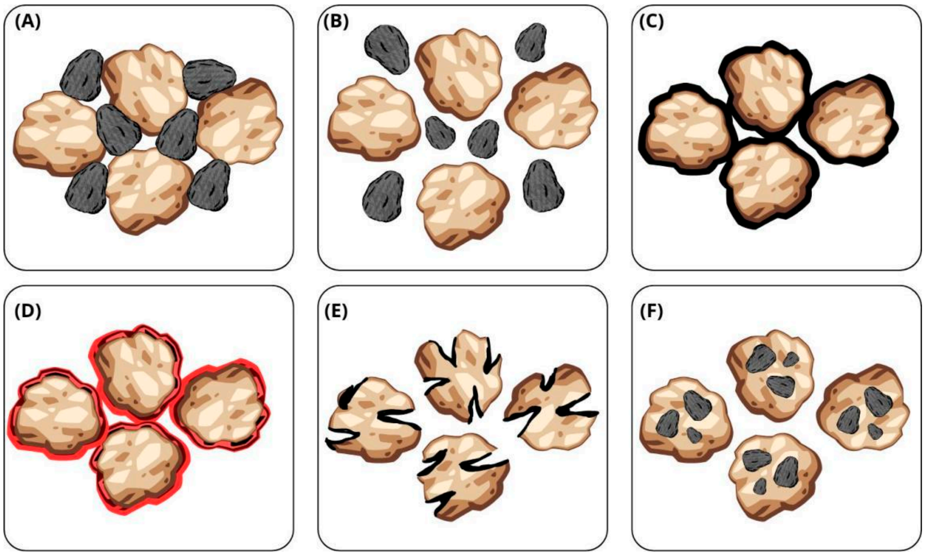

Figure 6. Forms of Contaminant Occurrence in Soil: (**A**) Adsorbed between grains; (**B**) As independent particles; (**C**) Liquid coatings surrounding the grains; (**D**) Precipitated around the grains; (**E**) Within porous soil particles, on the walls and around the grains; (**F**) Absorbed into the grains. Adapted from Fatin-Rouge [39].

Soils with high organic matter and clay content tend to retain contaminants more strongly due to the high cation exchange capacity (CEC) of these fractions, which significantly reduces the mobility of pollutants. Given this complexity, remediation techniques that promote the physical separation and mobilization of contaminants are considered promising strategies.

Soil washing using hydrocycloning is an ex situ remediation technique that involves a sediment dewatering system comprising a series of hydrocyclones (Figure 7). These devices apply centrifugal and gravitational forces to separate fine particles (clays and silts) from coarser fractions (sands and gravel). In addition to particle separation, the system also performs granulometric classification of the sediment, concentrating the pollutants, typically adsorbed onto finer particles, into a reduced volume, thereby facilitating their targeted treatment and final disposal.

The process consists of four main stages [40]:

1. Double-stage hydrocycloning: The contaminated soil is washed and subjected to successive cycles of particle size separation to isolate finer particles.
2. Coagulation in a conical tank: The liquid fraction containing fine particles (clay and silt) is directed to a tank, where a chemical coagulant (anionic polymer) is added to promote the aggregation of contaminants into flocs.
3. Sedimentation: The coagulated mixture (water + fine particles + coagulant) is transferred to a conical bottom settling tank, where the flocs are allowed to settle by gravity.
4. Closed-loop circuit: The clarified water is recirculated back into the system. At the same time, the sludge containing the concentrated contaminants is transferred to geotextile dewatering bags (geobags) for drying and subsequent disposal in a licensed landfill [41].

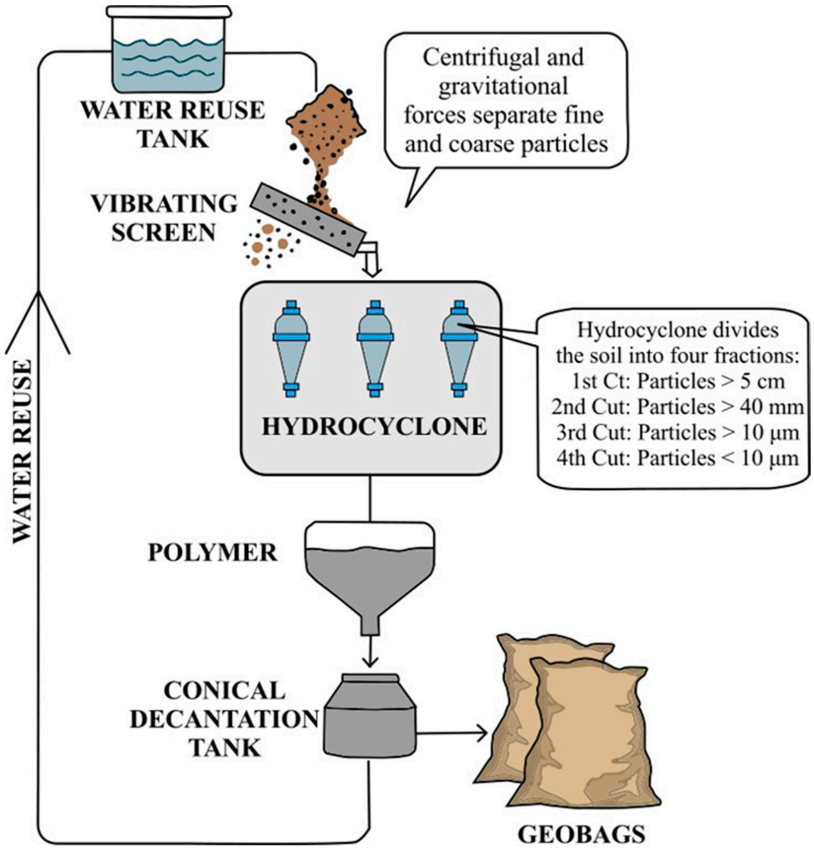

Figure 7. Schematic illustration of the stages of the soil washing process using hydrocycloning.

The soil used in the remediation process was sourced from excavation areas defined based on prior detailed site investigations and human health risk assessment studies, which enabled the identification and demarcation of zones containing solid waste and contaminated soil [42,43]. The intervention covered a total area of approximately 15,000 m^2 and involved the excavation of 6498 m^3 of material, including both waste and impacted soil. Figure 8 presents the breakdown of the volumes associated with each stage of the remediation process: the total volume excavated, the portion of construction and demolition waste (CDW) sent for reuse; the volume of soil treated using biopiles, due to high concentrations of petroleum hydrocarbons (BPF heavy-oil); and the fraction directed to primary screening, which preceded the hydrocyclone treatment [40,41].

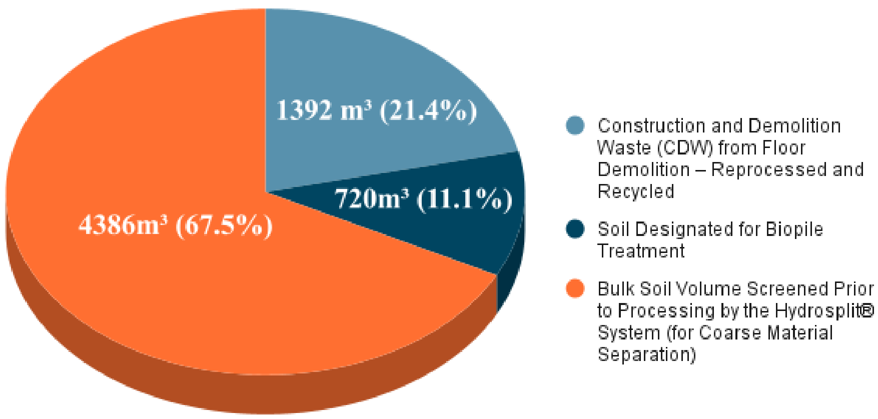

Figure 8. Excavated soil volumes (total = 6498 m^3).

Basic operational parameters were as follows:

i. Hydrocyclone model and geometry: 3 serial units Bradley style, 250 mm diameter.
ii. Feed pressure and flow: medium date 60–70 kPa and 5 to 10 L/s flow rate.
iii. Recirculation ratio: 85% to 95% in volume.
iv. Coagulant identity: anionic polymer (5 to 10 ppm) and limestone.
v. Sedimentation residence time: up to 12 h in conic decanter, and from 2 to 4 months in geobags.
vi. Geobags specifications: 25 m^3 volume, 4 units in parallel made of polyester material.

Approximately 900 m^3 of water was used in the soil washing operation, with 90% sourced from rainwater harvesting, demonstrating a sustainable approach to water resource management. The residual water (around 30 m^3) was destined for the wastewater treatment plant.

The washing process enabled the separation of excavated material into different grain-size fractions. These fractions were subsequently collected and subjected to laboratory analyses to assess their suitability for reuse in earth fill engineering works or their classification for final disposal. The residual fraction, essentially composed of fine particles with adsorbed contaminants, was stored in geobags for dewatering and later sent to a licensed hazardous waste landfill that is authorized to receive such classified materials.

3. Results and Discussion

3.1. Efficiency of Hydrocyclone Soil Washing

The application of the soil washing technique using hydrocycloning enables the effective treatment of a total volume of 3019 m^3 of contaminated soil, previously separated through a preliminary screening stage. The process was carried out in three main separation stages, as illustrated in Figure 9.

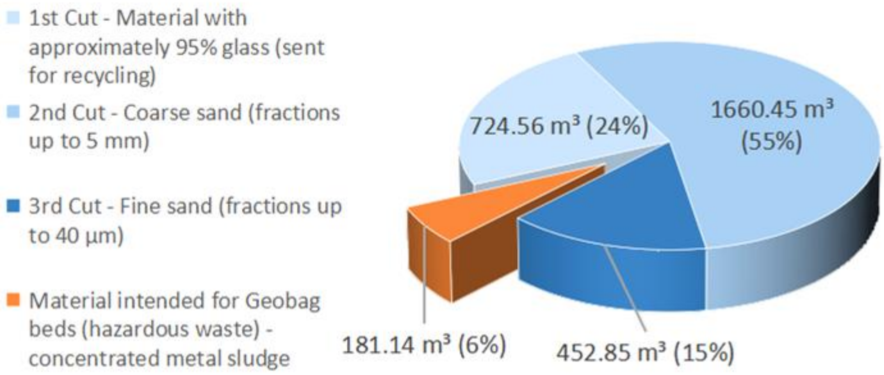

Figure 9. Volumes of materials treated by cutting in the hydrocycloning.

In the first separation stage (1st cut), approximately 724.56 m^3 of material composed of about 95% glass was recovered and sent for recycling. The second cut, corresponding to the coarse sand fraction (up to 5 mm), yielded 1660.45 m^3 of material. The third cut, referring to a fine sand fraction (up to 40 μm), resulted in 452.85 m^3 of finer material.

As a result of the contaminant separation and concentration step, the process generated approximately 181.14 m^3 of sludge with high concentrations of heavy metals. This material, considered hazardous waste, was destined for geobag beds and subsequently transported to a licensed hazardous waste landfill for final disposal.

Figure 9 summarizes the volumes treated and segregated through the hydrocycloning process, demonstrating the technology's effectiveness in reducing the final volume of hazardous waste while enabling the recovery and reuse of recyclable and inert materials.

In addition to the physical segregation of materials achieved during the soil washing process using hydrocycloning, chemical analyses were conducted to determine the concentration of heavy metals in distinct granulometric fractions: raw soil, coarse sand, fine sand, and the residual materials retained in geobags (Geobag 1 and Geobag 2).

The results were compared with the reference and intervention values for industrial land use defined by the Brazilian National Environmental Control Agency [41], which establishes soil quality criteria and guideline values related to the presence of chemical substances.

Following the separation and washing processes, a significant decrease in contaminant concentrations was observed in the recyclable fractions. Both the coarse and fine sand fractions exhibited heavy metal concentrations below the legal limits for all parameters analyzed, demonstrating the effectiveness of the hydrocycloning technique in reducing contamination and enabling the potential reuse of these materials.

Conversely, the residual fraction retained in the geobags presented elevated concentrations of heavy metals and was therefore classified as hazardous waste. This material was properly disposed of at a licensed hazardous waste landfill, preventing reintroduction of contaminants into the environment.

Table 3 presents the concentration levels of selected elements in each granulometric fraction (batch), along with the corresponding Brazilian regulatory thresholds, providing a clear overview of the separation process's efficiency and justification for the destination of each fraction. As mentioned, no additional environmental and ecotoxicological investigations were conducted, although such assessments remain important in future studies to evaluate potential impacts at the site and its surroundings.

Table 3. Concentrations of PTEs in the granulometric soil fractions of the different cuts [40] and comparison with target values of CONAMA Resolution n. 420/2009 [33] intervention values.

Parameter	Unit	Coarse Sand (ISM)		Fine Sand (ISM)		Geobag 1	Geobag 2	CONAMA 420
		Batch 1	Batch 2	Batch 1	Batch 2	Batch 1	Batch 2	SSTL
Antimony	mg·kg^{-1}	<1	<1	<1	<1	78	65	10
Arsenic	mg·kg^{-1}	<1	<1	5	7	356	435	55
Barium	mg·kg^{-1}	42	14	16	26	309	350	500
Cadmium	mg·kg^{-1}	3	5	6	6	63	73	8
Lead	mg·kg^{-1}	46	58	133	160	2270	2460	300
Cobalt	mg·kg^{-1}	1	<1	<1	2	103	89	65
Cooper	mg·kg^{-1}	13	20	20	34	450	520	400
Chromium	mg·kg^{-1}	123	104	88	72	131	128	300
Chromium VI	mg·kg^{-1}	<1	<1	<1	<1	131	645	-
Mercury	mg·kg^{-1}	139	979	101	174	10	14	36
Molybdenum	mg·kg^{-1}	5	4	4	3	4	4	100
Nickel	mg·kg^{-1}	32	26	24	24	55	63	100
Silver	mg·kg^{-1}	6	<1	<1	<1	109	116	50
Selenium	mg·kg^{-1}	<1	<1	<1	<1	32	17	-
Zinc	mg·kg^{-1}	114	112	30	50	770	844	1000

3.2. Resilience Facing Climate Change

The application of the soil washing remediation technique using hydrocycloning was not only effective in removing metallic contaminants from the soil but also proved to be strategically advantageous in the context of extreme weather events associated with climate change. As previously demonstrated in this study, the granulometric separation and washing process enabled the concentration of heavy metals, including lead, cadmium, antimony, copper, cobalt, nickel, and arsenic (metalloid), into the residual fraction retained in the geobags, which was subsequently disposed of in licensed Class I hazardous waste. The treated fractions, comprising coarse and fine sand, presented contamination concentrations below the thresholds established by the Brazilian National Environmental Control Agency [40], allowing for their safe reuse.

The effectiveness of the hydrocycloning system was further highlighted following the 2024 flood, reinforcing its value beyond immediate decontamination outcomes. In flood scenarios, the remobilization of heavy metals from contaminated soil poses a significant environmental and public health hazard, especially for populations exposed to contaminated water or the sediment-laden mud transported by floodwaters. By achieving prior decontamination of the affected soils, the technique acted preventively and effectively, significantly reducing the risks of human exposure and ecotoxicological impact during the extreme weather event. During the extreme flood events, although the site was inundated (Figure 2), the backfilled treated soil did not exhibit significant erosion due to controlled compaction. Furthermore, the native vegetation that established after backfilling (Figure 5d–h), due to the soil biota recovery, was not affected by the event and contributed to the site resilience.

The flood event would have negatively impacted alternative remediation techniques considered during the project's planning stages. Surface runoff and the erosion or removal of confining layers, such as in the case of localized clay capping, could have compromised their integrity. Similarly, chemical stabilization or biotreatment strategies could have led to the dispersion of partially treated soil, undermining their suitability under such conditions. Excavation, followed by off-site disposal, also posed sustainability challenges, particularly due to the environmental costs associated with the excavation process, transportation to the landfill, and the need to backfill the area with uncontaminated material.

Finally, it is worth highlighting that, beyond its efficacy in soil decontamination and its demonstrated resilience to climate-related disturbances, the adopted technique contributed significantly to the local regeneration of vegetation. As illustrated in Figure 5, the revegetation process initiated in 2019 has shown significant progress, indicating that the reestablishment of vegetation may have played a complementary role in mitigating the impacts of subsequent flood events.

4. Conclusions

This study, grounded in the principles of adaptative remediation and climate resilience, demonstrated the effectiveness of advanced soil washing with hydrocycloning for the local treatment of contaminated soils with PTEs, such as arsenic and chromium. The intervention not only removed contaminants (heavy metals and arsenic) successfully but also proved robust during the extreme flooding event of 2024, preventing the mobilization of PTEs and protecting nearby vulnerable communities from exposure risks.

The remediation process achieved key sustainability and performance indicators:

- Volume reduction: only 6.6% of the treated soil (200 m^3) required hazardous waste disposal.
- Water reuse: the system operated in a closed loop with 900 m^3 of water, 90% from rainwater harvesting.

- Material recovery: 93.4% of the soil was reused as granular material for backfilling.
- Risk prevention: since 2022, the area has remained free of contamination, reducing ecotoxicological and public health risks during flood-prone events.

These outcomes confirm the value of early, climate-adaptive remediation strategies in enhancing the resilience of contaminated sites under increasingly unstable climatic conditions.

In conclusion, the adoption of sustainable remediation measures must prioritize resilience, particularly considering climate change, which represents an additional challenge to maintaining the stability achieved in controlling environmental toxicological risks.

For remediation of PTEs using hydrocycloning, particular attention should be paid to the abrasive and degradative effect of soils and wastes on equipment components. These issues often cause significant operational difficulties for field teams, resulting in considerable time loss and increased project costs.

Complementary studies are recommended, including the assessment of ecotoxicological risk, the evaluation of sediment dispersion and the monitoring of long-term stability of the local backfill, as well as the determination of PTEs bioaccumulation factors in local plants and biota.

Author Contributions: Conceptualization, P.F.d.S., A.S. and G.B.; Methodology, P.F.d.S., A.S. and G.B.; Formal analysis, M.S.; Investigation, M.S.; Writing—original draft, M.S., P.F.d.S., A.S. and G.B.; Writing—review & editing, M.S., P.F.d.S., A.S. and G.B.; Supervision, P.F.d.S., A.S. and G.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The work was developed under the scope of SG-Vidros do Brasil Remediation Project and Paula F. da Silva & M. Graça Brito acknowledges the support given by R&D Unit GEOBIOTEC—UID/04035: GeoBioCiências, GeoTecnologias e GeoEngenharias.

Conflicts of Interest: The authors declare no conflicts of interest. The research was conducted without commercial or financial relationships that could be construed as a potential conflict of interest.

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