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Passive Treatment of Arsenic-Contaminated Dewatering Water Using a Natural Laterite Permeable Reactive Barrier (PRB): Performance Evaluation and Implications for Sustainable Mine Water Management

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Abstract

Arsenic contamination of dewatering water is a major environmental challenge associated with gold mining. Permeable Reactive Barriers (PRBs) offer a sustainable and low-cost passive treatment alternative to conventional technologies. This study evaluated the performance of a natural laterite-based PRB installed at the Sabodala-Massawa gold mine (Senegal) for treating arsenic-contaminated dewatering water. Monitoring was conducted from September 2023 to June 2026 using 49 paired measurements of arsenic concentrations upstream and downstream of the PRB. Influent arsenic concentrations ranged from 46 to 935 $\mu g \cdot L^{-1}$, while effluent concentrations varied between 0 and 386.5 $\mu g \cdot L^{-1}$. The PRB achieved a mean arsenic removal efficiency of 82.2 ± 22.2%, with a median of 88.9%, demonstrating consistently high treatment performance despite moderate temporal variability. Most treated water samples complied with the Senegalese discharge standard (300 $\mu g \cdot L^{-1}$) and frequently met the International Finance Corporation guideline value (100 $\mu g \cdot L^{-1}$). A moderate positive correlation was observed between influent and effluent arsenic concentrations (r = 0.457), while treatment efficiency improved during the initial months before showing a slight decline after September 2025, suggesting gradual ageing of the reactive material. Sediment analyses further revealed substantial reductions in arsenic (56.6%) and antimony (78.2%) concentrations between the upstream and downstream sections of the PRB, confirming efficient metalloid retention. The treatment performance is mainly attributed to physical filtration, adsorption onto iron oxyhydroxides contained in the lateritic material, and co-precipitation processes. Overall, the results demonstrate that natural laterite is an effective, sustainable, and cost-efficient reactive medium for passive treatment of arsenic-contaminated mine water under tropical conditions. Long-term monitoring is recommended to optimize PRB performance and support the wider application of this technology in mining environments affected by arsenic contamination.

Keywords

Permeable Reactive Barrier (PRB), Laterite, Arsenic Removal, Mine Water, Adsorption

1. Introduction

Mining is a major driver of economic development; however, it also generates significant environmental pressures, particularly through the contamination of water resources by metals and metalloids [1] [2]. Among these contaminants, arsenic (As) is considered one of the most critical because of its high toxicity, mobility in aquatic environments, and long-term persistence [3]. Dewatering water generated during mining operations often contains elevated arsenic concentrations, primarily resulting from the weathering and oxidation of sulfide minerals such as arsenopyrite (FeAsS). When discharged without appropriate treatment, these waters become a major source of surface water and groundwater contamination, posing serious risks to ecosystems and human health [1]. Chronic exposure to arsenic has been associated with numerous adverse health effects, including cancer and cardiovascular diseases [4]. Conventional arsenic treatment technologies, including coagulation-flocculation, chemical precipitation, ion exchange, adsorption onto synthetic materials, and membrane processes, generally achieve high arsenic removal efficiencies [5] [6]. However, these technologies remain expensive due to their high chemical and energy requirements, intensive maintenance, and the generation of arsenic-rich sludge that requires appropriate treatment and disposal [7] [8]. In response to these limitations, innovative and sustainable *in situ* remediation technologies have been developed, among which Permeable Reactive Barriers (PRBs) have emerged as an efficient, sustainable, and cost-effective solution for the remediation of contaminated groundwater plumes [9] [10]. When constructed from natural materials such as laterite, PRBs offer an economical alternative, particularly suitable for developing countries. The performance of a Permeable Reactive Barrier mainly depends on the physicochemical properties of the reactive material, including its specific surface area, porosity, hydraulic conductivity, and sorption capacity [10]. Iron oxyhydroxide-rich materials are widely recognized as highly effective natural adsorbents for arsenic removal because they promote the formation of stable surface complexes between arsenic species and hydroxyl groups on ferric minerals [11]. Specific adsorption, co-precipitation with iron oxyhydroxides, and, under certain geochemical conditions, redox reactions are currently recognized as the main mechanisms controlling arsenic immobilization in passive treatment systems [5]. In tropical regions, lateritic soils represent particularly promising materials for the construction of natural PRBs. Rich in goethite, hematite, gibbsite, and other iron and aluminum oxyhydroxides, laterites exhibit a high adsorption capacity toward both As(III) and As(V) species [4] [12]. Their widespread availability, low extraction cost, and excellent geochemical stability make them an attractive and sustainable alternative to engineered reactive materials [10]. Recent studies have reported arsenic removal efficiencies exceeding 90% using natural laterites, whereas iron oxide-modified laterites have achieved removal efficiencies approaching 99% under controlled laboratory conditions [13] [14]. The treatment system investigated in this study consists of a natural laterite-based Permeable Reactive Barrier located between two retention ponds at the Sabodala-Massawa gold mine (Senegal). The upstream pond (Dam 4 Upstream) receives arsenic-contaminated dewatering water generated by mining operations, whereas the downstream pond (Dam 4 Downstream) collects the treated water after it has passed through the natural lateritic barrier. The objective of this study was to evaluate the efficiency of this natural laterite-based PRB for the removal of dissolved arsenic from mine dewatering water. The selection of laterite as the reactive material was motivated by its high content of iron oxyhydroxides, particularly goethite and hematite, which exhibit a strong affinity for arsenic adsorption, as well as by its abundance in Senegal, making it an inexpensive and locally available material suitable for passive mine water treatment [13].

2. Materials and Methods

2.1. Study Area

The study was conducted at the Sabodala-Massawa mining complex, operated by Sabodala Gold Operations (SGO), located in the Saraya Department, Kédougou Region, southeastern Senegal. The mining district lies within the Mako Birimian Belt, one of the major gold-producing provinces of the West African Craton, where gold mineralization is associated with intensely altered volcano-sedimentary formations and sulfide-rich deposits containing abundant pyrite and arsenopyrite [15]. This study focused on dewatering water generated during open-pit mining operations. These groundwater inflows are continuously pumped to maintain safe mining conditions and contain elevated concentrations of dissolved arsenic, mainly resulting from the oxidation of arsenic-bearing sulfide minerals, particularly arsenopyrite, present in the ore and surrounding host rocks [16]. The release of arsenic into dewatering water represents one of the major environmental challenges associated with gold mining and requires effective treatment before discharge into the receiving environment [13] [17].

2.2. Description of the Natural Laterite-Based Permeable Reactive Barrier (PRB) System

The treatment system investigated in this study is based on a natural Permeable Reactive Barrier consisting of a lateritic formation located between two mining ponds (Figure 1). The upstream pond (Dam 4 Upstream) serves as the initial reservoir receiving arsenic-contaminated dewatering water, whereas the downstream pond (Dam 4 Downstream) functions as the receiving basin following passive treatment. The two ponds are hydraulically connected through a natural lateritic barrier whose geochemical properties are exploited to remove dissolved arsenic from the flowing water [13]. The lateritic material acts as a natural reactive medium, promoting arsenic attenuation through a combination of physical filtration, adsorption onto iron oxyhydroxides, and co-precipitation processes, thereby improving the quality of the discharged water.

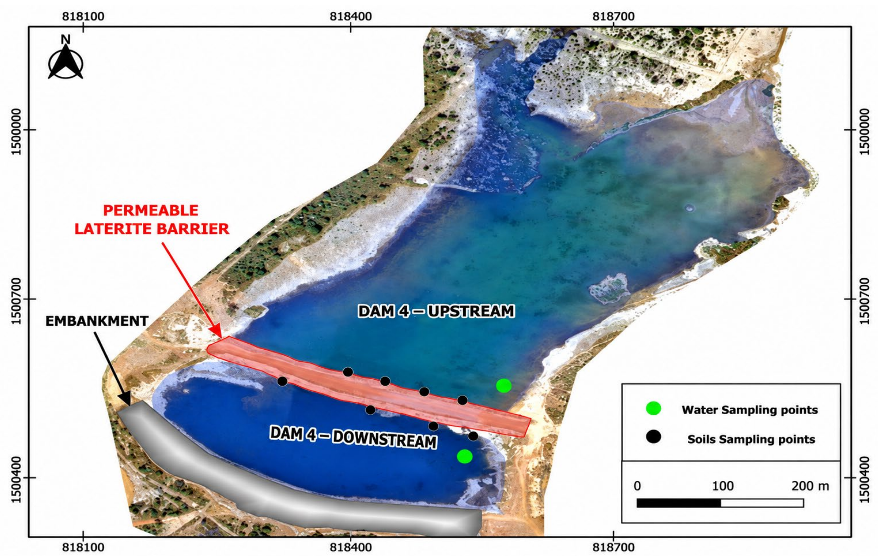

Figure 1. Natural laterite-based Permeable Reactive Barrier (PRB) and the upstream (Dam 4 Upstream) and downstream (Dam 4 Downstream) ponds.

The lateritic strip is characterized by a natural porosity resulting from its pedological and mineralogical organization, together with a network of fractures and structural discontinuities that control groundwater flow through the weathered formations [18] [19]. In addition to these natural features, secondary fractures generated during blasting operations for dam construction have further enhanced the hydraulic conductivity of the lateritic massif by creating preferential flow pathways that hydraulically connect the upstream and downstream ponds [20]-[22]. Water flowing through this fractured zone interacts extensively with the reactive minerals of the laterite, particularly iron oxides and oxyhydroxides, which are well known for their high affinity toward metalloids such as arsenic [10] [23]

[24]. The high abundance of iron oxides and oxyhydroxides (goethite, hematite, and ferrihydrite), together with aluminum hydroxides in the lateritic material [13], promotes the retention of arsenic species through the formation of stable Fe-O-As and Al-O-As surface complexes. These mechanisms are widely recognized as the dominant processes controlling arsenic mobility and bioavailability in both natural environments and passive treatment systems [11] [25].

2.3. Sampling Strategy and Monitoring

To evaluate the performance of the treatment system, water sampling points (green circles) were established upstream and downstream of the PRB, while sediment sampling points (black circles) were distributed along the reactive lateritic strip. Upstream and downstream sampling was carried out on the same day at a monthly frequency (at least once per month) throughout the study period, which made it possible to constitute the 49 upstream-downstream pairs of measurements analyzed. Hydraulic transit through the barrier occurs naturally as a function of the effective porosity of the lateritic material. This experimental design enabled the assessment of the spatial and temporal variations in arsenic concentrations in water, as well as arsenic accumulation in sediments, thereby providing insight into the retention mechanisms operating within the barrier and allowing evaluation of the efficiency of the natural Permeable Reactive Barrier for the passive treatment of mine dewatering water. Arsenic concentrations in water samples were determined using an Arsenator, whereas sediment arsenic concentrations were measured by X-ray fluorescence (XRF). Total arsenic determination was carried out using the Palintest Kemio™ analyzer, equipped with disposable sensors specific to total arsenic and an arsenator. The principle of this method is based on electrochemical detection, during which the arsenic dissolved in the sample reacts with specific reagents before being quantified by a single-use sensor inserted into the device. The electrochemical signal generated is directly proportional to the arsenic concentration and is automatically converted by the analyzer into a concentration, expressed in µg/L. Sediment sampling on either side of the barrier was carried out at one upstream point and one downstream point of the device. This sampling, of an exploratory nature, aimed to assess a general trend in arsenic concentrations on either side of the barrier, rather than to establish statistical proof of retention.

2.4. Statistical Analysis

Descriptive statistical indicators, including the mean, variance, standard deviation, and Pearson correlation coefficient, were used to evaluate the overall performance of the PRB, quantify the variability of arsenic removal efficiencies, and assess the stability of the treatment process throughout the monitoring period.

- **Arsenic Removal Efficiency (%)**

The arsenic removal efficiency for each sampling campaign was calculated as:

$$x(\%) = \frac{C_{\text{amont}} - C_{\text{aval}}}{C_{\text{amont}}} \times 100$$

where C_{amont} and C_{aval} represent the arsenic concentrations measured upstream and downstream of the PRB, respectively.

- **Mean Removal Efficiency**

The overall mean removal efficiency was calculated from the entire dataset (n observations) as:

$$\bar{x} = \frac{1}{n}\sum x_i .$$

- **Variance of Removal Efficiency (s^2)**

The variability of treatment performance was assessed using the sample variance:

$$s^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})1^2}{n-1}$$

where:

- s^2 = sample variance ($\%^2$);
- x_i = removal efficiency of the i^{th} observation (%);
- $\bar{x}$ = mean removal efficiency (%);
- n = number of observations.
- **Standard Deviation**

The standard deviation was calculated as: $S = \sqrt{s^2}$

- **Pearson Correlation Coefficient**

The Pearson correlation coefficient (r) was used to assess the strength and direction of the linear relationship between upstream and downstream arsenic concentrations. Its value ranges from −1 to +1, where:

- $r = +1$ indicates a perfect positive linear correlation;
- $r = -1$ indicates a perfect negative linear correlation;
- $r = 0$ indicates no linear correlation.

For a dataset containing n paired observations (x_i, y_i), the Pearson correlation coefficient was calculated as

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where:

- x_i = upstream arsenic concentration;
- y_i = downstream arsenic concentration;
- $\bar{x}$ = mean upstream arsenic concentration;
- $\bar{y}$ = mean downstream arsenic concentration.

3. Results and Discussion

3.1. Evaluation of Arsenic Concentrations before and after Treatment

The aerial photograph (**Figure 2**) illustrates the location of the natural Permeable

Reactive Barrier (PRB) between the upstream pond (Dam 4 Upstream), which receives arsenic-contaminated dewatering water, and the downstream pond (Dam 4 Downstream), where the treated water is collected. This aerial view highlights the hydraulic continuity of the treatment system and the natural lateritic strip that serves as the reactive medium through which the water flows, enabling passive arsenic removal before discharge to the downstream environment.

Figure 2. Drone aerial view of the experimental natural Permeable Reactive Barrier (PRB) system.

Table 1 and the temporal trends shown in **Figure 3** illustrate the evolution of arsenic concentrations in the upstream (Dam 4 Upstream) and downstream (Dam 4 Downstream) ponds throughout the monitoring period. Arsenic concentrations measured in the upstream dewatering water exhibited substantial temporal variability from September 6, 2024, to June 20, 2026, ranging from 46 to 935 $\mu g \cdot L^{-1}$. These fluctuations reflect changes in the contaminant load of the dewatering water associated with variations in mining activities, seasonal hydrological conditions, and the progressive weathering and oxidation of arsenic-bearing sulfide minerals within the ore body. Following passage through the natural PRB, arsenic concentrations decreased markedly, with effluent concentrations ranging from 0 to 386.5 $\mu g \cdot L^{-1}$. The relatively high concentrations observed at the outlet during the initial months of operation suggest a start-up or conditioning phase of the barrier. This period likely corresponds to the progressive stabilization of the hydraulic regime and the gradual development of adsorption processes on the iron oxides and oxyhydroxides contained in the lateritic material. As operation continued, downstream arsenic concentrations steadily declined, reaching very low levels and, during several monitoring campaigns, falling below the analytical detection limit. These results indicate a continuous improvement in the treatment efficiency of the Permeable Reactive Barrier up to September 13, 2025. After this period, a slight increase in downstream arsenic concentrations was observed, although the overall treatment performance remained consistently high.

Table 1. Arsenic concentrations and removal efficiency in Dam 4 (upstream/downstream).

N°	C_{amont} (μg/L)	C_{aval} (μg/L)	x_i (%)	N°	C_{amont} (μg/L)	C_{aval} (μg/L)	x_i (%)
1	120	45	62.5	26	99	9	90.9
2	140	9	93.6	27	465	8	98.3
3	110	25	77.3	28	500	18	96.4
4	150	30	80.0	29	500	4.5	99.1
5	125	15	88.0	30	500	5	99.0
6	135	20	85.2	31	500	5.5	98.9
7	110	30	72.7	32	500	6	98.8
8	90	14	84.4	33	500	208	58.4
9	50	6	88.0	34	500	386.5	22.7
10	63	8	87.3	35	500	366	26.8
11	81	10	87.7	36	362	352	2.8
12	63	8	87.3	37	204	132	35.3
13	65	8	87.7	38	139	76	45.3
14	46	4	91.3	39	600	129	78.5
15	87	2	97.7	40	250	119	52.4
16	125	0	100.0	41	250	43.6	82.6
17	140	6	95.7	42	924	193	79.1
18	145	5	96.6	43	935	137	85.3
19	250	8	96.8	44	596.5	66.4	88.9
20	200	0	100.0	45	571.5	60.5	89.4
21	170	0	100.0	46	564.3	55.9	90.1
22	150	0	100.0	47	350	55.2	84.2
23	340	9	97.4	48	797.5	11.2	98.6
24	130	8	93.8	49	924	193	79.1
25	225	10	95.6				

The performance of the Permeable Reactive Barrier (PRB) was evaluated using 49 paired measurements of arsenic concentrations collected upstream and downstream of the system. Arsenic removal efficiencies ranged from 2.76% to 100%, reflecting temporal variations in PRB performance that were likely associated with fluctuations in influent arsenic concentrations, hydraulic conditions, and the reactivity of the lateritic filtering material. Mean arsenic concentrations decreased from 313.10 $\mu g \cdot L^{-1}$ upstream to 59.60 $\mu g \cdot L^{-1}$ downstream, corresponding to an average reduction of 253.5 $\mu g \cdot L^{-1}$. This substantial decrease confirms the ability of the PRB to effectively mitigate arsenic contamination in mine dewatering water. The marked reductions in downstream arsenic concentrations (Table 1) demonstrate the capacity of the barrier to retain arsenic efficiently despite the considerable variability in influent concentrations. Overall, the observed removal efficiencies indicate a consistently high treatment performance, suggesting that the PRB achieved a substantial reduction in the arsenic load. The high treatment efficiency can be attributed to the physicochemical properties of the lateritic material, which is rich in iron and aluminum oxides [13] [26], minerals well known for their strong affinity toward arsenic species. The dominant removal mechanisms include adsorption onto iron oxyhydroxides, co-precipitation with newly formed iron phases, and physical filtration within the porous lateritic matrix. Overall, the PRB maintained most downstream arsenic concentrations below the Senegalese discharge standard NS 05-061 (300 μg·L^{-1}) [27] and, in many cases, at or below the International Finance Corporation (IFC) guideline value for mining effluents (100 μg·L^{-1}) [28]. These findings demonstrate the strong potential of natural laterite-based PRBs as a passive treatment technology for arsenic-contaminated mine water. The observed performance is consistent with numerous studies reporting that Permeable Reactive Barriers provide an efficient and sustainable solution for arsenic attenuation in groundwater and mining effluents [9] [10]. Descriptive statistical analyses were performed to assess the overall performance and temporal variability of the treatment system. The results indicate a high overall efficiency of the PRB for dissolved arsenic removal. The mean removal efficiency reached 82.19% ± 22.19% (n = 49; variance = 492.34%^{2}), indicating that, on average, the barrier removed more than four-fifths of the influent arsenic load throughout the monitoring period. Although removal efficiencies exhibited some variability (variance = 492.34%^{2}), the consistently high mean removal efficiency demonstrates the robustness and long-term reliability of the passive treatment system under field operating conditions.

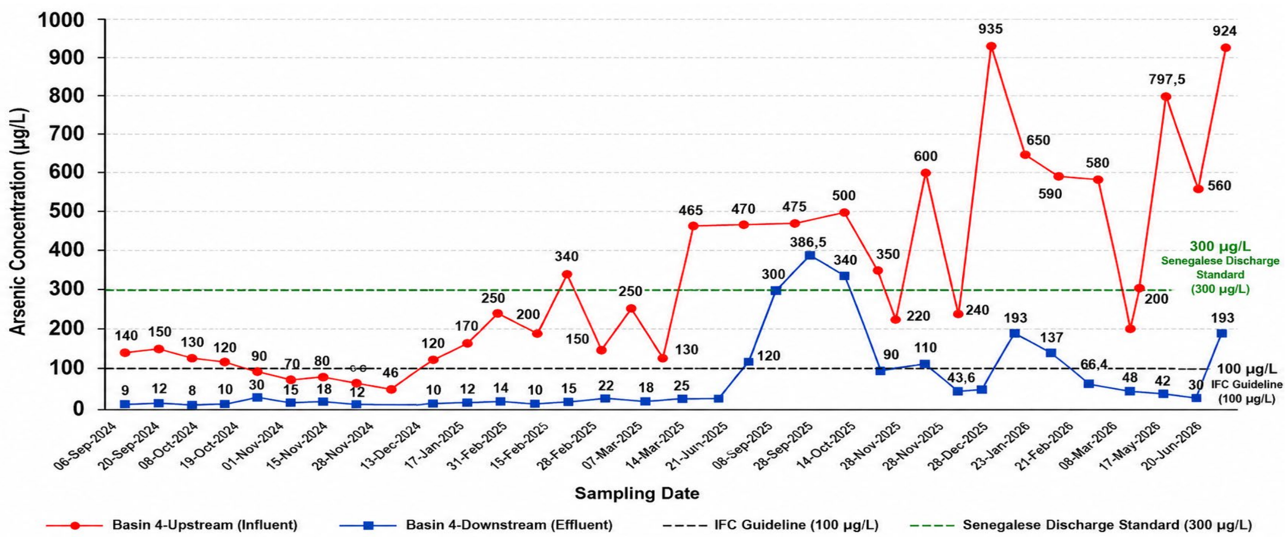

Figure 3. Temporal variation of arsenic concentration in dewatering water upstream and downstream of the naturel laterite-based Permeable Reactive Barrier (PRB).

This variability is likely associated with seasonal fluctuations, variations in mine dewatering rates, and differences in the lithology and mineralization of the drained zones. The median arsenic concentration (204 μg/L) is considerably lower than the mean concentration (313.10 μg/L), indicating a positively skewed distribution characterized by several episodes of very high arsenic concentrations (>800 μg/L). After treatment by the Permeable Reactive Barrier (PRB), the mean arsenic concentration decreased to 59.6 μg/L, corresponding to an average reduction of approximately 81%. The median concentration declined to only 11.2 μg/L, demonstrating that more than half of the collected samples contained very low residual arsenic concentrations. Nevertheless, effluent concentrations remained relatively dispersed (standard deviation = 96.5 μg/L), mainly because of a few isolated events during which the barrier temporarily exhibited lower removal efficiency (208 - 386.5 μg/L). The substantial difference between the mean and median further confirms a strongly skewed distribution dominated by a limited number of high values. Arsenic removal efficiencies ranged from 2.8% to 100%, with an average efficiency of 82.2%. The median removal efficiency (88.0%) exceeded the mean value, indicating that the relatively low removal efficiencies observed during a few sampling campaigns reduced the overall average. The quartile distribution further confirms the excellent overall performance of the PRB. The first quartile (Q1 = 79.1%) indicates that 75% of the observations achieved removal efficiencies greater than 79.1%, whereas the third quartile (Q3 = 96.8%) shows that 25% of the monitoring campaigns achieved removal efficiencies exceeding 96.8% (**Table 2**). These findings demonstrate that the treatment system maintained high and generally stable performance, with most removal efficiencies ranging between 79.1% and 96.8%. The coefficient of variation (27%) indicates only moderate variability in treatment performance. This variability can be mainly attributed to four isolated periods during which removal efficiencies declined sharply (2.8%, 22.7%, 26.8% and 35.3%). These episodes may have resulted from changes in hydrogeochemical conditions (Eh and pH), temporary increases in hydraulic flow that reduced residence time, or the remobilization of arsenic-bearing solid phases. Apart from these isolated events, the treatment performance remained remarkably stable. The Pearson correlation coefficient between upstream and downstream arsenic concentrations was $r = 0.46$, indicating a moderate positive correlation. This suggests that although effluent arsenic concentrations tend to increase when influent concentrations rise, the PRB substantially attenuates this increase through its retention mechanisms, including specific adsorption, coprecipitation with iron oxyhydroxides, and entrapment within the porous lateritic matrix. In contrast, the correlation between influent arsenic concentration and removal efficiency was very weak ($r \approx -0.07$), indicating that the treatment efficiency of the PRB was largely independent of the initial arsenic concentration over the concentration range investigated. Consequently, residual arsenic concentrations remained substantially lower than those measured in the untreated mine water.

Most downstream arsenic concentrations remained below the Senegalese discharge standard NS 05-061 (300 μg/L) and, for a large proportion of the monitoring period, below the International Finance Corporation (IFC) guideline value

Table 2. Descriptive statistics of arsenic concentrations and removal efficiency.

Parameters	Upstream (µg/L)	Downstream (µg/L)	Removal Efficiency (%)
Number of observations	49	49	49
Mean	313.10	59.60	82.19
Median	204.00	11.20	88.00
Minimum	46.00	0.00	2.80
Maximum	935.00	386.50	100.00
First quartile (Q1)	125.00	6.00	79.10
Third quartile (Q3)	500.00	60.50	96.80
Standard deviation	249.48	96.46	22.19
Coefficient of variation (%)	79.68	161.86	27.00

(100 µg/L) for mining effluents. Only a few sampling campaigns exceeded these thresholds, corresponding precisely to the periods of reduced treatment performance identified above. The excellent performance of the PRB can be attributed to the physicochemical properties of the lateritic material, which is rich in iron oxides and oxyhydroxides (goethite and hematite) as well as aluminum oxides. These minerals provide abundant active sites that promote specific adsorption of arsenic species, ligand-exchange reactions, and coprecipitation with ferric hydroxides. Furthermore, the porous and fractured structure of the barrier ensures sufficient hydraulic residence time, thereby enhancing interactions between dissolved arsenic and the reactive mineral surfaces. The results demonstrate that the natural Permeable Reactive Barrier (PRB) provides high and sustained efficiency for the removal of dissolved arsenic from mine dewatering water. The average removal efficiency of 82.2%, together with a median value of 88.0%, indicates that the system performed very effectively throughout most of the monitoring period. The few episodes of reduced performance were isolated and did not affect the overall treatment trend. The weak correlation between influent arsenic concentration and removal efficiency further confirms that the retention mechanisms remained effective despite substantial fluctuations in arsenic loading. These findings suggest that the laterite functions as a robust reactive medium capable of maintaining high removal efficiency over a broad range of influent arsenic concentrations, thereby confirming its suitability for the passive treatment of arsenic-contaminated mine water. The observed treatment performance is consistent with the high contents of iron and aluminum oxides previously reported in the Sabodala lateritic material [13]. These results are in agreement with previous studies. Mohan and Pittman (2007) [5] reported that iron oxide-rich materials possess a strong affinity for arsenic, enabling removal efficiencies exceeding 90%. Similarly, [9] demonstrated that permeable reactive barriers can maintain high treatment efficiency despite significant variations in influent water quality. The excellent performance of the investigated PRB can be attributed primarily to the min-

eralogical characteristics of the laterite. Mineralogical analyses showed that the material is rich in goethite, hematite, and gibbsite, minerals well known for their strong affinity toward arsenic species [13]. [19] demonstrated that iron oxide-rich laterites can remove more than 90% of dissolved arsenic under laboratory conditions. Likewise, Filella *et al.* [29] reported that ferruginous reactive media used in PRBs generally achieve arsenic removal efficiencies ranging from 70% to 95%, depending on water chemistry and hydraulic conditions. The removal efficiencies reaching 100% in the present study demonstrate that the natural laterites from Sabodala constitute a particularly effective reactive material. Unlike many previous investigations conducted under controlled laboratory conditions, the present study was performed under full-scale field conditions, representing a major strength. The observed performance therefore integrates the effects of seasonal variability, hydraulic fluctuations, and naturally occurring geochemical conditions, providing a more realistic assessment of the long-term behavior of a natural PRB. As emphasized by [23], field-scale investigations are essential for validating laboratory observations and assessing the long-term performance of permeable reactive barriers. Finally, the proposed technology offers several important environmental advantages. Unlike conventional treatment processes such as coagulation-precipitation, reverse osmosis, and ion exchange, the PRB operates without external energy input, chemical reagents, or significant waste generation. The use of locally available laterite also reduces operating costs and minimizes the carbon footprint associated with transporting reactive materials. Consequently, this approach is fully consistent with the principles of sustainable mine water management and Nature-based Solutions (NbS). Despite these promising results, long-term monitoring remains essential to evaluate the evolution of the barrier's sorption capacity, assess the risk of adsorption-site saturation, and investigate possible mineralogical transformations that could influence treatment performance over extended periods.

3.2. Analysis of Arsenic and Antimony Concentrations in Sediments Upstream and Downstream

The results show that the average arsenic concentration decreased from 520.7 ppm upstream to 226.0 ppm downstream, corresponding to a 56.6% reduction, whereas the average antimony concentration decreased from 234.0 ppm to 51.0 ppm, representing a 78.2% reduction (**Table 3**; **Figure 4**). These findings demonstrate the effectiveness of the Permeable Reactive Barrier (PRB) in immobilizing metalloids derived from mining-impacted waters.

Table 3. Arsenic (As) and Antimony (Sb) concentrations in sediments upstream and downstream of the Permeable Reactive Barrier (PRB).

Zone	As (ppm)	Mean As (ppm)	Sb (ppm)	Mean Sb (ppm)
Upstream (A1-A3)	442; 635; 485	520.7	308; 127; 267	234.0
Downstream (B1-B2)	193; 259	226.0	48; 54	51.0

However, the relatively high concentrations measured in the downstream sediments mainly result from the filtration effect of the PRB, which constitutes one of the principal mechanisms governing the operation of permeable reactive barriers [9]. As contaminated water flows through the barrier, its velocity decreases, promoting the settling of suspended solids and the trapping of fine particles enriched in arsenic and antimony (**Figure 4**). In mining environments, a substantial proportion of arsenic and antimony is transported in particulate or colloidal form, adsorbed onto iron oxyhydroxides, clay minerals, or particles generated by the weathering of mine wastes [1] [30]. As these particles pass through the PRB, they are retained within the pore network of the laterite or deposited immediately downstream, where the reduced flow velocity favors sedimentation. Consequently, the sediments located directly downstream of the barrier act as an accumulation zone for contaminated particles, explaining the relatively high concentrations that persist despite the marked improvement in water quality. This process is further enhanced by the mineralogical composition of the laterite used as the reactive material. Mineralogical analyses revealed that the laterite is rich in goethite, hematite, and aluminum oxyhydroxides, minerals well known for their high adsorption capacity toward arsenic and antimony [31]. Arsenate ions [As(V)] form highly stable inner-sphere complexes with hydroxyl groups on iron oxyhydroxide surfaces, thereby significantly reducing their mobility in the environment [11]. Similarly, antimony species, predominantly Sb(V), exhibit a strong affinity for these mineral surfaces, which explains why the reduction observed for antimony (78.2%) exceeded that of arsenic (56.6%) [31] [32].

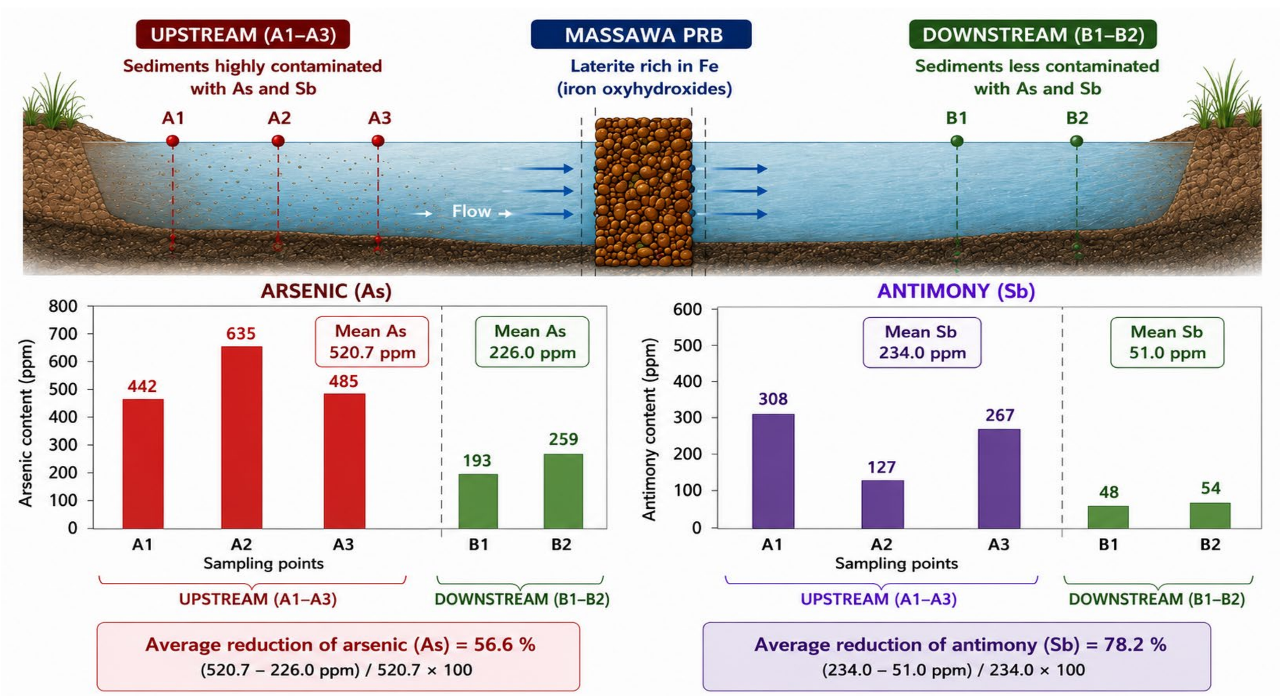

Figure 4. Spatial variation of arsenic (As) and antimony (Sb) concentrations in sediments upstream (A1-A3) and downstream (B1-B2) of the Permeable Reactive Barrier (PRB).

Furthermore, the PRB acts as a geochemical reactor that promotes the formation of new ferric phases. The oxidation of dissolved iron leads to the precipitation of amorphous iron oxyhydroxides, which incorporate arsenic and antimony through adsorption and coprecipitation processes [23] [33]. These mechanisms enhance the retention capacity of the barrier and contribute to the long-term immobilization of metalloids within the reactive zone. This behavior is characteristic of efficiently functioning permeable reactive barriers, in which contaminants are progressively trapped in solid phases adjacent to the barrier, thereby limiting their migration to downstream environments [9]. Overall, the PRB simultaneously provides physical filtration, geochemical adsorption, coprecipitation, and long-term stabilization of metalloids, confirming its potential as an effective passive technology for the treatment of arsenic- and antimony-contaminated mine waters.

3.3. Study Limitations

The present study has certain methodological limitations that should be highlighted for an appropriate interpretation of the results. First, the analytical monitoring focused on total arsenic concentration upstream and downstream of the device; pH, redox potential (Eh), dissolved iron, and competing ions (particularly phosphates, silicates, and sulfates) were not subject to concomitant measurements during the sampling campaigns. These parameters nonetheless play a determining role in the mechanisms of arsenic retention by iron oxyhydroxides (adsorption, coprecipitation). In their absence, the mechanisms discussed in the present study should be considered as interpretive hypotheses consistent with the existing literature on lateritic materials, rather than as processes directly demonstrated by our data. Complementary geochemical monitoring incorporating these parameters is recommended for subsequent phases of the pilot in order to confirm the proposed retention mechanisms. Second, despite this analytical limitation, the treatment performance observed throughout the monitoring period indicates that the permeable reactive barrier has not yet reached its retention capacity limits, with the variability in removal rate remaining within the expected range for this type of device over the study period. Third, sediment sampling on either side of the barrier was carried out at one upstream point and one downstream point of the device. This sampling, of an exploratory nature, aimed to assess a general trend in arsenic concentrations on either side of the barrier, rather than to establish statistical proof of retention. In the absence of replication, variability measurements, and independent background concentrations, these results should be interpreted with caution and considered indicative rather than conclusive. More systematic sampling, including replicates, background concentrations, and control points outside the device's zone of influence, would be necessary to confirm this trend in a statistically robust manner.

These limitations do not invalidate the general trends observed, but call for caution in interpreting the underlying mechanisms and invite continued monitoring of the device with a strengthened analytical protocol.

4. Conclusions

This study demonstrates that a laterite-based Permeable Reactive Barrier (PRB) is an effective passive solution for the treatment of arsenic-contaminated mine waters at the Sabodala-Massawa mining site (Senegal). It highlights the effectiveness of a natural laterite PRB for the passive remediation of arsenic-contaminated mining effluents. Analysis of 49 paired upstream-downstream measurements revealed an average arsenic removal efficiency of 82.2%, with a median of 88.0%, indicating consistently high and stable performance throughout the monitoring period.

The variability in removal efficiency, reflected by a moderate standard deviation and a coefficient of variation of approximately 27%, indicates that despite a few isolated fluctuations, the system maintained high treatment efficiency under most operating conditions. Statistical analyses further showed that 75% of the observed removal efficiencies exceeded approximately 79%, while 25% were greater than 97%, confirming that high treatment performance was the norm rather than the exception. The few low removal efficiencies recorded remained isolated events and did not alter the overall performance trend of the barrier. The monitoring results also demonstrated a significant reduction in arsenic concentrations between the upstream and downstream sides of the barrier, with removal efficiencies varying according to hydrogeological conditions and fluctuations in influent arsenic concentrations. Despite this variability, the PRB maintained downstream arsenic concentrations below the Senegalese discharge standard (NS 05-061: 300 μg/L) for most of the monitoring period and, on several occasions, close to or below the International Finance Corporation (IFC) guideline value of 100 μg/L, highlighting its strong potential for the passive treatment of mining effluents. The marked decrease in arsenic and antimony concentrations between the upstream and downstream sediments further demonstrates the effectiveness of the PRB in immobilizing these metalloids. These findings confirm the potential of laterite as a sustainable, low-cost reactive material for passive mine water treatment. Its local availability, low cost, and ability to maintain high removal efficiencies over an extended period make it a particularly suitable and sustainable solution for mining operations in tropical regions. Further investigations focusing on the maximum retention capacity of laterite, the mineralogical mechanisms governing metalloid immobilization, and the long-term evolution of barrier performance will contribute to optimizing the design, operational lifetime, and large-scale implementation of natural permeable reactive barriers. Overall, the results provide a robust scientific basis for the broader deployment of this technology and contribute to the development of innovative and sustainable mine water treatment strategies that combine high environmental performance, the use of locally available materials, and the mitigation of mining impacts on aquatic ecosystems.

Author Contributions

BD carried out the conceptualization, methodology, field data collection, laboratory analyses, data processing, and writing of the original manuscript draft. TD carried out the conceptualization, supervision, methodological validation, statistical analysis and interpretation of results, writing, review and editing of the manuscript, as well as project administration and funding acquisition. MD, MN, and EMS contributed to the analysis and interpretation of data as well as critical revision of the manuscript. TL carried out the laboratory analysis. All authors have read and approved the final version of the manuscript submitted for publication.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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