Evaluation of the Tailings Storage Facility for the Proposed Savannah Lithium Barroso Mine, Northern Portugal

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LIGHTNING SUMMARY

The proposal for the Barroso lithium mine in the north of Portugal by Savannah Lithium does not recognize that the embankment of waste rock that would surround the filtered tailings constitutes a dam and should conform to dam safety standards. There is no consideration of the consequences of dam failure, although the most-likely scenario will be a release of 8.5 million cubic meters of mine waste with a runout distance of 86 kilometers, affecting numerous communities along the Tâmega and Douro Rivers.

ABSTRACT

Savannah Lithium LDA has submitted a proposal for the Barroso hard-rock lithium mine in the north of Portugal. Over a 12-year period, the mine would extract 2.16 million metric tons of lithium concentrate and leave behind 83.792 million metric tons of mine waste, including 14.0 million metric tons of mine tailings. The tailings would be filtered, mixed with waste rock, compacted within a waste mound with a final height of 193 meters, and surrounded by an embankment of waste rock. The proposal is experimental in that there is no operating lithium mine that stores filtered tailings, the height of the tallest filtered tailings storage facility for a proposed lithium mine is 107 meters, and the tallest operating filtered tailings storage facility of any kind has a height of 70 meters. The target water content of the filtered tailings for adequate compaction is <15%, which exceeds the capability of current technology. Even so, tailings can be rewetted by occasional high precipitation, and there is no plan for managing the tailings that are too wet for adequate compaction. Although the tailings are susceptible to liquefaction, there is no analysis of the circumstances under which liquefaction could occur. The proposal does not recognize that the embankment of waste rock that would surround the mixture of filtered tailings and waste rock constitutes a dam and should conform to dam safety standards. In particular, there is no design flood for the dam, although the dam should be able to withstand a 500-year flood according to dam safety law in Portugal and at least a 1000-year flood by most international standards. The waste rock embankment would be constructed using the upstream method, which is illegal in Brazil, Chile, Ecuador and Peru, due to the likelihood of collapse of the dam in the event of liquefaction of the confined tailings. Even without liquefaction, slumping could carry the tailings for 2000 meters with numerous points of entry into the Covas River (a tributary of the Beça River) or the Beça River itself, so that the mixing of the tailings with downstream water bodies could develop into a flow phenomenon. Although the stability analysis indicated a minimum acceptable factor of safety FS = 1.5, the geotechnical properties of tailings were determined from only one sample. Moreover, the stability analysis assumed the “drained” loading condition with no consideration of the circumstances under which the pores would be saturated. Finally, the stability analysis included no justification for the assumed water table height, and no consideration of the dependence of the factor of safety on the height of the water table or the circumstances under which the water table would rise higher than the assumed height. Although satellite images and the proposal itself show a stream network that flows through the site of the waste mound, there is no apparent plan for any water management infrastructure that would prevent rewetting of the tailings by stream flow, surface runoff or groundwater. It is most important that the proposal does not include any consideration of the consequences of failure of the waste mound. Based on a statistical model of past tailings dam failures, the failure of the waste mound will release 8.5 million cubic meters of mine waste with a runout distance of 86 kilometers with impact on numerous communities along the Tâmega and Douro Rivers. Under the worst-case scenario (loss of 100% of the stored mine waste), 30.5 million cubic meters of mine waste will be released that will reach the Atlantic Ocean (128 kilometers) during the initial runout.

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OVERVIEW

Savannah Lithium LDA, a company of the Savannah Resources Group, has submitted an Environmental Impact Study for the proposed Barroso hard-rock lithium mine in northern Portugal (Savannah Lithium LDA, 2020a-g, 2021; see Figs. 1, 2, 3, and 4a-c). The open-pit mine would operate for 12 years and would extract an average of 1.446 million metric tons of lithium ore per year (total of 17.352 million metric tons of lithium ore). The on-site ore processing plant would reduce the lithium ore to 180,000 metric tons of lithium concentrate (5.5-6.0% lithium dioxide) per year, or 2.16 million metric tons of lithium concentrate over 12 years (Savannah

Lithium LDA, 2021). The lithium concentrate would be shipped to an unspecified site for further refining.

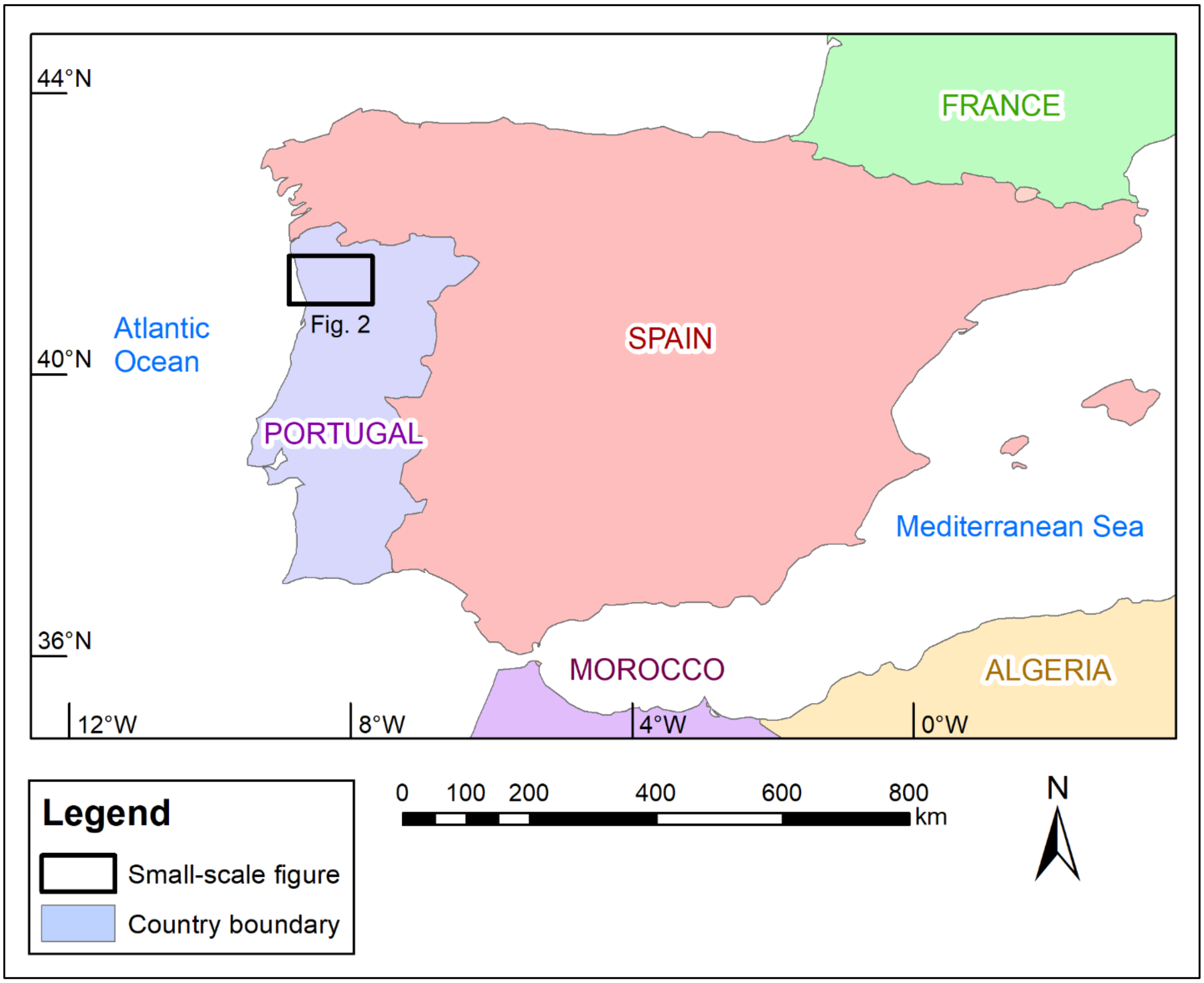

Figure 1. Savannah Lithium LDA has submitted a proposal for the Barroso hard-rock lithium mine in the north of Portugal. Over a 12-year period, the mine would extract 2.16 million metric tons of lithium concentrate and leave behind 83.792 million metric tons of mine waste, including 14.0 million metric tons of mine tailings.

A key aspect of any mining project is the plan for the permanent storage of mine waste. The chief categories of mine waste are the waste rock (the rock that must be removed to reach the ore body) and the tailings (the crushed rock particles that remain after the concentrate has been removed from the ore). The Barroso lithium mine would leave behind 83.792 million metric tons of mine waste (Savannah Lithium LDA, 2021) including 14.0 million metric tons of mine tailings (Savannah Lithium LDA, 2020a). However, based on the above values (1.446 million metric tons of lithium ore per year minus 0.18 million metric tons of lithium concentrate per year over 12 years) available in Savannah Lithium LDA (2021), the mass of remaining tailings should be 15.192 million metric tons. No document has clarified the contradiction and the smaller value (14.0 million metric tons) will be assumed in this report.

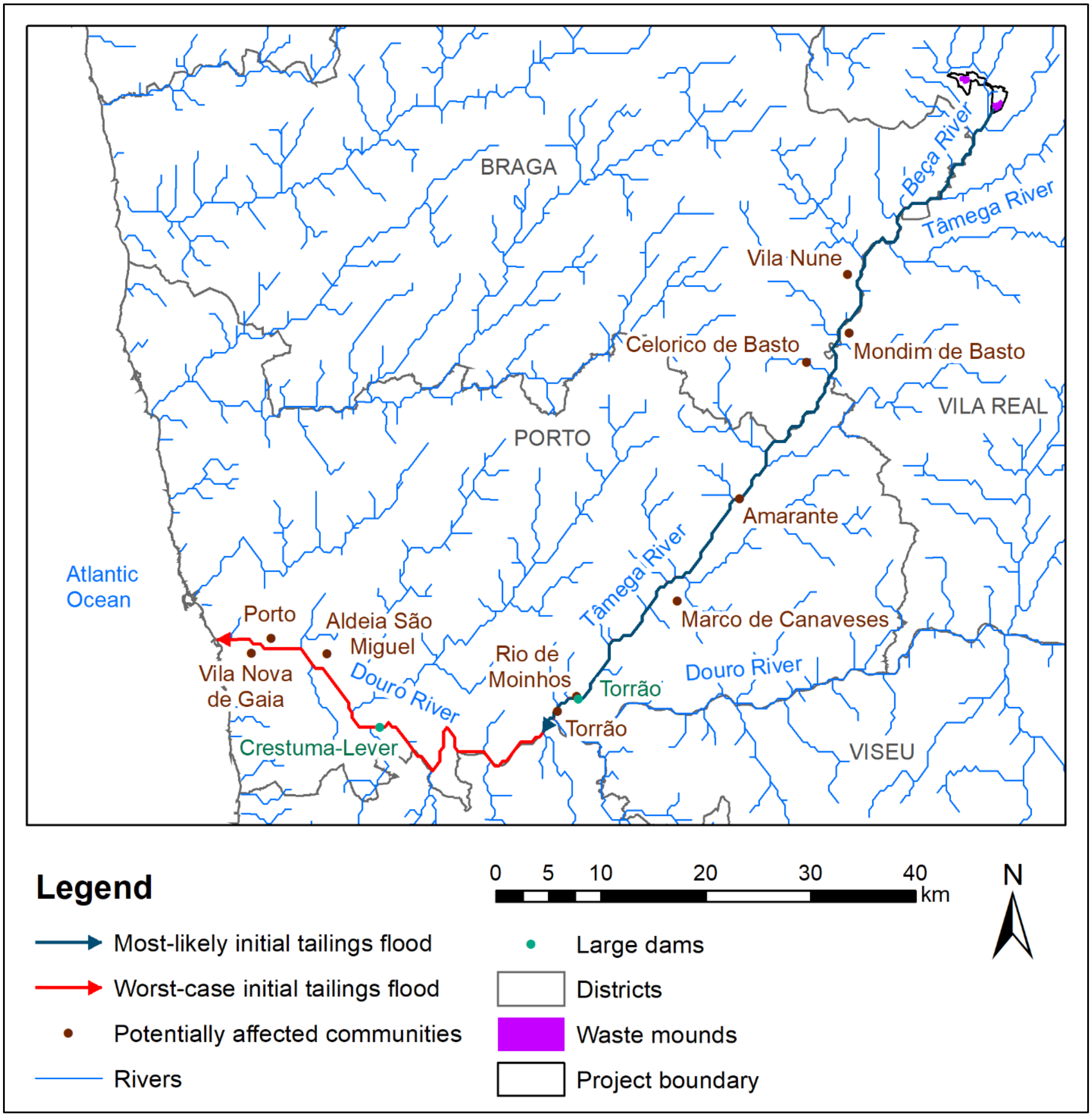

Figure 2. Based on a statistical model of past tailings dam failures by Larrauri and Lall (2018), the failure of the Southern Waste Mound at the Barroso mine will release 8.5 million cubic meters of mine waste with a runout distance of 86.1 kilometers. Following the initial runout, normal fluvial processes will transport the mine waste to the Atlantic Ocean. Under the worst-case scenario (loss of 100% of the stored mine waste), 30.5 million cubic meters of mine waste will be released that will reach the Atlantic Ocean (128 kilometers) during the initial runout, unless the tailings are impounded behind one of the large dams along the route to the ocean. The failure of the Southern Waste Mound could affect numerous communities along the Tâmega and Douro Rivers. Analysis based on Alternative 3 (see Table 1 and Figs. 4a-c). Rivers from HydroSHEDS (2021), large dams from Comissão Nacional Portuguesa das Grandes Barragens [Portuguese National Committee on Large Dams] (2021) and communities from MapCruzin (2021).

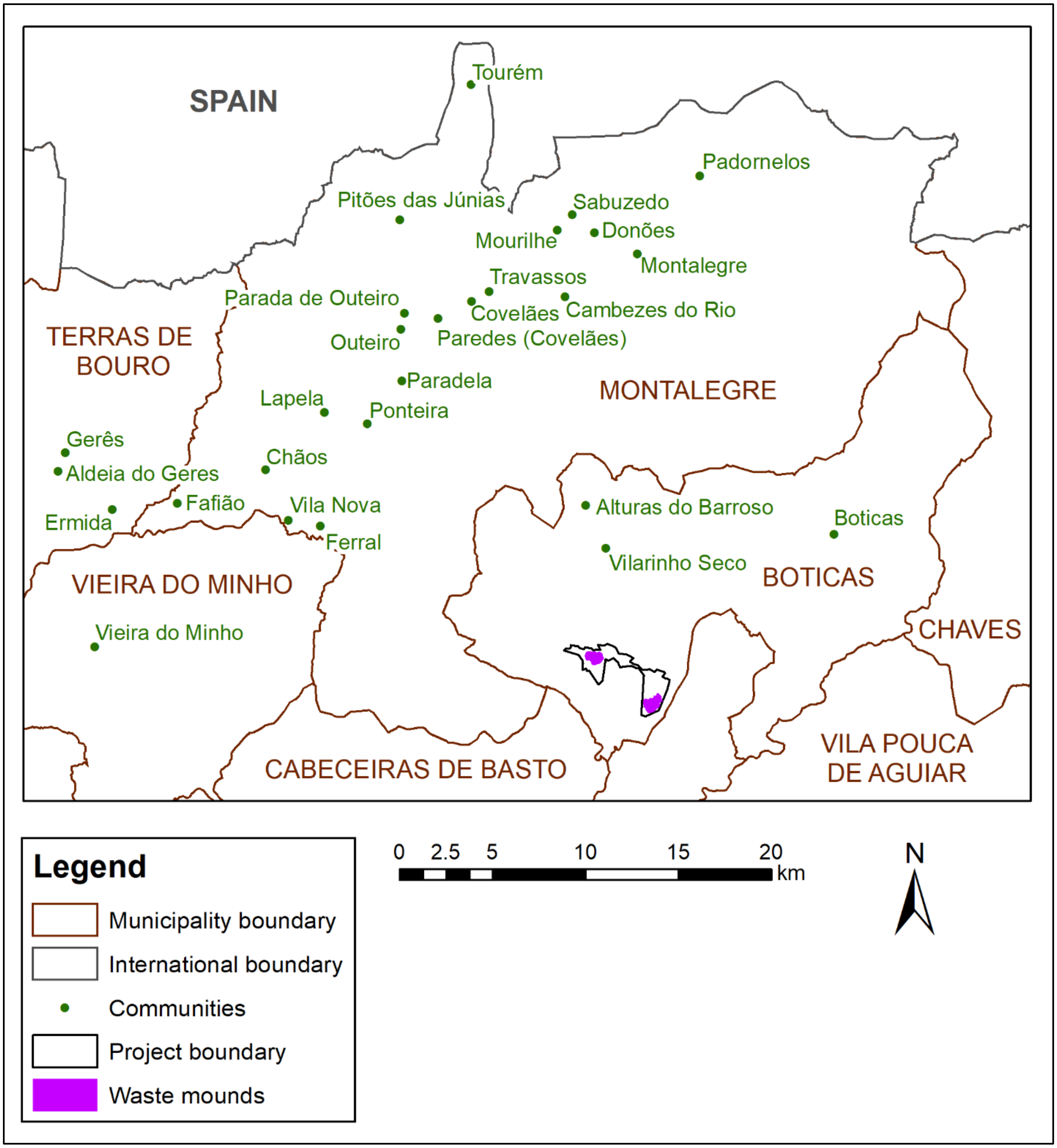

Figure 3. The problem of safe permanent tailings storage is especially acute in the Barroso region due to the designation of the municipalities of Boticas and Montalegre as a Globally Important Agricultural Heritage System (GIAHS) site by the United Nations Food and Agriculture Organization (Savannah Lithium LDA, 2021). Waste mounds are based on Alternative 3 (see Fig. 4c). Mine infrastructure from Savannah Lithium LDA (2020g).

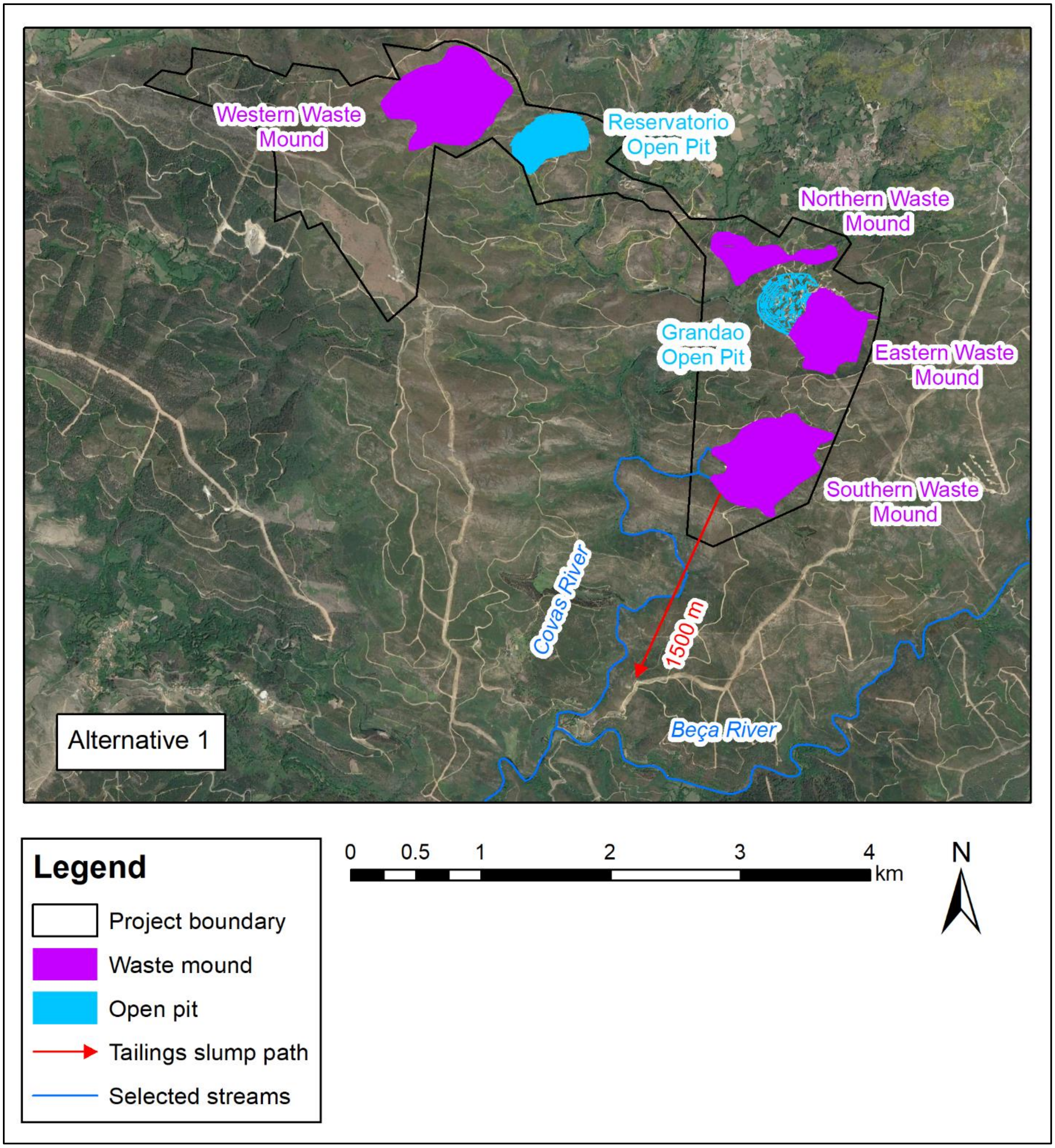

Figure 4a. According to Alternative 1, the Southern Waste Mound would be 149 meters high and would store 26.8 million metric tons of waste rock and 14.0 million metric tons of tailings. Even if the tailings did not undergo liquefaction, a slump could carry the mine waste for 1500 meters (ten times the height) with numerous points of entry into the Covas River (a tributary of the Beça River). This mixing with a downstream water body could cause the slump of mine waste to develop into a flow failure even without liquefaction of the tailings. Note that a tributary of the Covas River would emerge from beneath the Southern Waste Mound. The tailings slump path (red arrow) has a general downstream direction, but is otherwise arbitrary. Mine infrastructure from Savannah Lithium LDA (2020g). Background is Google Earth images from May 5 and May 24, 2019.

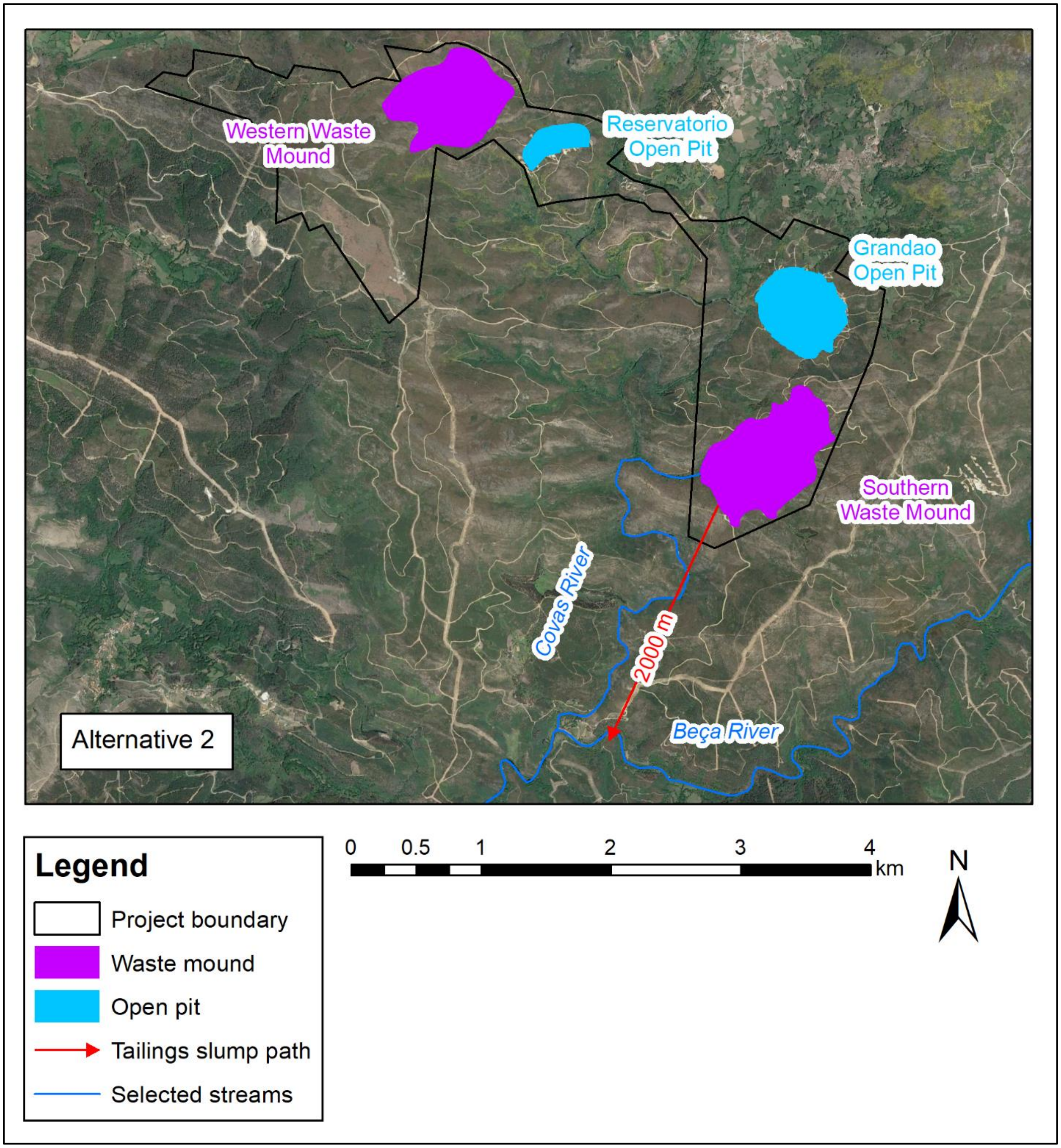

Figure 4b. According to Alternative 2, the Southern Waste Mound would be 193 meters high and would store 46.6 million metric tons of waste rock and 14.0 million metric tons of tailings. Even if the tailings did not undergo liquefaction, a slump could carry the mine waste for 2000 meters (ten times the height) with numerous points of entry into the Beça River or the Covas River (a tributary of the Beça River). This mixing with a downstream water body could cause the slump of mine waste to develop into a flow failure even without liquefaction of the tailings. Note that a tributary of the Covas River would emerge from beneath the Southern Waste Mound. The tailings slump path (red arrow) has a general downstream direction, but is otherwise arbitrary. Mine infrastructure from Savannah Lithium LDA (2020g). Background is Google Earth images from May 5 and May 24, 2019.

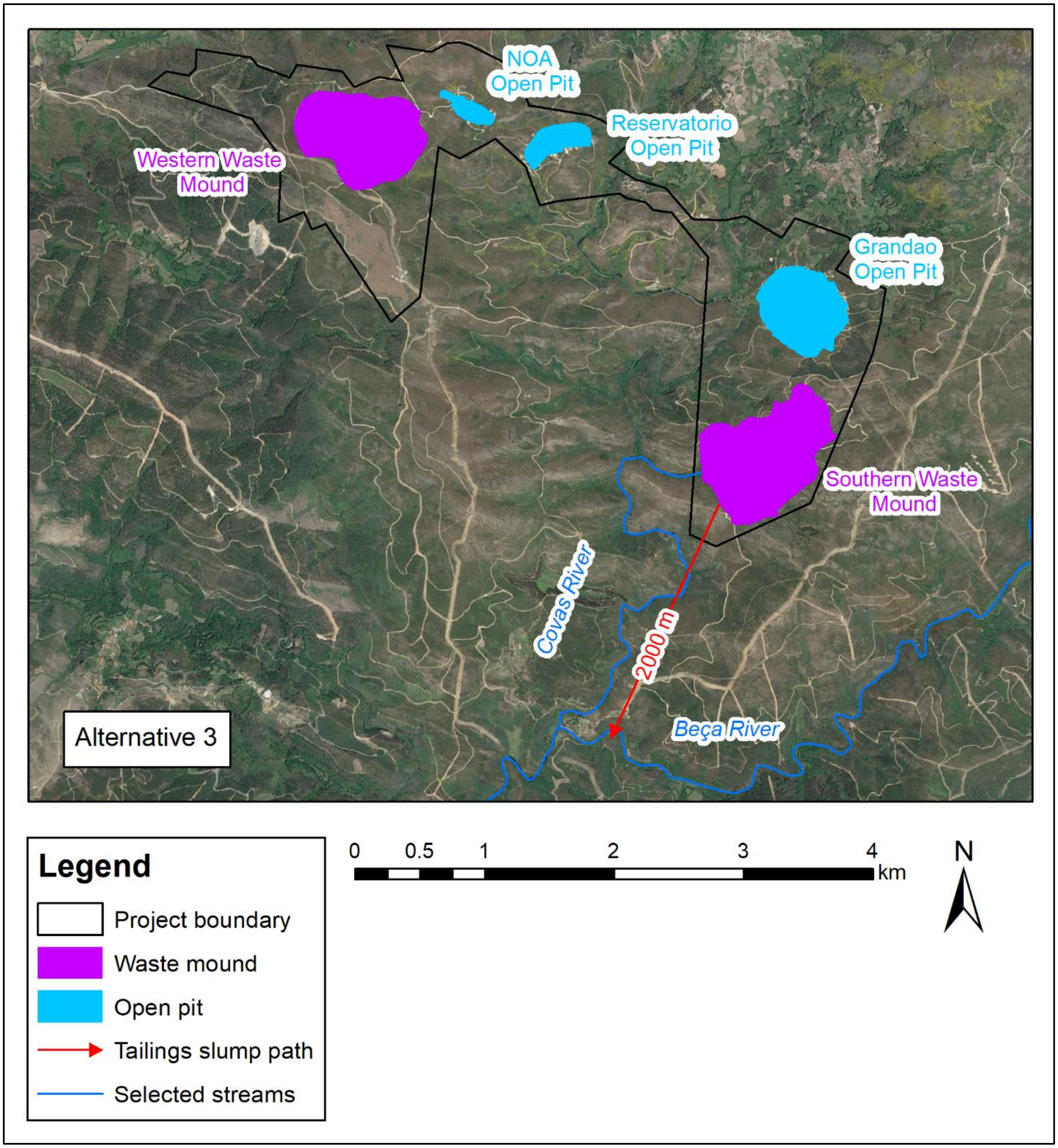

Figure 4c. According to Alternative 3, the Southern Waste Mound would be 193 meters high and would store 50.1 million metric tons of waste rock and 14.0 million metric tons of tailings. Even if the tailings did not undergo liquefaction, a slump could carry the mine waste for 2000 meters (ten times the height) with numerous points of entry into the Beça River or the Covas River (a tributary of the Beça River). This mixing with a downstream water body could cause the slump of mine waste to develop into a flow failure even without liquefaction of the tailings. Note that a tributary of the Covas River would emerge from beneath the Southern Waste Mound. The tailings slump path (red arrow) has a general downstream direction, but is otherwise arbitrary. Mine infrastructure from Savannah Lithium LDA (2020g). Background is Google Earth images from May 5 and May 24, 2019.

The most problematic aspect of mine waste management is the permanent aboveground storage of wet, fine-grained materials, such as mine tailings, due to the potential for catastrophic failure of the tailings storage facility. The problem is especially acute in the Barroso region due to the designation of the municipalities of Boticas and Montalegre (see Fig. 3) as a Globally Important Agricultural Heritage System (GIAHS) site by the United Nations Food and Agriculture Organization (Savannah Lithium LDA, 2021). The purpose of this report is to answer the following question: Does the Environmental Impact Study provide adequate protection for people and the environment from the possibility of failure of the proposed tailings storage facility? Before discussing the methodology for addressing the above question, I will first review some important topics related to tailings and tailings dams and then provide further information about the plan for tailings storage at the Barroso mine. It should be noted that the Environmental Impact Study never uses the word "dam." The significance of this omission will be a key aspect of this report.

REVIEW OF TAILINGS AND TAILINGS DAMS

Liquefaction

A mass of mine tailings consists of solid rock particles in which the pores between the particles are filled with a combination of air and water. From an engineering perspective, a mass of mine tailings is a type of soil. Of course, from an agricultural perspective, a soil should include organic matter and organisms and be able to support the growth of higher plants. However, these biological properties are not relevant for engineering purposes. An excellent reference for more complete information on the engineering properties of soils is Holtz et al. (2011). The phrases "soil" and "mass of tailings" will be used interchangeably in this subsection, which largely follows the presentation in Holtz et al. (2011).

A normal stress means any stress that is acting perpendicular to a surface (see Fig. 5). A normal stress acting on a soil can be partially counterbalanced by the water pressure within the pores. The effective stress is defined as the normal stress minus the pore water pressure. The effective stress is a measure of the extent to which the solid particles are interacting with or "touching" each other (see Fig. 5). The normal stress without subtracting the pore water pressure is also called the total stress.

Terzaghi's Principle states that the response of a soil mass to a change in stress is due exclusively to the change in effective stress (Holtz et al., 2011). For example, suppose that sediments are deposited on a river floodplain or tailings are hydraulically discharged into a tailings reservoir without compaction. The weight of the solid particles creates a normal stress, so that the particles will consolidate under their own weight. The amount and rate of consolidation is determined by the effective stress, that is, the extent to which the particles are interacting with each another. Sufficient water pressure can offset the normal stress, so that little consolidation could occur and at a slow rate.

The phenomenon of liquefaction, in which a soil loses its strength and behaves like a liquid, can be explained through an application of Terzaghi's Principle (see Fig. 6). In the diagram on the left-hand side of Fig. 6, although the solid particles are loosely packed and the pores are saturated with water, the particles touch each other. Because there is contact between the particles, the load (the weight of particles or other materials above the particles shown on the left-hand side of Fig. 6), is carried by the solid particles. The load is also partially borne by the water due to the water pressure. The term permeability refers to the ability of water to flow through the pores. A mix of coarse and fine particles will have low permeability because the finer particles will fill in the pores between the coarser particles and, thus, restrict the pore space for water flow.

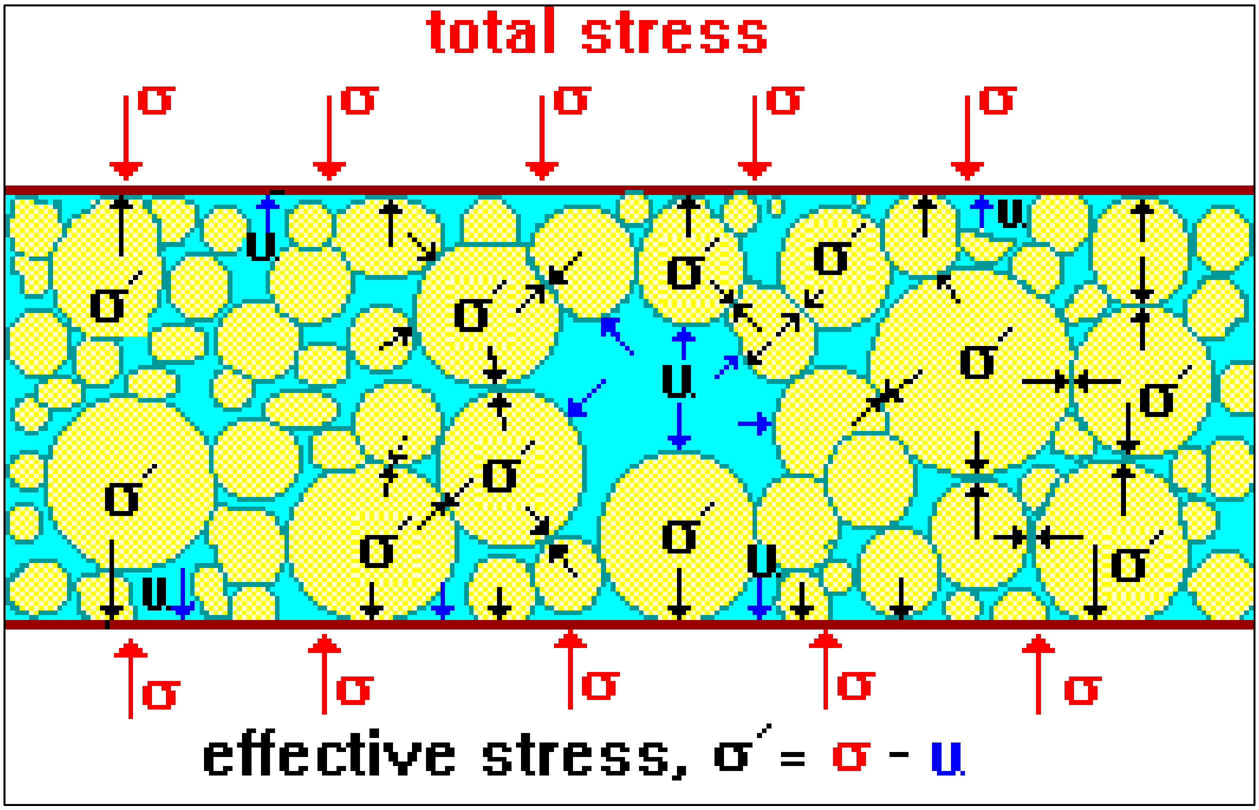

Figure 5. The effective stress in soil is equal to the total stress minus the pore water pressure. The effective stress is a measure of the extent to which the solid particles are interacting with or "touching" each other. Terzaghi's Principle states that the response of a soil mass to a change in stress is due exclusively to the change in effective stress. Figure from GeotechniCAL (2021).

Loose-packing means that the soil is in a contractile state, so that the solid particles will tend to compact to a more densely-packed state following an increase in load or a disturbance (such as an earthquake). If the water cannot escape (due to low permeability or the speed of the disturbance), the solids cannot compact so that the additional stress is converted into an increase in pore water pressure (see right-hand side of Fig. 6). The increased water pressure can decrease the effective stress almost to zero or to the point where the particles no longer "touch" each other (see Fig. 5). At this point, the soil mass has undergone liquefaction in which the water supports the entire load and the mass of particles and water behaves like a liquid.

This phenomenon of liquefaction is promoted by saturated pores and loosely-packed particles. Even if the pores between loosely-packed particles are unsaturated prior to the disturbance, some compaction can occur (decreasing the size of the pores), so that the pores become saturated. Any further contractile behavior will then convert the additional stress into increased pore water pressure. On that basis, liquefaction is possible even if the pores are only 80% saturated. There is a considerable literature on methods for evaluating the susceptibility of soil or tailings to liquefaction (Fell et al., 2015). For example, a mix of fine and coarse particles could make the tailings more susceptible to liquefaction by reducing their permeability (the fine particles will fill in the pores between the coarse particles).

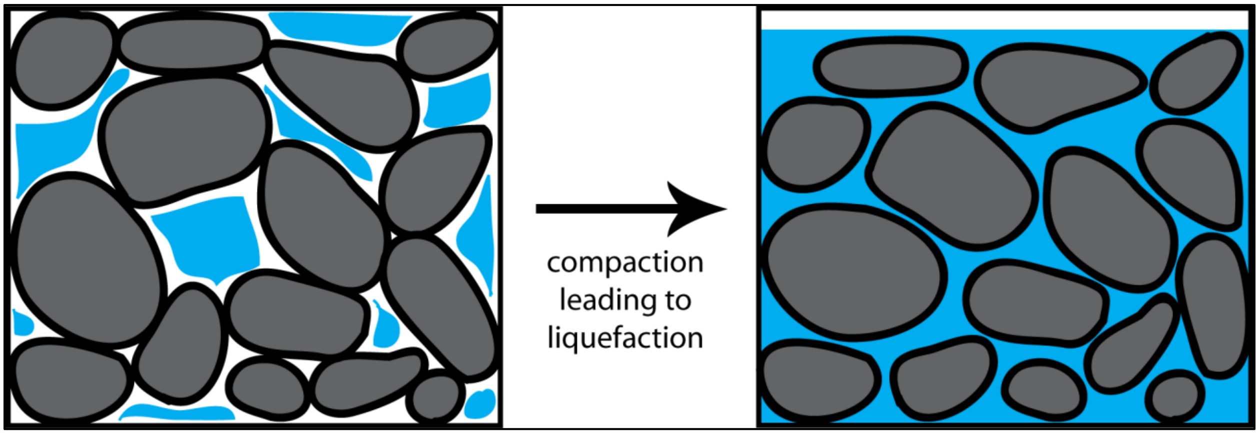

Figure 6. In the diagram on the left, although the solid particles are loosely packed and the pores are saturated with water, the particles touch each other, so that the load is supported by the particles (and partially by the water). Loose-packing means that the soil is in a contractile state, so that the solid particles will tend to compact to a more densely-packed state following an increase in load or a disturbance (such as an earthquake). If the water cannot escape (due to low permeability or the speed of the disturbance), the solids cannot compact so that the additional stress is converted into an increase in pore water pressure (see the diagram on the right). The increased water pressure can decrease the effective stress almost to zero or to the point where the particles no longer "touch" each other (see Fig. 5). At this point, the soil mass has undergone liquefaction in which the water supports the entire load and the mass of particles and water behaves like a liquid. This phenomenon of liquefaction is promoted by saturated pores and loosely-packed particles. If the pores are unsaturated prior to the disturbance, some compaction can occur (decreasing the size of the pores), so that the pores become saturated. Any further contractile behavior will then convert the additional stress into increased pore water pressure. On that basis, liquefaction is possible even if the pores are only 80% saturated. Figure from DoITPoMS (2021).

Filtered Tailings Technology

The current best practice for preventing liquefaction of a tailings pile is to filter the tailings prior to storage, so as to desaturate the pore spaces between the tailings and reduce the overall quantity of water in the tailings storage facility (see Fig. 7). Filtered tailings will behave more like a moist soil than a wet slurry. A typical cut-off water content below which tailings take on the behavior of a moist soil is 25%, where the water content is the ratio of the mass of water to the mass of dry tailings (Klohn Crippen Berger, 2017). However, the boundary between filtered and non-filtered tailings depends upon the physical and chemical properties of the tailings, and is defined by physical behavior, not water content. The reduction of the water content and desaturation of the tailings also makes it possible to compact the tailings within the tailings storage facility. This compaction further reduces the likelihood of liquefaction by putting the tailings into a dilative (as opposed to contractile) state in which they will expand rather than consolidate when they are sheared or disturbed.

The plan at the Barroso mine is to store a mixture of filtered tailings and waste rock. However, the Environmental Impact Study repeatedly refers to the tailings as "dry," which is non-standard terminology. The tailings are not literally dry and, if they were, it would be impossible to properly compact them for safe storage. According to Savannah Lithium LDA (2020a), "*A Savannah optou por usar um conceito de deposição a seco dos rejeitados, para armazenamento dos rejeitados provenientes da lavaria, em oposição a um sistema de deposição de lamas, devido à topografia muito acidentada da área do projeto e à sensibilidade ambiental da área envolvente … A deposição de resíduos em qualquer uma das escombreiras será realizada com materiais sólidos e secos, pelo que não existirão bacias de rejeitados na Mina do*

Barroso” [Savannah opted to use a dry deposition concept for the tailings for storage of the tailings from the ore processing plant, as opposed to a slurry deposition system, due to the very rugged topography of the project area and the environmental sensitivity of the surrounding area ... The deposition of mine waste in any of the waste mounds will be carried out with solid and dry materials, so there will be no tailings basins at the Barroso mine]. The designer of the tailings storage facility for the Barroso mine is the consulting firm Knight-Piésold and the appendices of the Environmental Impact Study include numerous memos and reports from Knight-Piésold (e.g., Savannah Lithium, 2020b-f). On their website, the same Knight-Piésold includes a publication by employees of Knight-Piésold that states, “Regarding terminology, the rather misleading term dry stack is generally not a good engineering term since the target moisture content coming from the filter plant is typically desired to be somewhere around the optimum moisture content based on the Proctor compaction procedure … Geotechnical engineers associate the optimum moisture content with moisture levels just below full saturation after compaction, thus terming such a facility as a dry stack is a misnomer. The present authors would encourage practitioners to abandon the use of the term dry stacking in favor of the more straightforward term, ‘filtered tailings.’ It is not desirable to unintentionally mislead the public at large with an industry term that is noticeably misused” (Ulrich and Coffin, 2017). In this report, the tailings will be referred to as “filtered” rather than “dry,” except to quote from the Environmental Impact Study.

Figure 3.5 Schematic of a Filtered Tailings Facility

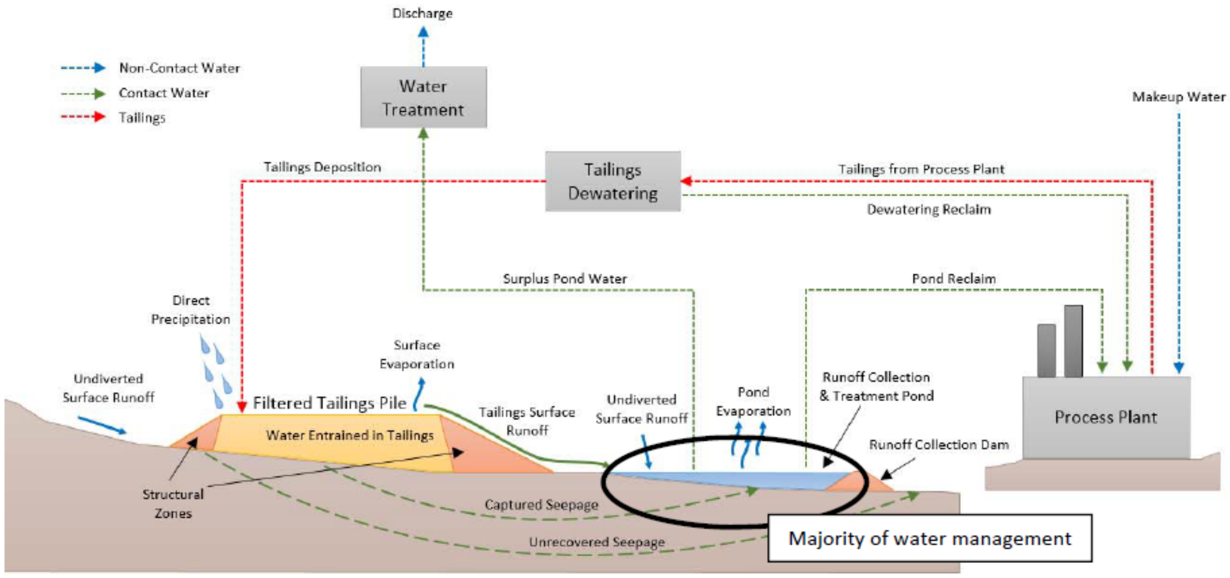

Figure 7. Based on current filter press technology, target water contents of 15% (typically required for adequate compaction) cannot be consistently met. Even if filtered tailings leave the filter presses with the target water content, they can be rewetted by precipitation. The standard response is to place the tailings that are too wet for adequate compaction in the center of the filtered tailings pile and to surround the wet tailings with “structural zones” constructed out of tailings that have the target water content for adequate compaction. The structural zone is a type of dam and should be designed to meet dam safety regulations. Savannah Lithium LDA (2020a-f, 2021) does not present any plan for managing the tailings that are too wet for adequate compaction and never uses the word “dam.” Figure from Klohn Crippen Berger (2017).

Most typically, filtered tailings storage facilities are constructed with an outer shell of compacted tailings (sometimes called the "structural zone") surrounding an inner core of uncompacted or lightly compacted tailings (see Fig. 7). Although some recent mining project plans have claimed that filtered tailings do not require a dam, the structural zone fulfills the exact same function as a dam, that is, it is an engineering structure that prevents the flow of water or other materials. For example, with regard to its proposal for a copper mine in Minnesota, USA, Twin Metals Minnesota (2021) writes, "Dry stacking filtered tailings means there is no need for a dam – dam failure is impossible." The response from the Minnesota Department of Natural Resources (2021) has been that a dam is a "structure that impounds water **and/or waste materials containing water**" (emphasis in the original). The Minnesota Department of Natural Resources (2021) further asked, "Is characterizing the tailings filter cake as being 'dry' a common terminology for a product exhibiting a 13% to 16% moisture content?" Klohn Crippen Berger (2017) has also emphasized that "if filtered tailings are placed in a stand-alone facility (pile/stack), the outer slopes must maintain structural stability (similar to a dam or a waste dump), particularly under seismic loading conditions." Finally, according to Safety First: Guidelines for Responsible Mine Tailings Management, "The structural zone of a filtered tailings facility is a type of tailings dam" (Morrill et al., 2020).

The inner core of a filtered tailings storage facility is, in fact, a requirement for the storage of tailings that left the filter presses with too much water for adequate compaction. Crystal et al. (2018) have emphasized that target water contents for filtered tailings are rarely achieved. According to Crystal et al. (2018), "Commonly, projects are specifying (or promising) a target filter-cake moisture at the limit of the filter performance (including at the limit of the thickener's ability to deliver feed at the required solids ratio). This has caused numerous examples where the operating performance does not consistently meet the target … Essentially, irrespective of site, ore body type, or filter press manufacturer, a 15% moisture content remains a typical target, while tracking of day-in and day-out moisture contents of filter cakes demonstrates that achievable moisture contents are often in the range of 17 to 18% when things are running smoothly and can be up to 20 to 23% when off-spec … 'Targets' may be cited or promised, but achievable filter cake moisture contents and the variability of the process are not generally within the tailings engineer's control." Even if the tailings leave the filter presses with the target water content, they can still be rewetted by precipitation. Thus far, these filtered tailings storage facilities have mostly been small and mostly constructed in areas with arid climates (Klohn Crippen Berger, 2017). The partial restriction to arid regions has partly been motivated by the greater need to recycle water in regions with high water scarcity. However, an additional factor has been the challenges in achieving the appropriate water content for adequate compaction in wet climates. At the present time, the standard solution in both arid and wet climates is to set aside an inner core (a region away from the outer slopes) for placement of tailings that cannot be adequately compacted. Crystal et al. (2018) continue, "The tailings engineer can, however, specify acceptable moisture contents for different areas of the dry stack, depending on stacking strategies. For example, external structural zones may have more stringent criteria than non-structural zones, for which reduced constraints may be allowed."

Although filtered tailings may be unsaturated when deposited in the tailings storage facility, it is still necessary to prevent resaturation of the tailings in order to prevent future liquefaction. The pore spaces between the tailing particles can become resaturated simply by consolidation under the weight of additional overlying tailings, which reduces the volume of pores so that they become filled with water (Klohn Crippen Berger, 2017). In wet climates, water can enter the filtered tailings storage facility through surface runoff, upward groundwater seepage, and direct precipitation onto the tailings. The above water sources require diversion canals that isolate the tailings storage facility from the rest of the watershed and appropriate drainage infrastructure for conveying any excess water out of the tailings.

It is important to point out that filtered tailings storage facilities have other possible failure mechanisms besides liquefaction. For example, surface runoff flowing over the structural zone could erode it away, thus exposing the uncompacted tailings that were behind the structural zone (see Fig. 7). Uneven settlement or failure of the foundation beneath the filtered tailings storage facility could cause failure of the entire structure. Finally, the structural zone (dam) could fail simply by sliding with no liquefaction or other flow behavior. According to Klohn Crippen Berger (2017), due to the typical low water content of filtered tailings, "Failure, if it occurs, would likely be local slumping and consequences would be restricted to the local area (or the distance equivalent to roughly 10 times the height [of the tailings dam]) … " On the other hand, flow behavior of the tailings could develop if the tailings mixed with sufficient water after dam failure. The above quote continues, " … unless the material slumps into a water body … When large water ponds are located downstream of high-density thickened/paste facilities, cascading failures are possible and should be accounted for when developing the risk profile of tailings failure management" (Klohn Crippen Berger, 2017). On the above basis, drainage and runoff collection ponds should be located sufficiently far downstream from the tailings dam and excessive accumulation of water in these ponds should be avoided (Klohn Crippen Berger, 2017; see Fig. 7).

Design Floods

Any tailings dam, including the structural zone of a filtered tailings storage facility, must be designed to resist a particular flood called the design flood. Without a knowledge of the design flood, there is no basis for determining the dimensions of the diversion canals or any other aspect of a tailings storage facility. Typically, the design flood depends upon the hazard potential or the consequences of the failure. In this section, three widely-recognized guidelines for determining design floods will be considered, which are the guidelines of the (U.S.) Federal Emergency Management Agency (FEMA, 2013), U.S. Army Corps of Engineers (USACE, 1991, 2014), and Canadian Dam Association (2013). All of the above guidelines refer to dams in general, rather than tailings dams in particular. The supplemental guidelines of Canadian Dam Association (2019) consider the application of general dam safety guidelines to tailings dams. Two recent guidelines that seek recognition as global standards (Morrill et al., 2020; ICMM-UNEP-PRI, 2020) will also be considered. Finally, the dam safety regulations in Portugal and Spain, which are not specific to tailings dams, will be taken into account.

The Federal Emergency Management Agency classifies dams in three categories according to the hazard potential (FEMA, 2013). High Hazard Potential means "probable loss of life due to dam failure or misoperation." It is clarified that "probable loss of life" refers to "one or more expected fatalities" and that "economic loss, environmental damage or disruption of lifeline facilities may also be probable but are not necessary for this classification." Significant Hazard Potential means "no probable loss of human life but can cause economic loss, environmental damage, or disruption of lifeline facilities due to dam failure or misoperation." Low Hazard Potential means "no probable loss of human life and low economic and/or environmental losses due to dam failure or misoperation."

Each of the classifications of hazard potential corresponds to an inflow design flood (FEMA, 2013). A dam with Low Hazard Potential must be designed for a 100-year flood (flood with a 1% exceedance probability in any given year) or "a smaller flood justified by rationale" (FEMA, 2013). A dam with Significant Hazard Potential should be designed for a 1,000-year flood (flood with an exceedance probability of 0.1% in any given year). However, a dam for which failure is expected to result in the loss of at least one life (High Hazard Potential) must be designed for the Probable Maximum Flood (PMF), which is defined as "the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the drainage basin under study" (FEMA, 2013). The magnitude of the PMF is usually derived from the Probable Maximum Precipitation (PMP), which is defined as "the theoretical greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year" (FEMA, 2013). It is worth noting that, according to the U.S. Army Corps of Engineers "the PMF does not incorporate a specific exceedance probability, but is generally thought to be well beyond the 10,000 year recurrence interval" (USACE-HCE, 2003).

In terms of design floods, the safety guidelines for dams designed by the U.S. Army Corps of Engineers are, in some cases, even stricter than those recommended by FEMA (2013). For all dams designed or maintained by the U.S. Army Corps of Engineers, "APF [Annual Probability of Failure] ≥ 1 in 10,000 (0.0001) Per Year. Annual probability of failure in this range is unacceptable except in extraordinary circumstances" (USACE, 2014). The U.S. Army Corps of Engineers has four categories of dam safety standards, similar to the three hazard potentials of the Federal Emergency Management Agency. The strictest "Standard 1 applies to the design of dams capable of placing human life at risk or causing a catastrophe, should they fail" (USACE, 1991). For this standard, "structural designs will be such that the dam will safely pass an IDF [Inflow Design Flood] computed from probable maximum precipitation (PMP) occurring over the watershed above the dam site" (USACE, 1991). For the third strictest Standard 3 dams, "the base safety standard will be met when a dam failure related to hydraulic capacity will result in no measurable increase in population at risk and a negligible increase in property damages over that which would have occurred if the dam had not failed" (USACE, 1991). For Standard 3 dams, "one-half of the PMF is the minimum acceptable IDF" (USACE, 1991).

The guidelines of the Canadian Dam Association (2013) include five dam classes, classified according to the consequences of failure. Risk to any permanent population places a dam in the three highest-consequence categories, in which the high-consequence, very high-consequence and extreme-consequence categories correspond to expected deaths of ten or less, 100 or less, and more than 100, respectively. Even with no permanent population at risk, the high-consequence category would apply if the consequences of failure included "significant loss or deterioration of important fish or wildlife habitat" or "high economic losses affecting infrastructure, public transportation and commercial facilities," while the lesser significant-consequence category would apply only if the consequences involved "no significant loss or deterioration of fish or wildlide habitat" and "losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes" (Canadian Dam Association, 2013). The guidelines consider flood design criteria based on both a risk-informed approach and a traditional, standards-based approach. According to the risk-informed approach, the minimum annual exceedance probability of the design flood in the high-consequence category should be 1/2475 (corresponding to a return period of 2475 years), while the minimum annual exceedance probability in the very high- or extreme-consequence categories should be 1/10,000 (corresponding to a return period of 10,000 years). According to the traditional, standards-based approach, for a dam in the high-consequence category, the design flood should be 1/3 between the 1000-year flood and the PMF. For the very high-consequence category, the design flood should be 2/3 between the 1,000-year flood and the PMF. For a dam in the extreme-consequence category, the design flood should be the PMF. The application to tailings dams follows the standards-based approach and makes the same recommendations (Canadian Dam Association, 2019).

The recent Safety First: Guidelines for Responsible Mine Tailings Management (Morrill et al., 2020) generally follows the guidelines of U.S. governmental agencies in calling for design for the PMF if there is potential loss of a single life and the 10,000-year flood (annual exceedance probability of 0.01%) otherwise. The even more recent Global Industry Standard on Tailings Management (GISTM) (ICMM-UNEP-PRI, 2020) is modeled on the Canadian Dam Association (2013, 2019) guidelines with five categories of dam failure consequences in which High, Very High, and Extreme refer to potential loss of 1-10, 10-100 and more than 100 lives, respectively. The high-consequence category also includes either “Significant loss or deterioration of critical habitat or rare and endangered species. Potential contamination of livestock/fauna water supply with no health effects” or “500-1,000 people affected by disruption of business, services or social dislocation. Disruption of regional heritage, recreation, community or cultural assets. Potential for short term human health effects” or “High economic losses affecting infrastructure, public transportation, and commercial facilities, or employment. Moderate relocation/compensation to communities.” According to ICMM-UNEP-PRI (2020), tailings dams in the high-consequence, very high-consequence, and extreme-consequence categories should be designed to withstand the 2475-year flood, the 5000-year flood, and the 10,000-year flood, respectively. Note the difficulty of comparing different design flood standards due to the varying uses of “potential,” “probable” and “expected” with respect to loss of life.

Although both of the above recent standards seek recognition as global standards, there is not yet any governmental regulatory agency that has adopted these standards. On the other hand, Morrill et al. (2020) has been endorsed by 142 civil organizations, as well as a Spanish political party, and the International Council on Mining & Metals (ICCM) is expecting its 27 member companies to implement the GISTM by August 2023 (ICMM, 2020a; ICMM-UNEP-PRI, 2020). Neither Savannah Lithium LDA nor Savannah Resources Group are member companies of ICMM, but it is noteworthy that Association Members include Eurometaux and Euromines (ICMM, 2020b).

Of course, the dam safety legislation in Portugal is the most relevant to a tailings dam in Portugal. It is disturbing that Portugal seems to have the weakest design flood criteria in the developed world. According to Diário da República [National Official Journal] (2018), “*Para cálculo da cheia de projeto deve ser adotado um período de retorno mínimo de 500 anos, exceto para as obras da classe III com albufeiras de capacidade de armazenamento inferior a 100 000 m3, para as quais pode ser adotado um período de retorno mínimo de 100 anos*” [In order to calculate the design flood, a minimum return period of 500 years must be adopted, except for Class III works with reservoirs with a storage capacity of less than 100,000 m^3, for which a minimum return period of 100 years can be adopted]. Class III dams are those for which, in the event of dam failure, there would be no danger to “*edificações fixas com carácter residencial permanente*” [fixed buildings with a permanent residential character] (Diário da República, 2018).

The current design flood criteria in Spain are equivalent to what is found in Portugal. Agencia Estatal Boletín Oficial del Estado [State Agency Official State Bulletin] (1996) distinguishes between the "*avenida de proyecto*" [design flood], which is the "*máxima avenida que debe tenerse en cuenta para el dimensionado del aliviadero, los órganos de desagüe y las estructuras de disipación de energía, de forma que funcionen correctamente* [maximum flood that must be taken into account for the dimensioning of the spillway, the drainage structures and the energy dissipation structures in such a way that they function correctly] and the "*avenida extrema* [extreme flood], which is "*la mayor avenida que la presa puede soportar*" [the largest flood that a dam can withstand]. Ministerio de Medio Ambiente [Ministry of Environment] (1996) then states, "*En la actualidad, la avenida de proyecto es, en la mayor parte de los casos, la correspondiente a un período de retorno de 500 años*" [At the present time, the design flood, in the majority of cases, corresponds to the 500-year flood]. Just as in Portugal, the design flood seems to have the same return period (annual exceedance probability) nearly independent of the consequences of dam failure. Moreover, Ministerio de Medio Ambiente (1996) does not state any return period or means of calculating the magnitude of the "extreme flood." However, in the case of tailings dams, the design flood and the extreme flood are not really different concepts, since there are few circumstances under which a tailings dam could survive the failure of the spillway.

The new proposed dam safety legislation aims to bring Spain up to date with the rest of the developed world (Ministerio para la Transición Ecológica [Ministry for Ecological Transition], 2018a-b). This legislation proposes return periods of 10,000 years, 5000 years and 1000 years for the "extreme flood" for earthen dams in Categories A, B and C, respectively (Ministerio para la Transición Ecológica, 2018b). The dam safety legislation in Spain already recognizes three categories of hazard potential (Agencia Estatal Boletín Oficial del Estado, 1996; Ministerio de Medio Ambiente, 1996). Category A "*corresponde a las presas cuya rotura o funcionamiento incorrecto puede afectar gravemente a núcleos urbanos o servicios esenciales, o producir daños materiales o medioambientales muy importantes*" [corresponds to dams for which rupture or malfunction could seriously affect urban centers or essential services, or cause very significant material or environmental damage] (Ministerio de Medio Ambiente, 1996). Category B "*corresponde a las presas cuya rotura o funcionamiento incorrecto puede ocasionar daños materiales o medioambientales importantes o afectar a un reducido número de viviendas*" [corresponds to dams for which rupture or malfunction could cause significant material or environmental damage or affect a small number of homes] (Ministerio de Medio Ambiente, 1996). Category C "*corresponde a las presas cuya rotura o funcionamiento incorrecto puede producir daños materiales de moderada importancia y sólo incidentalmente pérdida de vidas humanas*" [corresponds to dams for which rupture or malfunction could cause moderate material or environmental damage and only incidentally loss of human lives] (Ministerio de Medio Ambiente, 1996). Ministerio de Medio Ambiente (1996) further clarifies that an "urban center" requires as few as 50 inhabitants. On that basis, Category A roughly corresponds to High Hazard Potential (Federal Emergency Management Agency), Standard 1 (U.S. Army Corps of Engineers) and very high- or extreme-consequence dams (Canadian Dam Association, 2013, 2019; ICCM-UNEP-PRI, 2020). The above legislation would be quite similar to the guidelines of the Canadian Dam Association (2013), especially using its risk-informed approach. I am not aware of any similar effort to update the dam safety regulations in Portugal.

DESIGN OF THE TAILINGS STORAGE FACILITY AT THE BARROSO MINE

The Environmental Impact Study describes three alternative plans for the Barroso mine (see Figs. 4a-c). A common feature of all the plans is the permanent storage of 14.0 million metric tons of tailings in the Southern Waste Mound along with varying amounts of waste rock (see Figs. 4a-c). Alternative 1 would maximize the backfill of waste rock into the open pits and would store 26.8 million metric tons in the Southern Waste Mound, which would reach a final height of 149 meters (see Table 1). Alternatives 2 and 3 would store 46.6 and 50.1 million metric tons of waste rock, respectively, in the Southern Waste Mound, which would reach a final height of 193 meters in both cases (see Table 1). The final heights were not explicitly stated in the Environmental Impact Study, but were calculated from the difference between the maximum and minimum elevations of the proposed waste mounds. Savannah Lithium LDA (2020f) states, “Option 3 … is considered the most viable option at this stage.” However, the preceding quote comes from an appendix to the Environmental Impact Study that is a memo to Savannah Resources from the consulting firm Knight-Piésold dated December 20, 2019. There does not appear to be any sentence in the Environmental Impact Study that clarifies which is the preferred option according to the mining company.

Table 1. Most-likely and worst-case runout distances following tailings dam failure[1]

	Alternative 1	**Alternative 2**	**Alternative 3**
Dam Height[2] (m)	149	193	193
Tailings Mass (Mt)	14.0	14.0	14.0
Waste Rock Mass (Mt)	26.8	46.6	50.1
Tailings/Waste Rock Volume (Mm^3)	19.4	28.9	30.5
		Most-Likely Scenario[3]	
Spill Volume (Mm^3)	5.6	8.1	8.5
Runout Distance (km)	59.9	83.7	86.1
		Worst-Case Scenario[4]	
Spill Volume (Mm^3)	19.4	28.9	30.5
Runout Distance (km)	234.1	334.5	344.9

[1] Input data from Savannah Lithium (2020a), including assumption that the density of the mixture of tailings and waste rock will be 2.1 t/m^3.
[2] Calculated as difference between maximum and minimum elevation of tailings/waste rock mound.
[3] Most-likely scenario based on past tailings dam failures (Larrauri and Lall, 2018).
[4] Worst-case scenario based on past tailings dam failures (Larrauri and Lall, 2018) plus assumption of loss of 100% of stored tailings and waste rock. The actual maximum runout distance is limited by the distance to the Atlantic Ocean of 128 kilometers (see Fig. 2).

All alternatives would involve the compaction of a homogenous mix of waste rock and filtered tailings in the Southern Waste Mound at a 3:1 ratio of waste rock to tailings (Savannah Lithium LDA, 2020a). It was not clarified whether the ratio is based on mass or volume. Prior to compaction, the tailings would be filtered to achieve a water content <15% (Savannah Lithium LDA, 2020a). A wall of waste rock would surround the mix of waste rock and tailings on all sides (see Fig. 8). As mentioned earlier, the Environmental Impact Study does not refer to the wall of waste rock as a “dam,” nor does it explain why it is not a dam or use the word “dam” in any context. It should be noted that, at a water content of 15%, the wall of waste rock would confine 14.0 million metric tons of tailings and 2.1 million cubic meters of water.

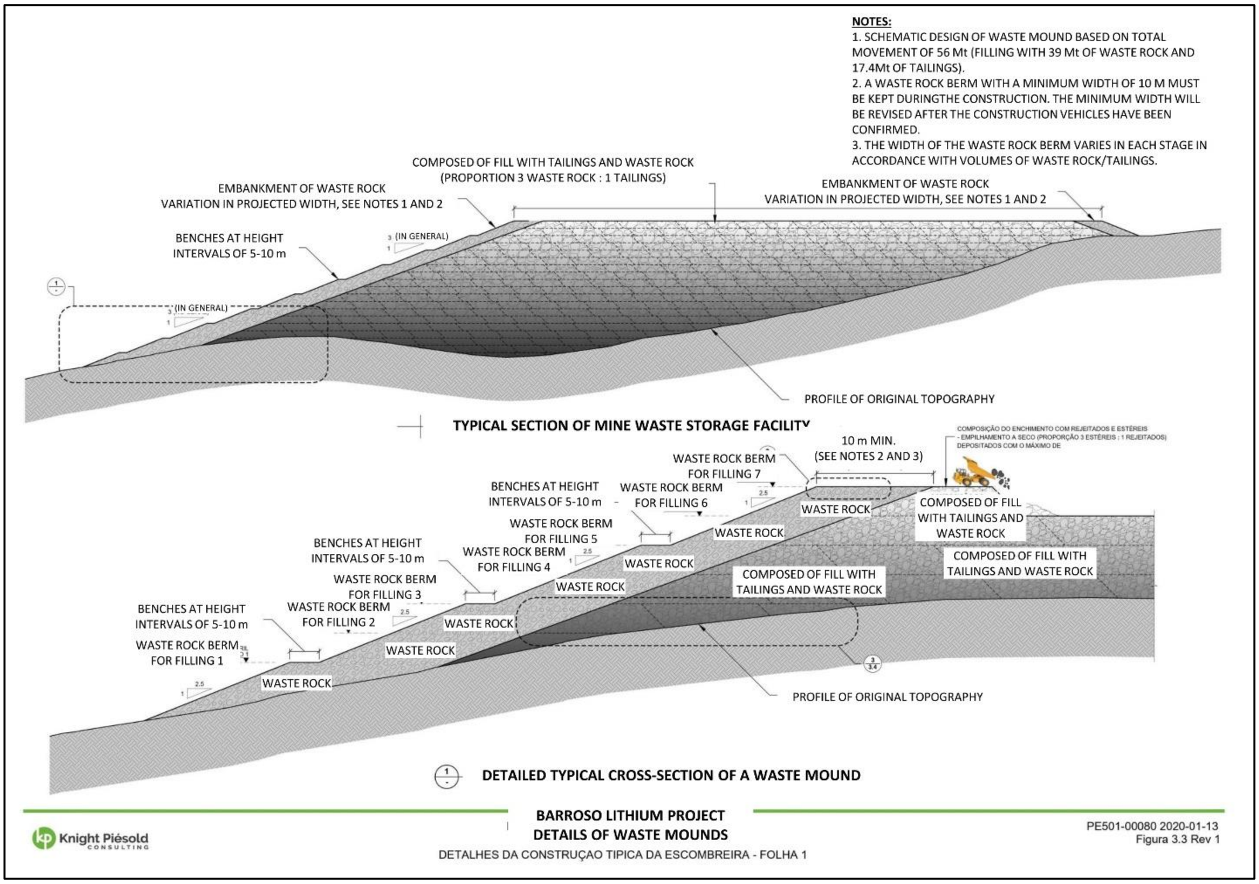

Figure 8. Although Savannah Lithium LDA (2020a-f) never uses the word "dam," the embankment of waste rock that would confine the mixture of waste rock and filtered tailings serves the function of a dam and should be designed to meet dam safety regulations. The above is especially true because, based on current filtered tailings technology and occasional high precipitation, a significant proportion of the tailings will be too wet for adequate compaction. The waste rock dam would be constructed using the upstream method, in which the dam is built on top of the tailings that it is confining. In the event of the liquefaction of the tailings, the dam will collapse into the underlying tailings. For that reason, the method of upstream construction is illegal in Brazil, Chile, Ecuador and Peru. Figure from Savannah Lithium LDA (2020b) with overlay of English labels.

A stability analysis was carried out to determine the factor of safety of the Southern Waste Mound (see Figs. 9a-b). The factor of safety FS is the minimum value of the ratio of the shear strength of the waste mound to the shear stress acting on the waste mound, as considered over all possible failure surfaces, so that FS = 1.0 indicates a waste mound on the cusp of failure. The factor of safety is based upon the assumed shear strength parameters (cohesion and friction angle) of the waste material and the assumed height of the water table within the waste mound (see Fig. 9b). A stability analysis and its corresponding factor of safety do not refer to the possibility of liquefaction, but to the tendency of the waste mound to fail by slumping or sliding without liquefaction. The factor of safety FS was found to be FS = 1.5, which is the minimum acceptable value of a factor of safety, according to most international standards (e.g, ANCOLD, 2012; Canada Dam Association, 2013). The Environmental Impact Study refers to the Australian standard (ANCOLD, 2012) and Portugal does not appear to have its own standard for a minimum factor of safety.

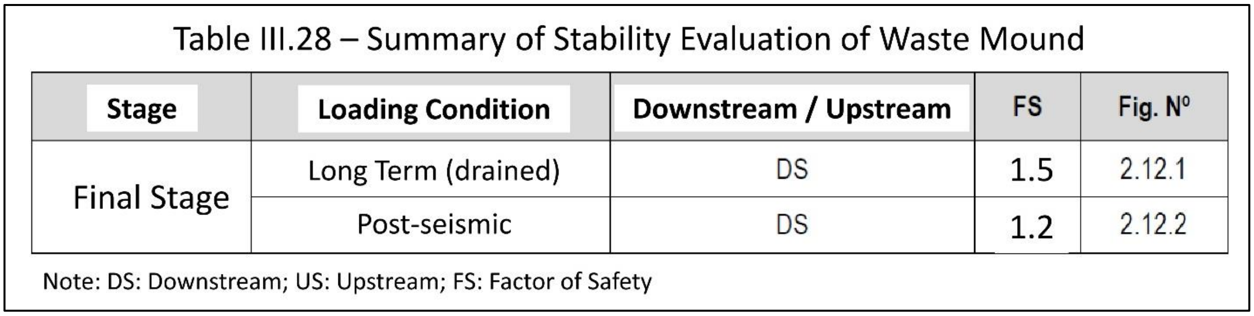

Table III.28 – Summary of Stability Evaluation of Waste Mound

Stage	Loading Condition	Downstream / Upstream	FS	Fig. Nº
Final Stage	Long Term (drained)	DS	1.5	2.12.1
	Post-seismic	DS	1.2	2.12.2

Note: DS: Downstream; US: Upstream; FS: Factor of Safety

Figure 9a. At the end of construction, the mound of waste rock and tailings would have a factor of safety (FS) of FS = 1.5, where the factor of safety is the ratio of the shear strength of the waste mound to the shear stress acting on the waste mound, so that FS = 1.0 indicates a waste mound on the cusp of failure. According to most international standards, FS = 1.5 is the minimum acceptable value. The factor of safety of the waste mound was calculated based on the geotechnical properties of only one sample of mine tailings. The "drained" loading condition means that it was assumed that water could escape from the pores during deformation. However, if the disturbance were sufficiently rapid or if the pores were saturated, the "undrained" loading condition would apply, which would lead to a lower factor of safety. Savannah Lithium LDA (2020a-f) does not include any consideration of undrained loading or the conditions under which the pores would become saturated. Figure from Savannah Lithium LDA (2020a) with overlay of English labels.

It should be emphasized that the plan for storage of tailings at the Barroso lithium mine, especially the storage of tailings to a height of 193 meters is highly innovative (see Table 2). According to the Global Tailings Dam Portal Project (GRID-Arendahl, 2021), the tallest tailings dam in the world is the Linga dam in Peru with a height of 265 meters, while the tallest tailings dam in Europe is the Skouries Integrated Waste Management Facility in Greece with a height of 220 meters. The second tallest tailings dam in Europe is the Saint Cyr dam in France with a height of 75 meters, while the tallest tailings dam in Portugal is the Cerro do Lobo Tailings Facility with a height of 42 meters. In response to the tailings dam failure near Brumadinho, Brazil, China prohibited the construction of any tailings dams taller than 200 meters (Zhang and Daly, 2019; Zhang and Singh, 2020). According to Klohn Crippen Berger (2017), the tallest filtered tailings storage facility in the world is at the La Coipa mine in Chile with a height of 70 meters. I am not aware of any operating lithium mine with a filtered tailings storage facility. However, besides the proposed Barroso mine, there at least seven other proposals for filtered tailings storage facilities at lithium mines (see Table 2). The proposed lithium mine with the tallest filtered tailings storage facility would be the Lithium Americas Thacker Pass mine in Nevada, USA (U.S. Bureau of Land Management, 2020). In summary, according to current databases and the knowledge of the author, the tailings dam at the Barroso mine would be the first filtered tailings dam at an operating lithium mine, the tallest filtered tailings dam out of all current proposed lithium mines, the tallest operating filtered tailings dam in the world, the tallest tailings dam in Portugal, and the second tallest tailings dam in Europe. Further information about the tailings storage facility will be provided in the Results section.

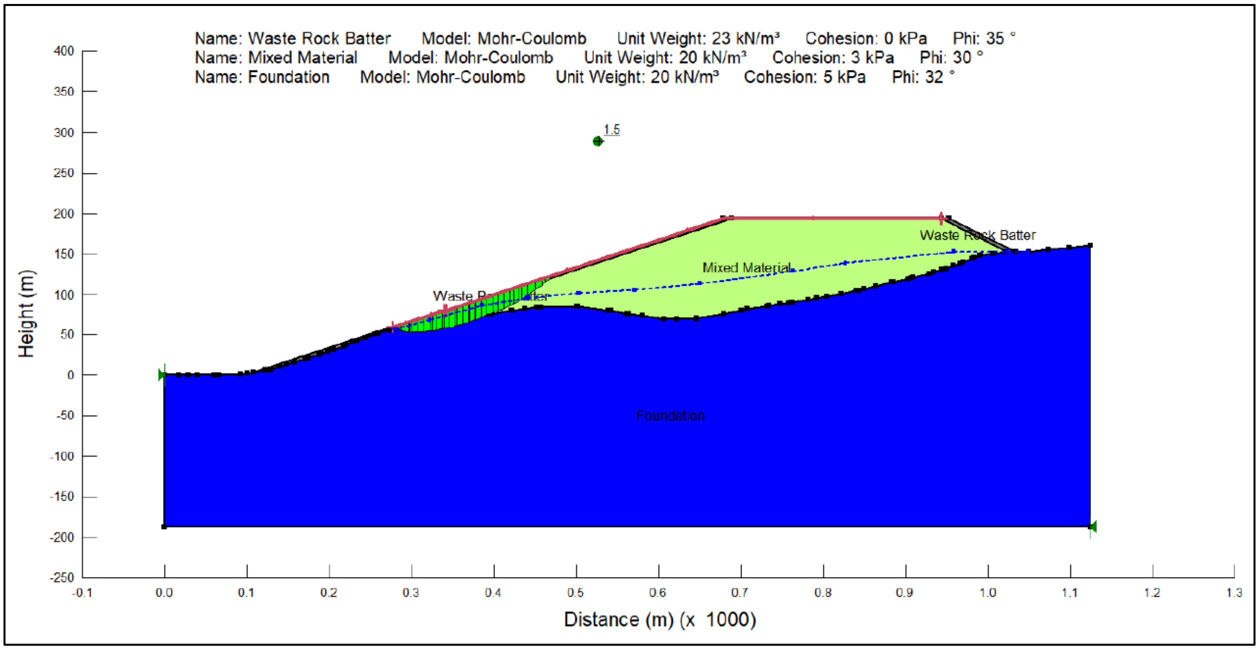

Figure 9b. At the end of construction, the mound of waste rock and tailings would have a factor of safety (FS) of FS = 1.5, where the factor of safety is the ratio of the shear strength of the waste mound to the shear stress acting on the waste mound, so that FS = 1.0 indicates a waste mound on the cusp of failure. According to most international standards, FS = 1.5 is the minimum acceptable value. The factor of safety of the waste mound was calculated based on the assumed shear strength parameters of the tailings, waste rock and foundation, and the assumed water table (dashed blue line). Presumably, lower shear strength parameters or a higher water table would result in FS < 1.5. There was no justification for the assumed water table height, and no consideration of the dependence of the factor of safety on the height of the water table or the circumstances under which the water table would rise higher than the assumed height. There is no document that describes any geotechnical testing of the waste rock or foundation, nor is there any document that explains how the shear strength parameters of the waste rock and foundation were estimated. The dark green slice indicates the region that would fail, that is, the bottom of the slice is the surface with the lowest factor of safety. It is the assumed shear strength of the foundation that prevents the failure surface from migrating into the foundation or farther upstream of the crest of the topographic high that underlies the waste mound (toward the right of the figure). In other words, a weaker foundation would result in a failure that would incorporate a larger fraction of the waste mound. Note that the stability analysis assumes that the waste rock has a larger friction angle (phi = 35°) than the foundation (phi = 32°). This is surprising, since, without further information, it should be assumed that the waste rock is simply foundation material, but in a crushed and less dense form. The figure was taken from Savannah Lithium LDA (2020c) and is available only in English.

METHODOLOGY

Based upon the preceding sections, the objective of this report can be subdivided into the following questions regarding the Environmental Impact Study:

1) Is there an adequate consideration of the consequences of failure of the waste mound?
2) Is there an adequate choice for the design flood for the waste mound?
3) Is there an adequate plan for prevention of liquefaction of the tailings?
4) Is there an adequate stability analysis for the waste mound?
5) Is there an adequate plan for water management infrastructure for the waste mound?

Table 2. Heights of filtered tailings storage facilities at proposed lithium mines

Proposal Date	Company	Mine	Location	Height (m)
2016	Bacanora Minerals[1]	Sonora	Mexico	20
2017	Critical Elements[2]	Rose	Quebec, Canada	80
2018	Nemaska Lithium[3]	Whabouchi	Quebec, Canada	30
2019	Galaxy Lithium[4]	James Bay	Quebec, Canada	100
2019	Sigma Lithium[5]	Grota do Cirilo	Minas Gerais, Brazil	28, 70
2020	Cypress Development[6]	Clayton Valley	Nevada, USA	30
2020	Lithium Americas[7]	Thacker Pass	Nevada, USA	107
2020	Savannah Lithium[8]	Barroso	Portugal	193

[1] Bacanora Minerals Ltd (2016)
[2] Critical Elements Corporation (2017)
[3] Nemaska Lithium (2017)
[4] Galaxy Lithium (Canada) (2019)
[5] Sigma Lithium (2019)
[6] Cypress Development Corp. (2020)
[7] U.S. Bureau of Land Management (2020)
[8] Savannah Lithium LDA (2020a)

The above questions were addressed largely by comparison of the Environmental Impact Study with the published literature on filtered tailings and with international and Portuguese dam safety standards. It was surprising that much of the information on tailings storage in the Environmental Impact Study is available only in English. For example Appendix III-1 (Savannah Lithium, 2020f) consists of a 104-page document in English (written by Knight-Piésold) and only a seven-page summary in Portuguese. It is disturbing that the Agência Portuguesa do Ambiente [Portuguese Environment Agency] does not expect documents that are submitted for public consultation to be written in the national language. In fact, some critical diagrams from the Environmental Impact Study were available only in English with no Portuguese version (see Figs. 9b and 12). In the Portuguese version of this report, all English-language diagrams are reproduced with overlay of Portuguese labels.

The subsection in the Results section on the consequences of failure of the waste mound includes an original analysis of the consequences, due to the absence of an adequate analysis in the Environmental Impact Study. The analysis of consequences was based upon the most recent statistical model of past tailings dam failures (Larrauri and Lall, 2018). The statistical model predicts the volume of spilled tailings and the initial runout of tailings following dam failure. The initial runout is the distance covered by the tailings due to the release of gravitational potential energy as the tailings fall out of the tailings pond. After the cessation of the initial runout, normal fluvial processes could transport the tailings downstream indefinitely until the tailings reach a major lake or the ocean. When the initial runout reaches a major river, as would happen in the failure of the tailings dam of the Barroso mine, it can be difficult to separate the initial runout from the subsequent normal fluvial processes. For example, the failure of the tailings dam at the Samarco mine in Minas Gerais, Brazil, spilled tailings into the Doce River, so that the initial runout extended 637 kilometers to the Atlantic Ocean (Larrauri and Lall, 2018).

According to Larrauri and Lall (2018), the best predictor of the initial runout of released tailings is the dam factor H_f, defined as

$$H_f = H\left(\frac{V_F}{V_T}\right)V_F \tag{1}$$

where H is the height of the dam (meters), V_T is the total volume of confined tailings and water (millions of cubic meters), and V_F is the volume of the spill (millions of cubic meters). The most-likely predictions for the volume of the spill and the initial runout D_{max} (kilometers) are then

$$V_F = 0.332 \times V_T^{0.95} \tag{2}$$

$$D_{max} = 3.04 \times H_f^{0.545} \tag{3}$$

It should be noted that Eqs. (2)-(3) express the most-likely consequences of dam failure. In particular, the most-likely consequence is that dam failure will result in the release of about one-third of the stored tailings (see Eq. (2)). However, the worst-case scenario is that dam failure will result in the release of 100% of the stored tailings, for which there are examples (Larrauri and Lall, 2018). Therefore, the worst-case runout ($V_F = V_T$) should be calculated using Eq. (3) with

$$H_f = HV_T \tag{4}$$

For use in the above equations, since the plan is to create a homogeneous mixture of tailings and waste rock in the Southern Waste Mound, V_T was assumed to be the combined volume of stored tailings and stored waste rock (see Table 1).

The database of tailings dam failures of Larrauri and Lall (2018) does not include any examples of failures of waste mounds that stored a mixture of tailings and waste rock. On the other hand, Hawley and Cunning (2017) present empirical formulae for the runout following failure of waste mounds that stored only waste rock with no tailings. There is considerable scatter in the runout data from Hawley and Cunning (2017) and the authors conclude, "In summary, the use of empirical correlations offers only very approximate means of predicting the runout of waste dump landslides. Perhaps the best approach is to seek precedents from data on failures observed in a given region and from physical and geomorphological settings comparable to those of the case being analysed. It is essential to make maximum use of local experience." By contrast, based on 35 tailings dam failures, Larrauri and Lall (2018) find $R^2 = 0.887$ and $R^2 = 0.53$ for predicting the spill volume and runout distance, respectively, from the dam height and volume of stored tailings. (The preceding means that the variation in dam height and volume of stored tailings predicts 88.7% and 53% of the variation in spill volume and runout distance, respectively.) Based on the above, it was decided to rely on the tailings dam failure database of Larrauri and Lall (2018) for prediction of the consequences of failure of the waste mound at the Barroso mine.

Particular attention was paid to communities that are within 10 kilometers downstream of the Southern Waste Mound, as measured along the path of flow. There have not been many measurements of the velocities of tailings flow slides, but they have ranged from 20-160 kilometers per hour (Jeyapalan, 1981). According to Petley (2019), the tailings flow slide following the recent failure of the dam near Brumadinho in Brazil in 2019 accelerated to 120 kilometers per hour and then slowed to 66 kilometers per hour. Based on the minimum tailings flow velocity of 20 kilometers per hour, the communities within 10 kilometers could be reached by the tailings flood within a maximum of 30 minutes.

Also in response to the tailings dam disaster near Brumadinho, Brazil, the new tailings dam legislation in Brazil advanced the concept of the "self-rescue zone." Within the state of Minas Gerais, Brazil, it is prohibited to construct or expand a tailings dam where there is a population residing within the self-rescue zone. According to Assembleia Legislativa de Minas Gerais [Legislative Assembly of Minas Gerais] (2019), "*Fica vedada a concessão de licença ambiental para construção, instalação, ampliação ou alteamento de barragem em cujos estudos de cenários de rupturas seja identificada comunidade na zona de autossalvamento. § 1º – Para os fins do disposto nesta lei, considera-se zona de autossalvamento a porção do vale a jusante da barragem em que não haja tempo suficiente para uma intervenção da autoridade competente em situação de emergência. § 2º – Para a delimitação da extensão da zona de autossalvamento, será considerada a maior entre as duas seguintes distâncias a partir da barragem: I – 10km (dez quilômetros) ao longo do curso do vale; II – a porção do vale passível de ser atingida pela onda de inundação num prazo de trinta minutos. § 3º – A critério do órgão ou da entidade competente do Sisema, a distância a que se refere o inciso I do § 2º poderá ser majorada para até 25km (vinte e cinco quilômetros), observados a densidade e a localização das áreas habitadas e os dados sobre os patrimônios natural e cultural da região"* [It is forbidden to grant an environmental license for the construction, installation, expansion or elevation of a dam for which studies of rupture scenarios identify a community in the self-rescue zone. § 1 – For the purposes of the provisions of this law, the portion of the valley downstream of the dam in which there is not enough time for intervention by the competent authority in an emergency situation is considered a self-rescue zone. § 2 – For the delimitation of the extent of the self-rescue zone, the greatest between the following two distances from the dam will be considered: I – 10 km (ten kilometers) along the course of the valley; II - the portion of the valley that can be reached by the flood wave within thirty minutes. § 3 - At the discretion of the competent body or entity of SISEMA, the distance referred to in item I of § 2 may be increased to up to 25 km (twenty-five kilometers), taking into account the density and location of the inhabited areas and the data on the region's natural and cultural heritage]. Although not stated, the generally accepted minimum tailings flow velocity of 20 kilometers per hour is the apparent basis for the equivalence between 10 kilometers and 30 minutes.

Ecuador adopted the same concept the following year. According to Ministerio de Energía y Recursos Naturales No Renovables [Ministry of Energy and Non Renewable Natural Resources] (Ecuador) (2020a), "*Se prohíbe el diseño y construcción de depósitos de relave en los casos que se identifique una zona poblada ubicada aguas abajo del mismo que pudiera ser afectada por la onda de inundación, la cual queda limitada por la mayor de las dos distancias: • A diez (10) kilómetros de distancia aguas abajo del pie de la presa a lo largo del curso del valle, o; • La porción de territorio que sea alcanzada por la onda de inundación en un plazo de 30 minutos*" [The design and construction of tailings deposits is prohibited in cases where a populated area located downstream of the same is identified that could be affected by the flood wave, which is limited by the greater of the two distances: • Up to ten (10) kilometers downstream from the toe of the dam along the course of the valley, or; • The portion of territory that could be reached by the flood wave within 30 minutes]. Morrill et al. (2020) critiqued the above distances and arrival times in writing, "Although these limits can be seen as progress compared to a lack of any regulation, they are arbitrary and will not necessarily ensure safe evacuation in every situation. Therefore, minimum distance between communities and new dams must be defined on a case-by-case basis."

RESULTS

Adequacy of Analysis of Consequences of Dam Failure

The simple answer is that the Environmental Impact Study does not include any consideration of the consequences of failure of the waste mound. In fact, the Environmental Impact Study takes the opposite approach in denying any possibility of failure. According to Savannah Lithium LDA (2020a), "*Com base numa avaliação de rutura, é provável que o risco esteja confinado apenas aos operadores nas proximidades da estrutura nesse momento e o risco geral seja baixo ou insignificante* [Based on a failure assessment, the risk is likely to be confined only to operators in the vicinity of the structure at that time and the overall risk is low or negligible]. Savannah Lithium LDA (2020a) continues to deny the possibility of failure in an even stronger way by writing, "*não se perspetiva a perda de vidas humanas, uma vez que a integridade estrutural e o bom funcionamento da instalação de resíduos se encontram assegurados* [the loss of human life is not expected, as the structural integrity and proper functioning of the waste facility are assured]. Of course, it is very dangerous to assume that the structural integrity and proper functioning of any engineering structure is ever "assured."

It is unlikely that the failure of the waste mound would result in the deposition of spilled tailings over an extended distance (such as tens of kilometers) unless the spilled tailings develop a flow behavior. According to Klohn Crippen Berger (2017), a slump or slide of filtered tailings could extend for ten times the height of the facility without liquefaction or other flow behavior. On that basis, a slump or slide of tailings could extend for about 1500 meters if Alternative 1 were chosen and about 2000 meters if either Alternatives 2 or 3 were chosen (see Figs. 4a-c). In the case of Alternative 1, the pathway of the slump of tailings will provide numerous points of entry into the Covas River (a tributary of the Beça River) (see Fig. 4a). In the case of Alternatives 2 or 3, the pathway of the slump of tailings will provide numerous points of entry into either the Covas River or the Beça River itself (see Figs. 4b-c). In that way, regardless of the water content of the filtered tailings before failure, the mixing of the tailings with the downstream water bodies could allow for the development of flow behavior. In Figs. 4a-c, the tailings slump path is drawn in a general downstream direction, but is otherwise arbitrary. It should be noted that a tributary of the Covas River actually emerges from beneath the western side of the Southern Waste Mound (see Figs. 4a-c), so that, if tailings spilled from the western side of the waste mound, mixing of the tailings with water will occur immediately after failure of the waste mound.

Based on the statistical model by Larrauri and Lall (2018), the most-likely prediction is that the initial flow of tailings will extend for 59.9, 83.7 and 86.1 kilometers for Alternatives 1, 2 and 3, respectively (see Table 1). Based on the preferred Alternative 3, in the initial event, the spilled tailings will flow along the Beça River to the Tâmega River and down to the confluence with the Douro River with the potential of impacting numerous communities along the rivers, including (in downstream order) Vila Nune, Mondim de Basto, Celorico de Basto, Amarante, Marco de Canaveses, Rio de Moinhos, and Torrão (see Fig. 2). Following the initial event, normal fluvial processes will continue to transport the spilled tailings along the Douro River past the communities of Aldeia São Miguel, Porto and Vila Nova de Gaia to the Atlantic Ocean (see

Fig. 2). The above communities are only representative and are not intended to be a complete list.

Using the same statistical model (Larrauri and Lall, 2018), the most-likely predictions for the volumes of spilled mine waste are 5.6, 8.1, and 8.5 million cubic meters for Alternatives 1, 2 and 3, respectively (see Table 1), corresponding to 28-29% of the stored mine waste. The worst-case scenario will be the release of 100% of the stored mine waste (19.4, 28.9, and 30.5 million cubic meters for Alternatives 1, 2 and 3, respectively; see Table 1). In this case, according to Eqs. (3)-(4), in the initial event, the spilled tailings will travel for 234.1, 334.5 and 344.9 kilometers for Alternatives 1, 2 and 3, respectively (see Table 1). However, in the worst-case scenario, the actual initial event will be limited by the 128-kilometer distance to the Atlantic Ocean (see Fig. 2).

An exception that could prevent the arrival of the tailings in the Atlantic Ocean, either in the case of the most-likely or the worst-case scenario, could be the impoundment of the tailings in the reservoirs behind one of the large dams along the route to the ocean. The International Commission on Large Dams (2021) defines a large dam as "a dam with a height of 15 metres or greater from lowest foundation to crest or a dam between 5 metres and 15 metres impounding more than 3 million cubic metres." On that basis, there are two large dams along the route, which are the Torrão dam along the Tâmega River and the Crestuma-Lever dam along the Douro River (see Fig. 2; Comissão Nacional Portuguesa das Grandes Barragens [Portuguese National Committee on Large Dams], 2021). The Torrão dam has a height of 69 meters above the foundation, gross capacity of 124 million cubic meters, effective storage of 77 million cubic meters, and a design flood with a return period of 500 years. The Crestuma-Lever dam has a height of 65 meters above the foundation, gross capacity of 110 million cubic meters, effective storage of 22.5 million cubic meters, and a design flood with a return period of 1000 years (Comissão Nacional Portuguesa das Grandes Barragens, 2021). It cannot be assumed that either of these large dams would prevent the further downstream transport of spilled mine waste from the Barroso mine. First, the same extreme flood or precipitation event that destroys the Southern Waste Mound could also result in flow over the crest or the spillway of the Torrão dam or Crestuma-Lever dam. Second, it is noteworthy that, based on the preferred Alternative 3, the volume of mine waste that would be stored at the Southern Waste Mound is already 40% of the effective storage of the Torrão dam and 136% of the effective storage of the Crestuma-Lever dam (see Table 1).

Adequacy of Design Flood

As in the previous subsection, the simple answer is that the Environmental Impact Study does not include any consideration of a design flood. In other words, the Southern Waste Mound has not been designed to withstand any particular flood or precipitation event. In terms of the proper choice for the design flood, the important question is whether there is potential loss of life in the event of failure of the waste mound. It is not possible to answer this question without a rigorous analysis of the consequences of failure of the waste mound, which has not been a part of the Environmental Impact Study.

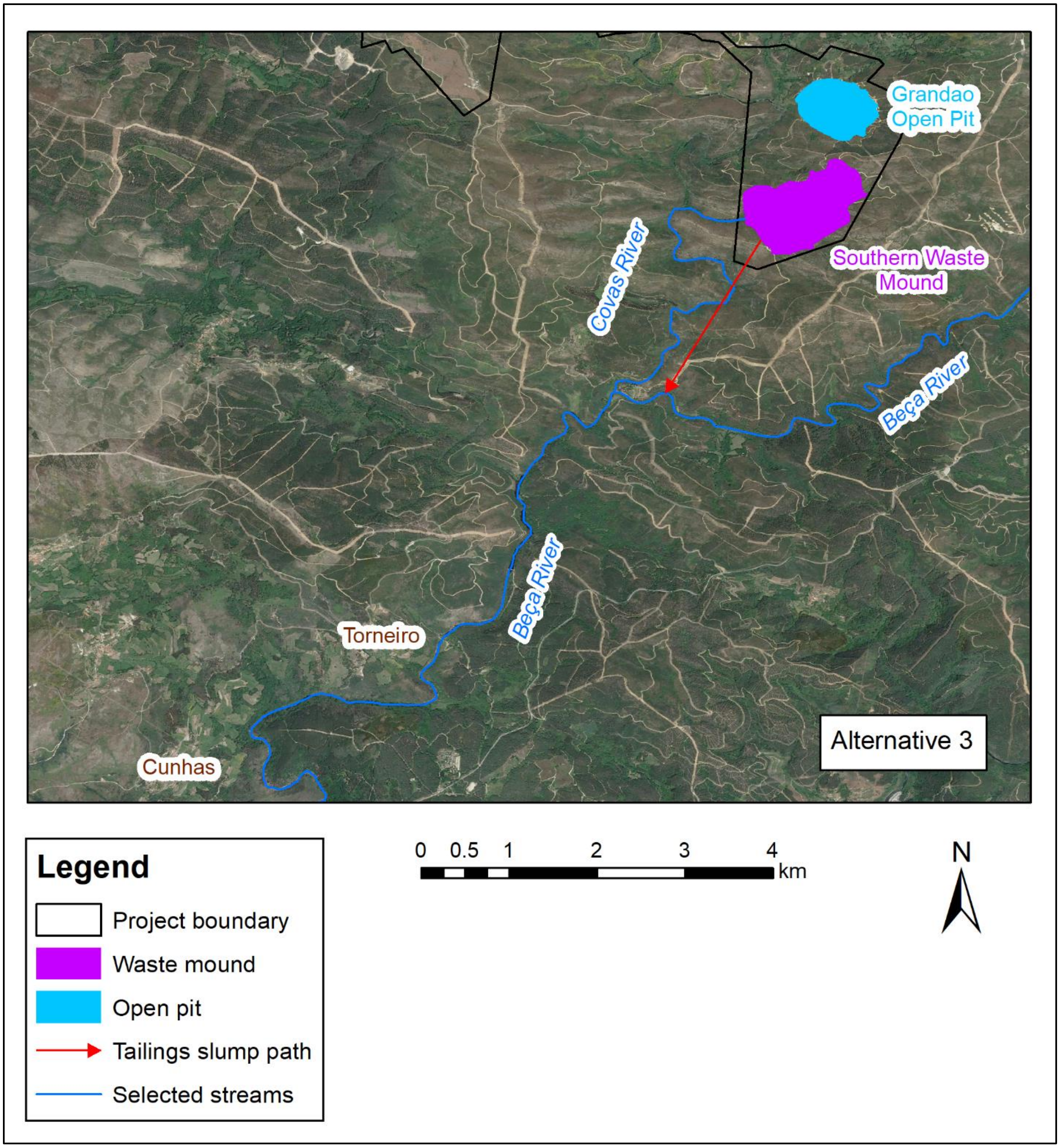

Figure 10. There are two communities (Torneiro and Cunhas) within 10 kilometers downstream of the tailings dam along the course of the flow path (see Table 3). It is assumed that the tailings flood will travel in a straight line in a general downstream direction (called the tailings slump path) until reaching the Beça River, after which it will flow downstream along the Beça River. In Brazilian and Ecuadorian legislation, the "self-rescue zone" is defined as 10 kilometers downstream of the tailings dam along the course of the valley or the region that can be reached by the tailings flood in 30 minutes, whichever is farther. In Brazil and Ecuador, it is prohibited to construct or expand a tailings dam where there is a population residing within the self-rescue zone. Mine infrastructure based on Alternative 3 from Savannah Lithium LDA (2020g). Background and community locations are from Google Earth images from May 5 and May 24, 2019.

There are two communities (Torneiro and Cunhas) within 10 kilometers downstream of the tailings dam along the course of the flow path (see Table 3 and Fig. 10), not including isolated farmhouses. It is assumed that the tailings flood will travel in a straight line in a general downstream direction (called the tailings slump path in Fig. 10) until reaching the Beça River, after which it will flow downstream along the Beça River. Based on the minimum tailings flow velocity of 20 kilometers per hour, the tailings flood will reach Torneiro and Cunhas in a maximum of 19 and 28 minutes, respectively (see Table 3). However, based on presently available information, it is not obvious whether there would be potential loss of life in the event of failure of the waste mound. Due to the rugged topography, the average elevations of Torneiro and Cunhas are, respectively, 99 and 170 meters above the Beça River (see Table 3). A rigorous study would be required to determine whether the three communities within 10 kilometers of the Southern Waste Mound (see Fig. 10) or any of the communities even farther downstream (see Fig. 2) could be or should be evacuated prior to arrival of the tailings flood. However, it should be noted that the Environmental Impact Study does not include any consideration of an alarm system for the downstream communities or any other emergency plan of any kind.

Table 3. Predicted maximum arrival times for tailings flood

Community	Population[1]	Elevation above Beça River (m)	Distance along Flood Pathway[2] (m)	Maximum Arrival Time[3] (min)
Torneiro	<50	99	6459	19
Cunhas	79	170	9251	28

[1] Populations from City Population (2021). Communities with fewer than 50 inhabitants are not listed in City Population (2021), but are labeled on Google Earth image dated May 24, 2019.

[2] See Fig. 10 for assumed tailings flood pathway.

[3] Based on minimum velocity of tailings flood of 20 km/h.

In order to simplify this discussion, it will be assumed that there is no potential loss of life in the event of failure of the waste mound. On that basis, at the very least, the consequences will be Significant by the standards of the Federal Emergency Management Agency (2013) and High by the standards of the Canadian Dam Association (2013, 2019) and the Global Industry Standard on Tailings Management (ICMM-UNEP-PRI, 2020). By comparison with the design flood standards discussed previously, at a minimum, the Southern Waste Mound should be designed to withstand a precipitation event corresponding to a 1000-year storm (FEMA, 2013), one-half the Probable Maximum Flood (USACE, 1991), either a 2475-year storm or one-third between a 1000-year storm and the Probable Maximum Flood (Canadian Dam Association, 2013, 2019), a 10,000-year storm (Morrill et al., 2020), or a 2475-year storm (ICMM-UNEP-PRI, 2020). Even by the very weak standards of Portugal and Spain, the waste mound should be designed to withstand a 500-year storm. The above standards will be considered further in the subsection Adequacy of Water Management Infrastructure.

Adequacy of Plan for Prevention of Liquefaction

As in the previous subsections, there is no plan to prevent liquefaction aside from the general concept that filtered tailings will have a lower probability of liquefaction than non-filtered tailings. It was mentioned previously that a soil or a mass of tailings with a mix of fine and coarse particles will tend to be liquefiable. The finer particles will fill the spaces between the coarse particles and thus prevent the escape of water during shearing or other deformation (see

Fig. 6). The Environmental Impact Study acknowledges that the tailings will have the mix of particle sizes that will tend to lead to liquefaction (see Fig. 11). According to Savannah Lithium LDA (2020a), "*A curva de classificação indica que a amostra da Savannah cai dentro dos limites de solos potencialmente liqueficáveis e, portanto, a liquefação da massa de rejeitados precisa ser considerada no projeto* [The classification curve indicates that the Savannah sample falls within the limits of potentially liquefiable soils and therefore the liquefaction of the mass of tailings needs to be considered in the design]. However, the remainder of the Environmental Impact Study does not include any consideration of the circumstances under which liquefaction will occur and simply denies the possibility of liquefaction. Savannah Lithium LDA (2020a) continues, "*Foram tidos em conta os seguintes pressupostos para a modelação de estabilidade … Nenhuma desagregação decorrente da carga ou materiais com potencial de liquefação estarão presentes nas estruturas avaliadas ou nas suas fundações … Os materiais de construção são considerados não suscetíveis à liquefação*" [The following assumptions were taken into account for the stability modeling: … No disaggregation due to load or materials with liquefaction potential will be present in the evaluated structures or in their foundations … Construction materials are considered to be not susceptible to liquefaction].

The plan at the Barroso mine is to filter the tailings to a water content less than 15%. Based on the previous quote ("a 15% moisture content remains a typical target, while tracking of day-in and day-out moisture contents of filter cakes demonstrates that achievable moisture contents are often in the range of 17 to 18% when things are running smoothly and can be up to 20 to 23% when off-spec") in the review by Crystal et al. (2018), the plan seems to be somewhat beyond the limits of current filter press technology. However, the Environmental Impact Study does not include any consideration of a plan for how to manage the tailings that are too wet for adequate compaction, either because they left the filter presses with excessive water content or because they were rewetted by precipitation. For example, there is no plan to store tailings in a shelter during periods of heavy rainfall. The implicit plan simply seems to be to attempt to compact the tailings and the waste rock together in the waste mound, regardless of the actual water content of the tailings. On that basis, it should be assumed that the mixture of tailings and waste rock will not be fully compacted.

The liquefiable nature of the tailings and the probable lack of adequate compaction of the tailings emphasizes that the wall of waste rock that would surround the tailings (see Fig. 8) should be regarded as a dam and should be expected to conform to dam safety standards. It is important to note that the wall of waste rock (the dam) would be constructed on top of the mixture of tailings and waste rock, which is known as the method of upstream construction (see Fig. 8). The method of upstream construction is the cheapest method of dam construction because it uses the minimum amount of construction material (waste rock). On the other hand, the method of upstream construction is dangerous because, if the underlying tailings undergo liquefaction, the dam will simply fall backwards and downwards into the liquefied tailings, even if the dam itself does not liquefy. For this reason, the method of upstream construction for tailings dams is illegal in Brazil (Agência Nacional de Mineração [National Mining Agency], 2019), Chile (Ministerio de Minería (Chile) [Ministry of Mining (Chile)], 2007), Ecuador (Ministerio de Energía y Recursos Naturales No Renovables (Ecuador), 2020b) and Peru (Sistema Nacional de Información Ambiental (Perú) [National System of Environmental Information (Peru)], 2014).

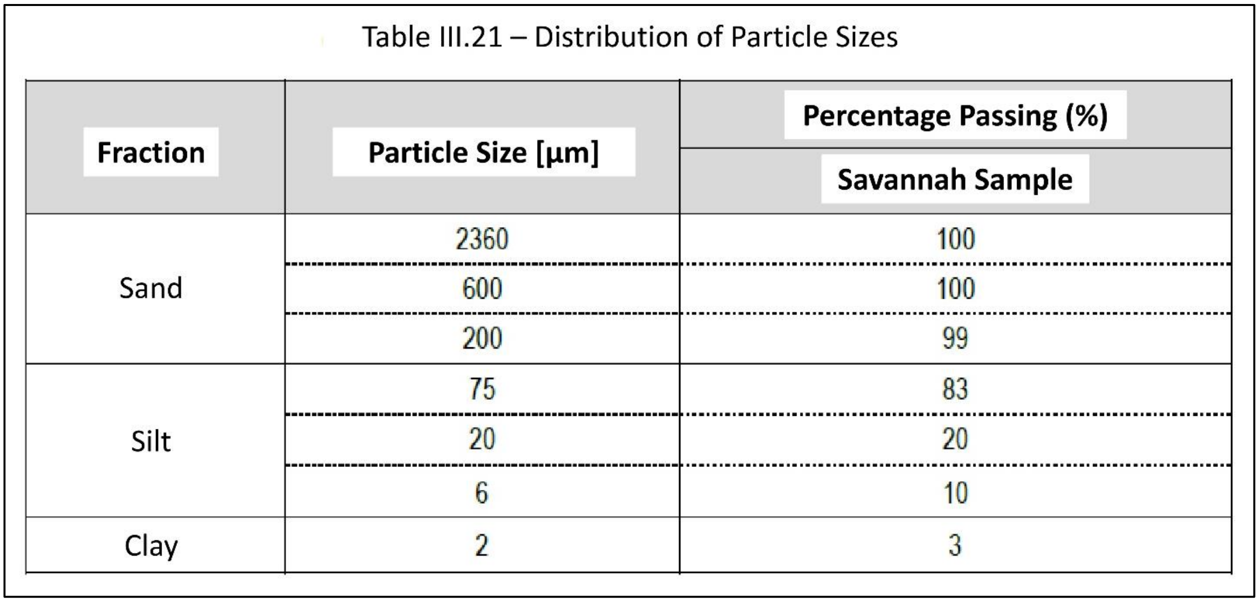

Table III.21 – Distribution of Particle Sizes

Fraction	Particle Size [µm]	Percentage Passing (%)
		Savannah Sample
Sand	2360	100
	600	100
	200	99
Silt	75	83
	20	20
	6	10
Clay	2	3

Figure 11. A mix of fine and coarse particles can have a low permeability because the finer particles will fill in the spaces between the coarser particles. This low permeability could cause a mass of tailings to be susceptible to liquefaction because water will not be able to escape from the pores during deformation (see Fig. 6). According to Savannah Lithium LDA (2020a), "*A curva de classificação indica que a amostra da Savannah cai dentro dos limites de solos potencialmente liquefícáveis e, portanto, a liquefação da massa de rejeitados precisa ser considerada no projeto* [The classification curve indicates that the Savannah sample falls within the limits of potentially liquefiable soils and therefore the liquefaction of the mass of tailings needs to be considered in the design]. However, the remainder of the Environmental Impact Study does not include any consideration of the circumstances under which liquefaction will occur and simply denies the possibility of liquefaction. Savannah Lithium LDA (2020a) continues, "*Foram tidos em conta os seguintes pressupostos para a modelação de estabilidade … Nenhuma desagregação decorrente da carga ou materiais com potencial de liquefação estarão presentes nas estruturas avaliadas ou nas suas fundações … Os materiais de construção são considerados não suscetíveis à liquefação*" [The following assumptions were taken into account for the stability modeling: … No disaggregation due to load or materials with liquefaction potential will be present in the evaluated structures or in their foundations … Construction materials are considered to be not susceptible to liquefaction]. Figure from Savannah Lithium LDA (2020a) with overlay of English labels.

Adequacy of Stability Analysis

The stability analysis yielded a factor of safety FS for resistance against sliding without liquefaction of FS = 1.5 (see Figs. 9a-b), which is the minimum acceptable factor of safety according to most international standards (e.g., ANCOLD, 2012; Canadian Dam Association, 2013, 2019). The factor of safety was calculated based on assumed shear strength parameters (cohesion and friction angle) of the tailings (see Figs. 9a-b), so that, presumably, lower shear strength parameters would result in a factor of safety FS < 1.5, which would be unacceptably low. The shear strength parameters of the tailings were estimated based on the drained condition (see Fig. 9a), meaning that water is free to escape from the pores during shearing or other deformation. Testing under the undrained condition means that the sample is sealed so that water cannot escape during deformation of the sample. The undrained shear strength parameters are nearly always lower than the drained shear strength parameters, and thus nearly always produce a lower factor of safety. The undrained shear strength parameters are typically relevant for field situations in which the pores are saturated and/or the tailings have low permeability. The assumption that the pores would be unsaturated during field loading was not accompanied with any explanation as to the circumstances under which the pores would be saturated. Moreover, the previous description of the tailings as having low permeability (and thus high liquefaction potential) based on the grain size distribution (see Fig. 11) seems inconsistent with the assumption of drained loading. Savannah Lithium LDA (2020e) confirms that tailings properties were measured for only a single sample by writing "One bag of tailings sample was … sent to the KP [Knight-Piésold] laboratory in Perth in November 2019." Savannah Lithium LDA (2020e) also confirms that shear strength parameters were not actually measured, but were only estimated from the grain size distribution. According to Savannah Lithium LDA (2020e), "The typical effective friction angle and cohesion has been estimated based on the limited classification testing completed to date and empirical relationships." Based on the above, it should be assumed that the geotechnical properties of the tailings are very poorly known.

The stability analysis was also based on assumed shear strength parameters of the waste rock dam and the underlying foundation (see Fig. 9b). However, there is no document that describes any geotechnical testing of the waste rock or foundation, nor is there any document that explains how the shear strength parameters of the waste rock and foundation were estimated. As above, it should be assumed that lower values of the shear stress parameters of the waste rock or foundation would result in an unacceptably low FS < 1.5. Note that the dark green slice in Fig. 9b indicates the region that would fail, that is, the bottom of the slice is the surface with the lowest factor of safety. It is the assumed shear strength of the foundation that prevents the failure surface from migrating into the foundation or farther upstream of the crest of the topographic high that underlies the waste mound. In other words, a weaker foundation would result in a failure that would incorporate a larger fraction of the waste mound ((toward the right of Fig. 9b). Note that the stability analysis assumes that the waste rock has a larger friction angle (phi = 35°) than the foundation (phi = 32°) (see Fig. 9b). This is surprising, since, without further information, it should be assumed that the waste rock is simply foundation material, but in a crushed and less dense form.

The calculation of the factor of safety was finally based on an assumed water table height, so that, presumably, a higher water table would result in a factor of safety FS < 1.5, which would again be unacceptably low (see Fig. 9b). However, the stability analysis included no justification for the assumed water table height. There was also no consideration of the dependence of the factor of safety on the height of the water table nor a consideration of the circumstances under which the water table would rise higher than the assumed height. It should be noted that high water tables could result from any combination of excessive water in the tailings, precipitation onto the waste mound, surface runoff onto the waste mound, or upward seepage of groundwater into the waste mound. In summary, in light of its numerous unjustified assumptions, the stability analysis cannot be regarded as reliable. In fact, the final calculation of FS = 1.5 based upon unjustified input data suggests that the input data were chosen only to guarantee that the factor of safety would be the minimum acceptable value.

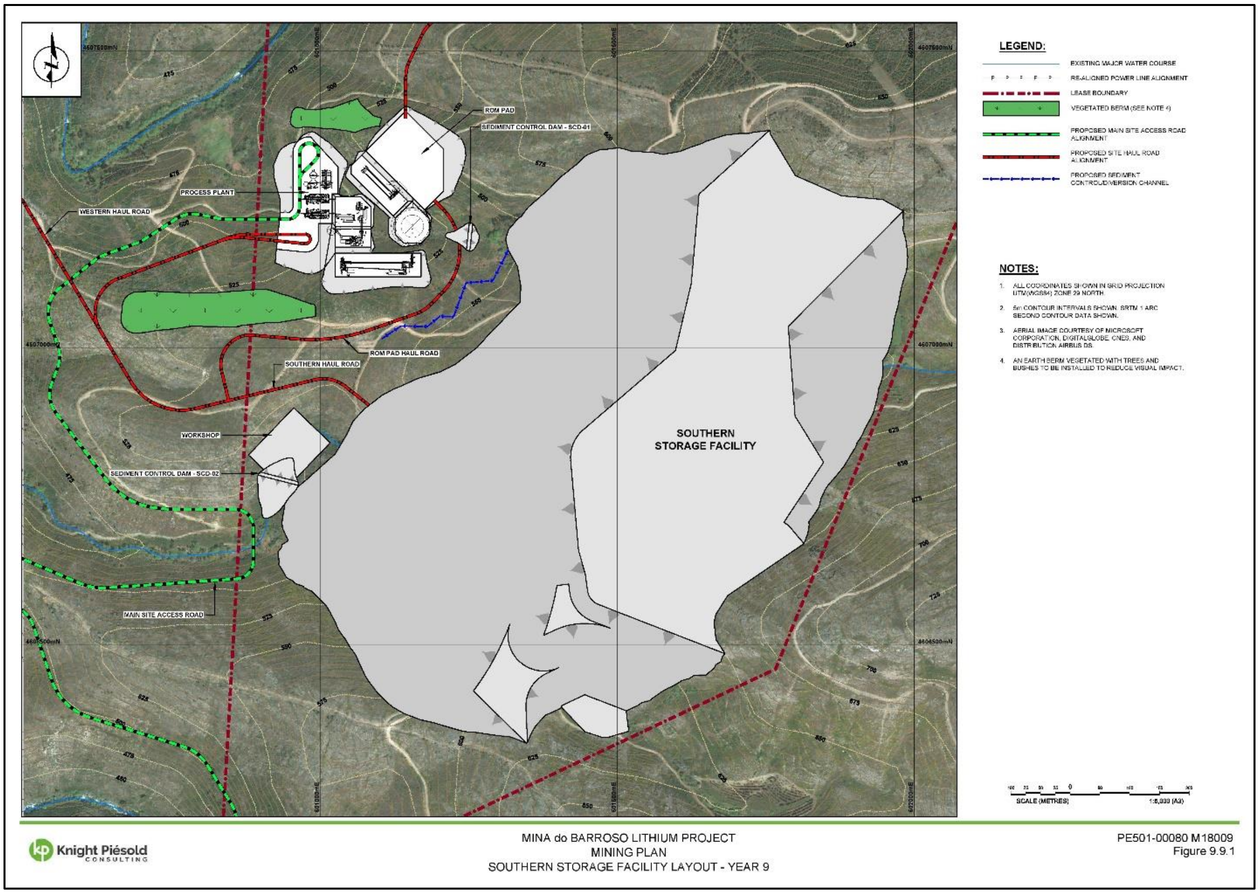

Figure 12. The figure clarifies that an existing stream flows through the site of the planned Southern Waste Mound (also called Southern Storage Facility), entering from the eastern side and exiting on the western side. There is no apparent plan for any water management infrastructure that would convey the stream and other surface runoff around the waste mound so as to prevent rewetting of the tailings. The outline of the Southern Waste Mound corresponds to Alternative 3 (see Table 1 and Fig. 4c). The figure was taken from Savannah Lithium LDA (2020d) and is available only in English.

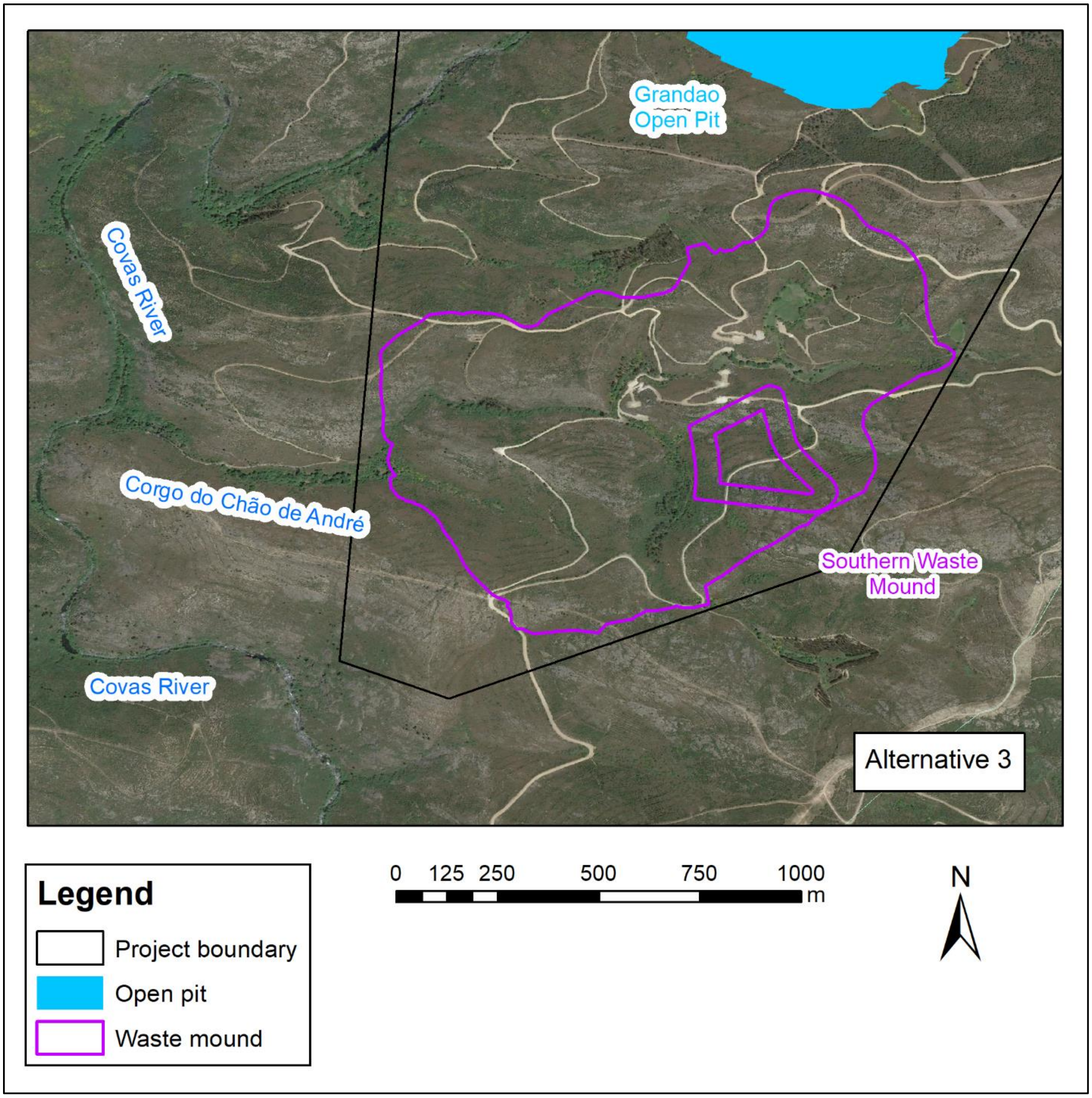

Figure 13. The Google Earth image from May 24, 2019, clarifies that an existing stream network flows through the site of the planned Southern Waste Mound. There is no apparent plan for any canals that would convey the streams and other surface runoff around the waste mound nor any plans for any drains that would convey groundwater from underneath the waste mound. Typically, such a water management infrastructure is needed to prevent rewetting of the tailings. "Corgo do Chão de André" is the local name for the stream that flows westward across the site of the planned waste mound. The outline of the Southern Waste Mound corresponds to Alternative 3 (see Table 1 and Fig. 4c). Mine infrastructure from Savannah Lithium LDA (2020g).

Adequacy of Water Management Infrastructure

As discussed in the previous subsection, adequate water management infrastructure is crucial to prevent an excessive rise of the water table within the Southern Waste Mound, which could lead to instability of the waste mound. However, there is no consideration in the Environmental Impact Study of the particular flood or precipitation event (or its corresponding return period) that the water management infrastructure should be able to accommodate. According to the Environmental Impact Study, the existence of a water management infrastructure was an assumption underlying the calculation of the factor of safety. Savannah Lithium LDA (2020a) writes, *Foram tidos em conta os seguintes pressupostos para a modelação de estabilidade … A drenagem superficial será instalada para desviar a água superficial para longe das estruturas e a sub-drenagem será construída para manter os níveis freáticos baixos*" [The following assumptions were taken into account for stability modeling: … Surface drainage will be installed to divert surface water away from structures and sub-drainage will be constructed to keep groundwater levels low]. However, there is essentially no other discussion of the water management infrastructure for the waste mound so that is not even clear that there is any plan to construct water management infrastructure, besides the simple statement of an intention. For example, Savannah Lithium LDA (2020d) confirms that a stream would enter the east side of the Southern Waste Mound and exit from the west side (see Fig. 12 and compare with Figs. 4a-c). The superposition of the outline of the Southern Waste Mound on the satellite imagery shows a network of streams on the site of the proposed waste mound with streams entering from both the eastern and southern sides (see Fig. 13). However, there are no diagrams for diversionary canals that would convey either stream flow or surface runoff around the Southern Waste Mound, although the available diagrams indicate sediment control diversion canals and sediment check dams (see Fig. 12). Moreover, the Environmental Impact Study does not discuss nor show any diagrams for overdrains (channels that would be placed on top of a liner to convey water draining from the tailings pile) or underdrains (channels constructed under a liner for the conveyance of groundwater). There is also no mention of a liner that would prevent the exchange of water (in either direction) between the tailings pile and the underlying soil.

DISCUSSION

There is no denying that the design of the tailings storage facility for the proposed Barroso mine is highly creative. The tailings storage facility would be the first filtered tailings storage facility at an operating lithium mine, nearly five times taller than the tallest tailings dam in Portugal, and the second tallest tailings dam in Europe. The co-deposition of waste rock and tailings may not be completely new, but it is certainly far from common. Hawley and Cumming (2017) report on field trials of storing homogenous mixtures of waste rock and tailings that have been thickened into a paste at the Porgera mine in Papua New Guinea and at the Copper Cliff mine in Sudbury, Canada. They did not describe any field trials of creating mixtures of filtered tailings and waste rock, nor any operating mines that have used co-disposal of tailings and waste rock on an operational scale. Klohn Crippen Berger (2017) writes, "Co-deposition of tailings and waste rock involves encapsulating tailings within waste rock dumps." After listing numerous possible advantages, Klohn Crippen Berger (2017) concludes, "Despite its potential advantages, the authors were not able to identify examples of practical application of co-deposition technologies." At the present time, the author of this report is aware of other proposals for storing homogeneous mixtures of waste rock and tailings, but not of any operating mines that are using this technology.

At the same time, while creativity is generally considered to be a positive human endeavor, creativity is not an unmitigated good. In fact, there is another concept of "Reckless Creativity," which is prejudicial to human welfare. For example, a proposal to immediately replace all automobiles in Lisbon with driverless vehicles would be a type of Reckless Creativity. Reckless Creativity has one or more of the following characteristics:

1) There is no scaffolding, meaning that the new innovation does not build upon previous innovations through a series of intermediate steps with proper testing and verification of each step.
2) One or more of the technologies required to carry out the innovation does not currently exist.
3) Predictions are based upon single input values or best-case scenarios without considering the range of possible inputs.
4) Although potential problems are recognized, they are quickly dismissed as irrelevant without justification.
5) Basic precautions are not taken that would be routine for previous innovations.
6) There is no consideration of the consequences of being wrong, that is, of the consequences of failure.

The proposal for the tailings storage facility at the Barroso mine fulfills all of the characteristics of Reckless Creativity. This does not mean no version of the proposed tailings facility could ever be permitted, but this proposal should not be permitted at this place at this time.

The first characteristic is fulfilled because the proposal comes as a quantum leap without intermediate steps. Each designer of tailings storage facilities and the mining industry as a whole needs to gain experience with the safe construction and operation of mounds that store a mixture of waste rock and filtered tailings at ever-increasing heights. It would be reassuring if there were already an operating hard-rock lithium mine with a waste mound that stored a mixture of waste rock and filtered tailings with a height of, say, 154 meters (80% of the planned height of the waste mound at the Barroso mine). However, nothing close to that exists at the present time. I am not aware of any operating lithium mine that uses filtered tailings technology. I am not aware of any operating mine that stores a homogeneous mixture of waste rock and tailings (either filtered or not) in a single waste mound. As of 2017, the tallest filtered tailings storage facility of any type was only 70 meters high (Klohn Crippen Berger, 2017). Even if taller filtered tailings storage facilities have emerged over the past four years, it still requires time for the mining industry to learn how to maintain the stability of taller facilities. In particular, the designers of each new filtered tailings storage facility need to learn from the mistakes of previous facilities. In summary, it is disturbing that the Environmental Impact Study does not present any history of their concept for a new type of tailings storage facility. Of course, any history should include an emphasis on how they have learned from that history.

The second characteristic is fulfilled because the plan assumes that tailings can be filtered to a water content less than 15%. The most recent literature on filtered tailings confirms that, at the present time, although a water content of 15% is a typical target, water contents of 17-23% are more realistic. The proposal for the Barroso mine has no explanation as to how it will achieve water contents lower than any operating filtered tailings storage facility. Moreover, the proposal does not include any back-up plan for how it will manage the tailings that do not meet the target water content.

The third characteristic is fulfilled because the input values for the stability analysis are some combination of a best-case scenario, wishful thinking, or values that were deliberately chosen so as to achieve the minimum acceptable value of the factor of safety (FS = 1.5). The assumed height of the water table was not justified in any way. The geotechnical parameters of the tailings were deduced from a single sample and assumed that loading would occur under the drained condition. The shear strength parameters were not even actually measured, but were estimated from the distribution of grain sizes. There was no attempt to determine how varying the input values would result in different results for the factor of safety.

The fourth characteristic is fulfilled because the Environmental Impact Study acknowledges that, based on the distribution of grain sizes, the tailings should be susceptible to liquefaction. However, the Environmental Impact Study then simply dismisses the possibility that liquefaction could actually occur. There is no analysis of the circumstances, however unlikely, under which liquefaction could occur. Liquefaction could occur as a result of excessive water in the filtered tailings, inadequate compaction of the tailings, or excessive water in the waste mound from precipitation, surface runoff, or groundwater seepage.

The fifth characteristic is fulfilled because of the use of the upstream construction method (already illegal in four countries due to its susceptibility to failure), because of the lack of design for any particular flood or precipitation event, and because of the lack of description of a water management infrastructure for the waste mound. Based on the information in the Environmental Impact Study, it is not even clear that there is any plan to construct water management infrastructure, aside from the simple statement that the existence of such infrastructure was assumed in the stability analysis. Any other plan for a filtered tailings storage facility would include a detailed description of diversionary canals, overdrains and underdrains (see Fig. 7) to prevent rewetting of the filtered tailings. There is certainly no specification of a particular precipitation event that the water management infrastructure should be able to accommodate, just as there is no specification of a particular precipitation event that the waste mound as a whole should be able to accommodate.

The sixth characteristic is fulfilled because there is absolutely no consideration of any kind of the consequences of failure of the waste mound. There is no consideration of the potential loss of human lives, the potential impacts on aquatic or wildlife habitat, the potential impacts on livestock, the potential economic losses, or any other kinds of impacts. The rigorous analysis of the consequences of failure, however unlikely, are standard practice in high-risk industries, such as aviation, pipelines and nuclear power. Instead, the Environmental Impact Study simply dismisses the possibility of failure by writing “the loss of human life is not expected, as the structural integrity and proper functioning of the waste facility are assured” (Savannah Lithium LDA, 2020a). Simply writing the above sentence should be sufficient cause to reject the proposal.

CONCLUSIONS

The chief conclusions of this report can be summarized as follows:

1) The proposal for a hard-rock lithium mine with a waste mound that stores a homogeneous mixture of waste rock and filtered tailings with a final height of 193 meters is highly experimental. To the best knowledge of the author, there is no operating lithium mine that stores filtered tailings, the height of the tallest filtered tailings storage facility for a proposed lithium mine is 107 meters, there is no operating mine that stores a homogeneous mixture of waste rock and filtered tailings, and the tallest operating filtered tailings storage facility of any kind has a height of 70 meters.
2) The target water content of the filtered tailings for adequate compaction is <15%, which exceeds the capability of current technology. Even so, tailings can be rewetted by occasional high precipitation, and there is no plan for managing the tailings that are too wet for adequate compaction.

3) Although, based on the grain size distribution, the tailings are susceptible to liquefaction, there is no analysis of the circumstances under which liquefaction could occur.
4) The proposal does not recognize that the embankment of waste rock that would surround the mixture of filtered tailings and waste rock constitutes a dam and should conform to dam safety standards. In particular, there is no design flood for the dam, although the dam should be able to withstand a 500-year flood according to dam safety law in Portugal and at least a 1000-year flood by most international standards.
5) The waste rock embankment would be constructed using the upstream method, which is illegal in Brazil, Chile, Ecuador and Peru, due to the likelihood of collapse of the dam in the event of liquefaction of the confined tailings.
6) Even without liquefaction, slumping could carry the tailings for 2000 meters with numerous points of entry into the Covas River (a tributary of the Beça River) or the Beça River itself, so that the mixing of the tailings with downstream water bodies could develop into a flow phenomenon.
7) Although the stability analysis indicated a minimum acceptable factor of safety FS = 1.5, the shear strength parameters of the tailings were determined from only one sample and were not actually measured, but estimated from the grain size distribution. Moreover, the stability analysis assumed the "drained" loading condition with no consideration of the circumstances under which the pores would be saturated. In addition, there is no document that describes any geotechnical testing of the waste rock or foundation, nor is there any document that explains how the shear strength parameters of the waste rock and foundation were estimated. Finally, the stability analysis included no justification for the assumed water table height, and no consideration of the dependence of the factor of safety on the height of the water table or the circumstances under which the water table would rise higher than the assumed height.
8) Although satellite images and the proposal itself show a stream network that flows through the site of the waste mound, there is no apparent plan for any water management infrastructure that would prevent rewetting of the tailings by stream flow, surface runoff or groundwater.
9) The proposal does not include any consideration of the consequences of failure of the waste mound. Based on a statistical model of past tailings dam failures, the failure of the waste mound will release 8.5 million cubic meters of mine waste with a runout distance of 86 kilometers with impact on numerous communities along the Tâmega and Douro Rivers.
10) Under the worst-case scenario (loss of 100% of the stored mine waste), 30.5 million cubic meters of mine waste will be released that will reach the Atlantic Ocean (128 kilometers) during the initial runout. It cannot be assumed that the large dams along the Tâmega and Douro Rivers will impound the spilled mine waste because the volume of spilled mine waste from the Barroso mine would be already 40% and 136% of the effective storage of the Torrão dam and Crestuma-Lever dam, respectively.

RECOMMENDATIONS

The recommendation of this report is to reject the proposal for the Savannah Lithium Barroso mine without further consideration.

ABOUT THE AUTHOR

Dr. Steven H. Emerman has a B.S. in Mathematics from The Ohio State University, M.A. in Geophysics from Princeton University, and Ph.D. in Geophysics from Cornell University. Dr. Emerman has 31 years of experience teaching hydrology and geophysics, including teaching as a Fulbright Professor in Ecuador and Nepal, and has 70 peer-reviewed publications in these areas. Dr. Emerman is the owner of Malach Consulting, which specializes in evaluating the environmental impacts of mining for mining companies, as well as governmental and non-governmental organizations. Dr. Emerman has evaluated proposed and existing tailings dams in North America, South America, Europe, Africa, Asia and Oceania, and has testified on tailings dams before the U.S. House of Representatives Subcommittee on Indigenous Peoples of the United States and the United Nations Permanent Forum on Indigenous Issues. Dr. Emerman is the Chair of the Body of Knowledge Subcommittee of the U.S. Society on Dams and one of the authors of Safety First: Guidelines for Responsible Mine Tailings Management.

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