

Examining the Bauxite Residue Management Framework in Jamaica

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Abstract

In Jamaica, the proximity of bauxite and alumina operations to communities creates a particularly critical context for the environmental risks associated with the bauxite residue disposal sites. Additionally, the protection of water supply as a consequence of the geological setting and potential impacts on the watersheds are high priority objectives of the nation. The recent severe incidents in Hungary (Ajka) and Brazil (Brumadinho) have brought particular attention to the geotechnical engineering of the tailings sites. This has financial implications for the companies and the country, as well as for the sustainability of the local mining industry and associated processing operation. This also creates some governance challenges if the ownership of operations changes and results in differences in operational approaches. There is large variability in local regional geology, dam construction techniques, tailings properties and treatment. Though the general concepts of risk assessment are tacit, changes in global attitudes, seasonal climatic variations and environmental legal obligations are evolving. Further, for a mature industry these issues should be considered in light of current closure objectives. The utilization of bauxite residue is currently only modest, 3-4 % of the tonnage generated globally, but is being extensively investigated by many companies and universities, often with substantial national funds such as the European Union (EU), and is widely accepted to become more important with global trends towards the circular economy as alumina producers become more conscious of the importance of ESG.

Keywords: Bauxite residue management, Red mud, Governance, Risk assessment

1. Introduction

Jamaica had five refineries extracting alumina from bauxite: Jamalco, Ewarton Works, Alpart, Kirkvine Works and Revere. Only the first two refineries are currently in operation. JISCO Alpart suspended operations in 2019, and Kirkvine Works has not reopened since 2009 when the operations were halted during the worldwide economic crisis. The fifth, Revere, was closed in 1975 and the refinery dismantled. Each refinery has its own bauxite residue (red mud) disposal site or sites and consequently there are three operational bauxite residue disposal areas on the island. The inactive areas are at Revere and the ponds associated with the former Alcan operations located at Kirkvine, and Mount Rosser. The Alcan ponds at Kirkvine are closed and the Mount Rosser Pond which straddles the St. Catherine/ St. Ann parish border is in the closure phase.

The areas where bauxite is located, the four (4) alumina refineries, the bauxite residue disposal areas and the Revere area are indicated individually in Figure 1 below by name and location. Geographically the bauxite residue sites can be found in five parishes – St. Elizabeth, Manchester, Clarendon, St. Catherine and St. Ann. The spatial distribution impacts emergent rural towns which have expanded over time in relation to the alumina industry, as well as major waterways and aquifers. Operations in St. Catherine may directly impact the Rio Cobre treatment plant, which is the water supply for Spanish Town, a major populated area close to the capital city of Kingston. Meanwhile, the operations in St. Elizabeth have the potential to impact the water supply for

Mandeville, the capital city for the adjacent parish of Manchester. Operations in Clarendon may impact the Rio Minho.

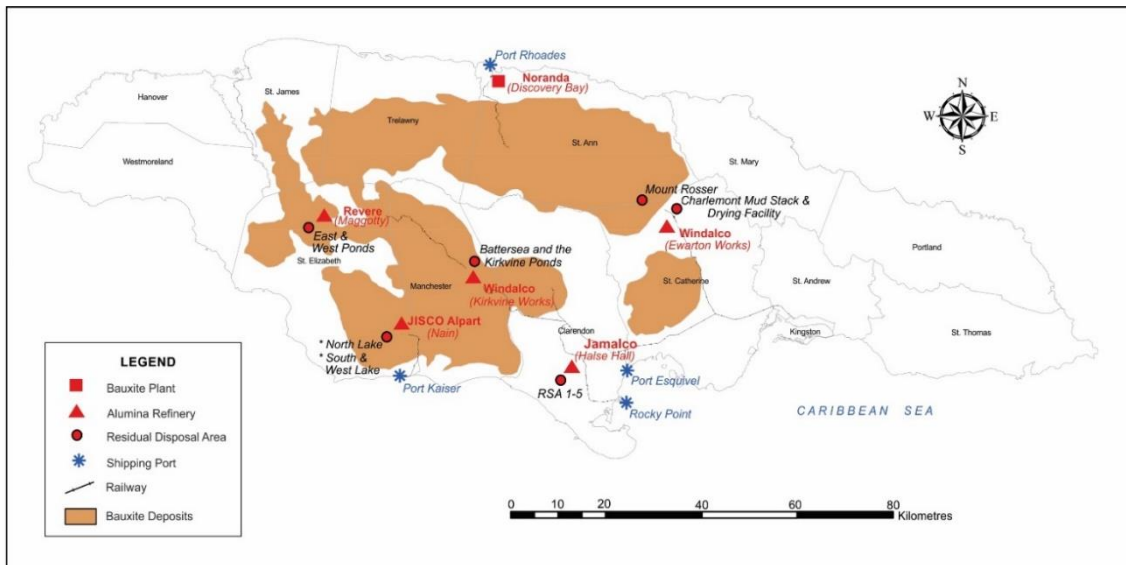


Figure 1. Location of bauxite residue disposal sites in Jamaica.

Jamaican bauxite residues are generated at a ratio of 1 tonne of alumina to roughly 1 tonne of mud; the volumes at each location are estimated and shown in Table 1. This results in a total of approximately 130 million tonnes of bauxite residue stored in residue areas; volumes from each location are shown in Table 1.

Table 1. Current Bauxite Residue Stocks in Jamaica.

Location		Parish	Area (ha)	Volume (Millions Mt)
Kirkvine Works	Kirkvine Ponds and Battersea Mud Disposal Site	Manchester	100 (+ small ponds cumulative area)	22 (+ 3 in old Kirkvine Ponds)
Ewarton Works	Mt Rosser Mud Disposal Site	St. Ann/St. Catherine	35	11
	Charlemont Mud Stack	St. Catherine	100	15
Alpart	South/West Lake	St. Elizabeth	220	44
	North Lake	St. Elizabeth	40	
Jamalco	RSA 1-5	Clarendon	330	40
Revere	East Revere and West Revere Ponds	St. Elizabeth	2	0.6
Total			627	135.6

*Source: Monitoring Reports – where none located, conversion ratios used for reported production. (2020).

1.1 Construction of Residue Disposal Areas

Several methods of preparing and constructing bauxite residue disposal areas have been employed based on the practices, engineering considerations and technological developments of that era. At the start of alumina production in Jamaica, bauxite residue was stored in mined-out bauxite pits and valleys across which rock-filled dams were constructed to form the containment area. Later, ponds with earthen dams and clay seals were constructed. As the technology developed, underdrain systems were integrated into new storage areas. This was followed using geosynthetic materials as the protective seal. Except for some small mined out pits at Kirkvine, all bauxite residue storage areas in Jamaica have dams which are engineered structures.

The dams were designed and constructed to withstand at least a Richter magnitude 7 earthquake. In addition, a factor of safety was applied; this being the ratio of forces resisting failure to the destabilizing forces.

Dam construction to store residue adds to the cost of doing business. Storage capacity increase may be undertaken by construction on a new site or on an existing site. There are three methods of construction when expanding on an existing site: these are upstream, downstream and centerline. These are well illustrated in Figure 2 below [1].

The upstream construction method is at the lower end of the cost spectrum. In this method, the centerline/crest moves progressively inward onto the residue as the dam is raised to provide capacity. A starter dam is constructed at the extreme downstream point and the dam wall is progressively raised on the upstream side as the need arises. The stability of this structure depends on the load-bearing capacity of the residue on which the lifts are constructed.

Downstream construction involves raising of the dam wall on the downstream side of the starter dam. The lifts start at foundation level and the centerline progressively moves downstream. Downstream construction uses more fill material, costs more and is safer than upstream construction.

The three methods of dam lifts/construction have been applied in Jamaica.

Regionally, the geology in Jamaica determines the environmental baseline. In all cases except Clarendon, the dams are constructed on limestone which typically will have solution features resulting in an irregular underlying rock basement. The connections to the freshwater reservoirs in the aquifer are through sinkholes, caves, and fractures. Storm water run-on and run-off of the individual sites are varied and ultimately the sites are open catchment areas for rainfall. For this reason, the water balance of the disposal sites *vis a vis* the meteorological conditions are of particular importance.

1.2 Residue Disposal Technology

A broad range of mud disposal technologies has been employed in Jamaica, so there is limited similarity between the sites. Advances in mud thickening and dewatering, and acquisition of new technology has facilitated the transitioning of residue disposal technology from wet storage systems, where the mud is covered with effluent through thickened mud systems, to dry stacking, where there is no effluent on the mud. Dry stacking sites are designed to operate such that effluent drains and evaporates to the extent that the layer of mud dries and cracks before a fresh layer is added. The effluent is collected and stored in a holding pond before it is recycled. With dry stacking, the potential for dam failure and the related impacts are greatly reduced [2].

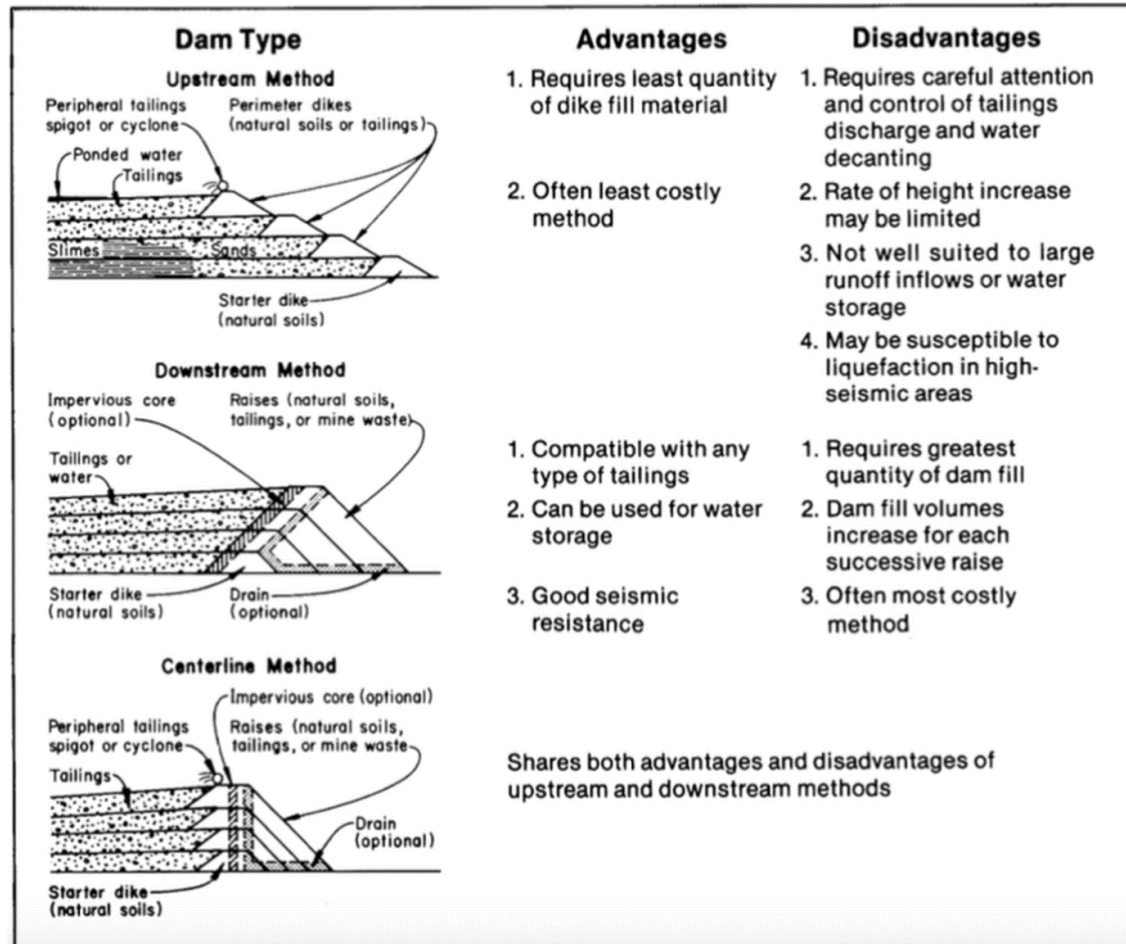


Figure 2. Tailings embankment construction methods [1].

2. Dam Failures

Dams and containment areas all have specific design criteria which take account of the potential for failures due to ground movement, including seismic events and capacity exceedances which may create precursors to failure of these structures.

2.1 Causes

Failures of earthen embankment dams or dykes can generally be grouped into three classifications: hydraulic, seepage and structural.

2.2 Hydraulic Failures

Hydraulic failures are caused by the erosive action of water on the embankment slopes and generally occur when water flows uncontrollably over and/or adjacent to the embankment. Earth embankments or dykes are not normally designed for water to flow over the top (overtopping) and therefore are particularly susceptible to erosion. Hydraulic failures may be related directly or indirectly to the following:

- Overtopping - This is as a consequence of the capacity of the dam being exceeded and could arise in storm events during which the inflows are greater than the outflows.
- Wave action - Erosion of the upstream face by wave action reduces the thickness of the cross section and weakens embankment material.

- Toe Erosion - Erosion of downstream toe of the earth slope caused by spillway outlet discharge being misdirected.
- Gullying - Rainfall erosion of embankment slopes.

2.3 Seepage Failures

Most embankments exhibit some seepage whereby liquid/effluent flows slowly through a porous area of the dam wall or foundation to the downstream slope. This seepage must be controlled in velocity and quantity. Seepage if uncontrolled, can erode fine soil material from the downstream slope or foundation; the erosion continues inwards to the upstream slope to form a pipe or cavity to the pond often leading to a complete failure of the embankment. This action is known as “piping.” Seepage failures account for approximately 40 percent of all embankments or dyke failures.

Seepage can also cause slope failures by saturating the slope material with liquid, thereby weakening the adhesive properties of the soil and hence its stability. Tree roots can provide a pathway for seepage to travel along and decaying roots can leave passageways for seepage to occur.

2.4 Structural Failures

Structural failures involve the separation (rupture) of the embankment material and/or its foundation. Structural failure of an earthen embankment may take on the form of a slide or displacement of material in either the downstream or upstream face. Sloughs, bulges, cracks or other irregularities in the embankment or dyke generally are signs of serious instability and may indicate structural failure.

2.5 Other

Tree growth on an earthen embankment can be a contributing factor in the failure of an earthen structure and a part of any one of the three types of failures above. Tree growth directly on the crest or top of the structure can lead to a hydraulic failure should the tree be blown over. This may displace embankment material within the root ball creating a low area susceptible to flows from the impoundment. Tree root systems may also create seepage paths through an earthen embankment or dyke and structural failure of an upstream or downstream slope can occur with the displacement of a large tree implanted within the earthen slope.

2.6 Mitigation Measures – Failure, Technology

There are several factors or combination of factors for dam/embankment failure and therefore design, operation and monitoring must consider these.

2.7 Hydraulic failures

The bauxite residue/tailings dams are designed to accommodate storm events of a certain magnitude, typically a 50 year return period rainfall event. As a condition of the environmental permit issued by the National Environment and Planning Agency (NEPA), the residue disposal area has to be operated at all times with a freeboard (sufficient space) to accommodate rainfall associated with the storm event of a certain magnitude (recurrence interval) to minimize the potential for overtopping. In addition, since 2004 a standard engineering feature that has been implemented is a spillway installation, which is considered an open pressure release valve for when the accumulation of water poses a significant risk to the engineered structures.

Residue disposal technology has been moving away from wet systems to thick mud and dry stacking - in which there is no caustic effluent in the pond/bed. Consequently, this eliminates wave action. Furthermore, the effect of wave action resulting from the accumulation of rainwater on the inner slope is being minimized with synthetic liners, concrete and rip-rap.

Erosion of the downstream toe of the slope by spillway discharge is prevented by:

- Constructing a concrete spillway to resist erosion.
- A splayed spillway to reduce velocity
- Directing spillway discharge into an appropriately sized receptor/drainage channel.

Rainfall erosion of the outer embankment slopes (gullyng) is being minimized by construction of slope drains. In addition, slopes damaged through gullyng must be repaired as soon as possible.

2.2.2 Seepage

Following the detection of seepage, an engineering assessment must be carried out and a strategy developed for addressing it which includes regular visual inspection. Corrective measures have included additional stabilization berms, French drains and dam redesign and reconstruction.

2.2.3 Structural

The installation of piezometers on dams allows the monitoring of water levels in the structure. Regular engineering and visual reviews are standard industry practices and has had renewed emphasis following the failure at Ajka, Hungary in 2010 and tailings dam failures (not bauxite residue dams) in Brazil in 2015 and 2019.

2.2.4 Maintenance

While trees will grow on the external slopes of embankment dams, trees are not allowed to grow on the internal slopes or the crest. Generally:

- there are no trees on the inner slope of the residue disposal area because the root systems would be directly exposed to the highly alkaline conditions of the disposal site.
- the crest is a motorable driving surface to provide access for operation, inspection, and security.
- there is de-bushing of the external slope as needed to allow full line of sight for the surface of the dam wall.

3. Risk Assessment and Management

In Jamaica, the principal government agency with oversight of the bauxite and alumina industry is the Jamaica Bauxite Institute (JBI). The oversight is a combination of technical and non-technical functions and includes advisory services to support the Government's regulatory requirements [3]. Additionally, from time to time, the JBI has either convened technical subcommittees or worked as a technical partner in industry forums. This provides a local industry-wide space for discussions and sharing of expertise. Logically, there may be some reticence for proprietary technology, but the point where the performance of constructed areas is to be monitored and measured, the value of a proven methodology cannot be underestimated. Additionally, the JBI meets with each local bauxite company at a minimum on a biannual basis for matters related to environmental management.

The most recent initiative of an alumina industry technical cohort was started in 2019. The matter of bauxite residue and attendant issues, such as the challenges in operation of the disposal areas

was added to the agenda. The cohort continued meeting through the onset of, and the evolving continuing Covid-19 pandemic. All companies were asked to provide detailed descriptions of their bauxite residue disposal sites as well as elucidate the individual approaches to risk management. The oversight of the JBI would include, but not be limited to information management and monitoring of:

- Proximity of residue disposal sites to communities.
- Methods of construction of the residue disposal areas.
- Historical and current issues with the sites, such as, dust emissions, leachate levels and risks associated with the leachate profile.
- Remediation measures implemented.
- Residue disposal technology.
- Classification of dam failure mechanisms and mitigation measures.
- Measures incorporated to reduce the risk of failure.
- Significant findings of engineering and inspection reports.
- Schedule for engineering and inspection reports.

The alumina operations have been transitioning to dry stacking technology since 1986 whereby no liquid would be stored on the mud. This will produce a more stable mass of mud with a lower risk of significant mud flow if a dam fails. The use of press filters to achieve a moisture content of 25 % or less in the residue is growing but not yet utilized in Jamaica. There are two operating plants with bauxite residue disposal management areas that create significant environmental risk by nature of the technology applied for residues disposal, the issues identified and the proximity of communities. Follow-up actions were identified to include site inspections and engineering safety reviews inclusive of dam failure analyses.

Being mindful of closure objectives, Jamaica's National Minerals Policy 2019-2030 [4] still contemplates the operation of the alumina refineries, and certainly the bauxite residue disposal sites will be an enduring legacy in the landscape.

Globally, the resolution on mineral resource governance at the United Nations Environment Assembly [5] determines that generally, mining fuels future development, that environmental management permits are key to mitigate negative social and environmental impacts, and there is the need for a Global Industry Standard on Tailings Management (GISTM) [6]. Much still needs to be done to achieve the international sustainable development goals and move towards a functional circular economy; the matters relating to legacy residue disposal sites have to be considered as accessory to these.

3.1 Environmental Permits and the Requirement for Environmental Performance Bonds

From the regulatory standpoint, the relevance and increasing importance for national environmental management objectives of environmental permits has been emergent since 1998. The overarching environmental legislation in Jamaica is the Natural Resources Conservation Authority Act of 1991. This act allows regulations to be developed, one of which allows development activities that may have environmental impacts to be permitted with specific conditions [7]. The Natural Resource Conservation (Permits and Licences) Regulations were enacted in 1996 [8], but operationalized in 1998, with the first permits being issued to the alumina industry. There were grandfather clauses included which did not immediately trigger the need for environmental permits for the residue disposal areas. Instead, the practice was to seek a permit for modifications and expansions. There were a few unicorn sites already out of use and requiring closure – the development of these closure plans and objectives have been described previously in the joint paper of the JBI and Rio Tinto Alcan (RTA) in 2011 [9]. In 2015, the NRCA's (Permits and Licences) Regulations (administered by the National Environment and Planning

Agency (NEPA)) were amended to remove the grandfather clause, as well as require renewal on a five-year cycle. The coherence with new dam safety requirements from 2021 in the Ajka and Brumadinho aftermath is yet to be fully achieved.

As part of newer permits in the last five years, there are clauses (specific conditions) that operationalizes the regulatory oversight. The specific conditions speak to schedules for construction, integrity inspections, report submissions, emergency response requirements, as well as a condition that indicates the value of an environmental performance bond. The intent of the bond is wholly to address environmental damage, so any restitution to community or individuals would have to be addressed in legal civil proceedings. A typical condition will appear as below [10]:

“SPECIAL MONITORING AND STAKEHOLDER ENGAGEMENT

The Permittee shall, submit to the Agency (to the attention of the Chief Executive Officer) an Environmental Performance Bond of [calculated value] secured by bank guarantee to be held by the Authority against the proper conduct of the Permitted Activity in accordance with this and related Environmental Permit(s) (Ref#s). The bond may be applied by the Authority to, amongst other things, remedy any breaches of the said Permit(s), mitigate any environmental damage, or restore natural resources impacted by the Permitted Activities.”

4. Discussion

The extraction of alumina from bauxite, like many other ore processing activities, produces a residue/tailling that has to be stored/disposed in an impoundment area or dam. Presently there is impetus for these residues to be used and there are growing global initiatives and focus on finding large scale uses, especially in the cement and construction industries. When the residue is stored as a fairly dry solid, a dam failure is less consequential compared to when the residue is stored as a slurry.

During the early years of bauxite processing in Jamaica, residue was disposed of in mined out bauxite pits and valleys which were dammed to provide impoundment areas. The residue was stored in a state such that it was covered with dilute caustic soda solution. With these systems, there is a significant ground water impact potential. The need to prevent contamination led to the development and implementation in the mid-1980s of dry stacking technology in which case the caustic soda solution that runs off the residue is stored in a separate cell/pond which is designed to store a liquid. If operated as designed, there should be no caustic liquor stored on the residue which then achieves the desired state of a mass that is highly consolidated relative to a wet disposal system, stable and load bearing. This minimizes the number of dams that could fail, minimizes the impact of failure and makes subsequent remediation easier. Failure of a dam with residue accumulated by dry stacking in a storm event should not cause a significant release of mud to the environment since the amount of mud released from a storage facility will be dependent on the amount of water with the mud and the stability of the deposit. A disadvantage of dry stacking is the potential for dust emissions from the surface and so invariably a sprinkler system is installed.

When water is allowed to accumulate on the dry stacking beds (sites) the mass of mud is not as stable and there is the potential to create seepage pathways through the earthen dam.

In principle, the operation of a thick mud disposal system is in some aspect similar to dry stacking, however, the mud is not dried to the same extent as dry stacking (the surface is moist), it is not as stable and can re-slurry more readily.

Dry stacking technology has also been applied to brownfield residue disposal sites and also to thick mud disposal sites which are in operation. This may involve the use of mud farming, slope stacking or filtered mud. The strategic objectives are lower capital cost, extended life of site, minimization of the footprint and enhanced stability with a lower closure cost at the end of life.

With mud stacking technology and more so, dry stacking, the greater risk of dam failure is on the cell/pond storing the runoff. The cells/ponds in Jamaica storing runoff caustic liquor are constructed or retrofitted with engineered spillways to prevent dam failure caused by overtopping. The spillway discharge is directed into channels to minimize the impact on the environment. The runoff water/effluent storage ponds in Jamaica have this feature, to minimize the risk of hydraulic failures; overtopping being one of the modes.

A dam failure is a particular risk where the total structures exist at higher elevations and upstream above communities and sensitive environment receptors and consequently all of the residue/tailings it contains. In the Jamaican landscape, environmental incidents have resulted from capacity exceedances – both at water holding areas as well as residue holding areas. These have been caused by significant rainfall events and hurricanes, as well as human errors. Many meteorological forecasters are predicting more frequent and more extreme weather events unless climate change is halted. This could be particularly severe in Jamaica as the country already experiences intense rainfall events on a frequent, but irregular basis. It was also noted that in Jamaica some of the bauxite residue is stored below ground elevation and the remainder contained by the embankment dam constructed from material excavated from the site.

Earthen dams generally exhibit some degree of seepage and the Jamaican residue storage sites are not the exception. In addition, the operation may not conform to design and therefore it is of paramount importance that:

- Regular visual inspections are done. At a minimum, this should be done weekly.
- Piezometers are installed and are functional, preferably automated, but at a minimum monthly
- There are annual engineering assessments of the structure.
- Tracking of volumes stored in water holding areas connected to the disposal sites, especially in the hurricane season.
- Where seepage is detected, assessments are done, and the appropriate measures promptly implemented to reduce the risk of failure.

Measures aimed at reducing the potential for dam failures are being implemented in Jamaica. This, however, is not suggesting that there will be no dam failures.

a. Ground water impact, surface water impact potential

Due to historical disposal practices, there is a significant ground water impact potential. Initial bauxite residue disposal occurred in mined out bauxite pits in the 1950's. Subsequently, compacted clay lining and eventually geo-synthetic liners have been employed to constrain/eliminate the movement of contaminants into the ground. The assessment of this potential is primarily achieved through mitigation measures and discharge standards, ground water monitoring networks, hydrogeological modelling and periodic reviews and examination of the water balance. The greatest environmental risk of the disposal sites is the impact on ground water through seepages.

b. Strategic aspects

Historically a lack of discharge from the closed loops at the refineries were considered part of the local best practice, however, recent meteorological trends are indicative that this will be part of the way forward for the industry's climate adaptation approach.

4.1 Report Submissions, Requirements and Inspections

Typically, all sites will have annual visual inspections by JBI technical experts, with detailed engineering reviews at longer periods, usually by consultants with the relevant expertise. In light of this request for status reviews, all companies will be engaged for thorough engineering assessments with additional requirements to address evolving environmental risk concerns, such as dam failure analyses, updates to existing hydrogeological models and demonstration of site properties of the residues and engineered structures. It was particularly noted that typically, dam safety reviews had not regularly included failure analyses. All active sites have a number of environmental permits, and this will also be a facet of the detailed audit exercise. Additionally, details of current status of residue disposal areas are part of the biannual environmental review process between the regulating stakeholders (JBI, the National Environment and Planning Agency (NEPA), Water Resources Authority (WRA), the Mines and Geology Division (MGD), the Environmental Health Unit (of the Ministry of Health) (EHU) and Jamaica's engineering agency the National Works Agency (NWA)) and the individual bauxite companies [11].

Moving forward, the approach focusses on:

- Areas of concern that have been identified and monitoring corrective works that are being undertaken. Implementation schedules monitored.
- Piezometers that are non-functional/ inaccessible are important for the management framework. All companies should maintain and measure water elevations and quality.
- Visual inspections annually and engineering reviews at least every five years.

However, this should be done more frequently on dams with safety factor less than design or currently below the international safety requirements.

4.2 Closure Planning and the Circular Economy

The Jamaican approaches to closure planning have been elaborated elsewhere but it bears mentioning that much learning in the governance approach and closure objectives have been documented locally [12] and align with the global ambit for bauxite residue management [13]. Though there are expectations of technology changes on the existing sites, as well as potential lateral and vertical expansions, it is unlikely that a wholly new site would be created for bauxite residue. So, the integrated approach to envision closure objectives at the outset would not likely occur. The integration of the concepts related to a local circular economy is in formative stages, and the most likely prospects would be evaluating the use of bauxite residue in cement or other large scale use. However, challenges are anticipated with the attendant logistics, as the residues, once there is significant moisture content, may be considered hazardous and requiring permits for handling and transport [14].

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