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Salitre Project – dewatered phosphate rocks tailings as alternatives to conventional tailings disposal, Vale Fertilizantes Minas Gerais State, Brazil

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Abstract

Fosfertil Fertilizantes Fosfatados S.A., now Vale Fertilizantes (that represents Vale actives in the fertiliser operations) was contracted by Golder Associates Peru S.A. to conduct a trade-off study to assess the potential for a cost-effective long-term solution for tailings disposal. The focus of the study was based on identifying innovative dewatering/disposal techniques for the phosphate tailings for the green field Salitre Project. The study focused on a comparative evaluation of process dewatering options and disposal strategies relative to the currently planned conventional tailings disposal system. The evaluation included technical, operational, economical and environmental aspects of the Salitre Project.

The main objective of tailing thickening process was to obtain high underflow density and, if possible, overflow clarity. The scope of work involved a laboratory testing program (material characterisation, process dewatering and rheological testing) and a concept level trade-off study examining a number of high-level strategies consisting of combinations of process dewatering options and disposal scenarios.

Based on the material testing results, site conditions and input from Vale Fertilizantes it was recommended to dewater the Salitre tailings to achieve non-segregating thickened slurry having a solids concentration greater than 45 wt% solids. At this pulp density, the slurry behaves similar to high density tailings, albeit with significantly lower yield stress. The conceptual deposition plan utilises this rheology to develop a thin-layer disposal, relying on in situ desiccation to obtain even higher strength once deposited. Such an approach provides Vale Fertilizantes an opportunity to consider managing the tailings solids stream separately from the process water stream.

1 Introduction

Salitre phosphate rocks deposit belongs to Vale Fertilizantes' Salitre Project is located 20 km east of the city of Patrocínio, in Minas Gerais State, southeast of Brazil.

The project area is situated at an elevation of 1,000 m above sea level, in a gently rolling topography. The average annual temperature is around 20°C and total annual media precipitation and evaporation is 1,470 and 1,566 mm per year, respectively. In the wet period (October to March) the average monthly precipitation is approximately 150 mm, while in the dry period (April to September) it is less than 70 mm.

Ore resource of phosphate rocks is estimated at 196 million tonnes (Mt) and the Mill Plant operation was designed for 20 years open pit mine, involving two phases:

- Module I: Year 1–3, with run-of-mine (ROM) ore containing 15% P_2O_5.
- Module II: Year 4–20, with ROM ore containing 10% P_2O_5.

Module I concentrator plant capacity is 5.5 Mt per year (Mtpy) and Module II is 10.6 Mtpy producing 1.5 and 2 Mtpy of concentrate and 3.0 and 6.9 Mtpy of tailings for surface disposal, respectively.

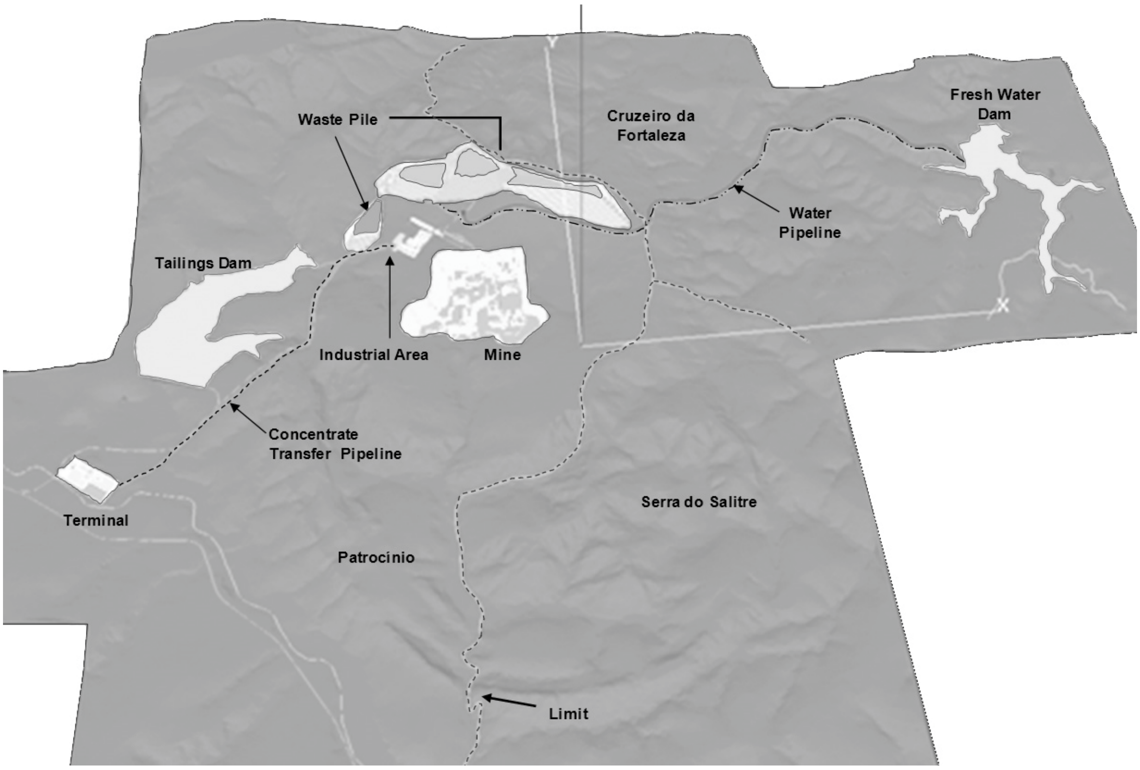

Figure 1 Salitre Project general layout

The process upgrades the grade of the phosphate in the ore by removing gangue minerals prior to further processing. Basically the process combines crushing/grinding, scrubbing, water washing, hydrocycloning, froth flotation and column flotation to recover the ultra-fine phosphate normally lost within the clay tailings. The following tailings flow will be produced:

- Natural slime (deslime stage): 34.5 wt% of the total tailings produced.
- Generated slime (deslime stage): 31.4 wt% of the total tailings produced.
- Ultra-fine tailings (column flotation circuit): 9.2 wt% of the total tailings produced.
- Coarse tailings flotation: 9.4 wt% of the total tailings produced.
- Fine tailings flotation: 15.5 wt% of the total tailings produced.

It was initially recommended that the project be constructed with conventional dilute tailings slurry disposal system. However, as Vale Fertilizantes further developed its commitment to sustainability and prepared its Sustainability Statement, the project team reconsidered this so as to reduce the social-environmental impact and selected Golder Associates Peru S.A. to propose a solution to minimise this impact.

The study involved a material characterisation and laboratory testing program and a trade-off study at conceptual level that considered the tailings dewatering process, transport and disposal.

The main criteria considered during the evaluation of alternatives were:

- The footprint of the tailings disposal area.
- The overall water balance around the tailings disposal area.
- The capital and operating costs:
  - of dewatering and thickening of the tailings

- of transporting and handling the thickened tailings and the process water
- of the containment structures for the storage and handling of the tailings and process water.

This paper discusses the solution proposed, presenting the three alternatives evaluated that were compared to the base case considering conventional dilute tailings slurry disposal and was prepared based on Golder Associates (2010).

2 Lab testing program

2.1 Test samples

Two samples (flotation tailings (RT) and ultra-fine tailings (LT)) and process water were shipped by Vale Fertilizantes to the Golder PasteTec Laboratory. Figure 2 illustrates the process source of the two tailings samples received for testing (highlighted – RT and LT). The purpose of the testing was to determine the applicability of dewatering technologies to produce thickened tailings or paste from the Salitre's phosphate ore processing facility.

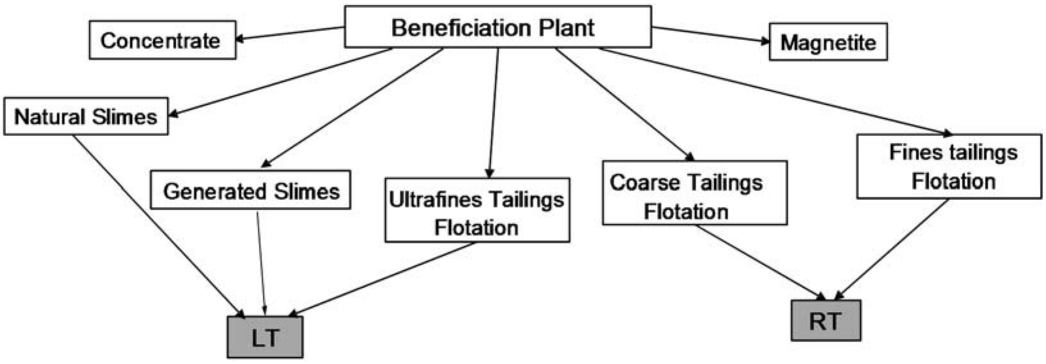

Figure 2 Salitre samples tested

Both samples were obtained from the pilot plant tests performed by Vale Fertilizantes on Salitre ore containing 15% P_2O_5, Module I samples was tested individually and as blend of both (RT and LT) at a ratio of approximately 75 wt% LT (fine tailings) and 25 wt% RT (coarse tailings). Figures 3 and 4 illustrate the samples received.

Figure 3 Flotation tailings as received

Figure 4 Slimes as received

2.2 Laboratory tests

The two samples received (RT and LT), including a blend of LT and RT prepared at the laboratory, were submitted for material characterisation, rheological properties assessment, settling and dewatering tests. The Figures 5 and 6 (a) and (b) illustrate slump versus solids content.

Solids content measurement was conducted for each slump along with yield stress. Slump measurements were determined by typical full size ASTM slump cone and yield stress values were measured using a Brookfield DV-II. Figures 6 (c) and (d) are indicative of deep tube settling tests using PEO (poly-ethylene oxide) and Alum and Figure 7 illustrate yield stress versus solids content tests on the blended tailings.

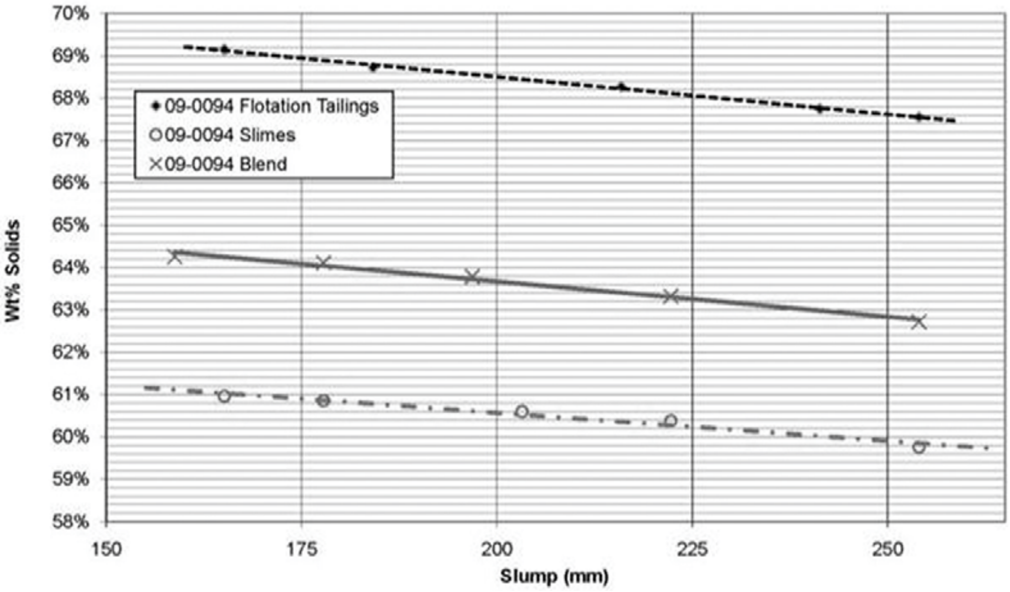

Figure 5 Slump versus solids content

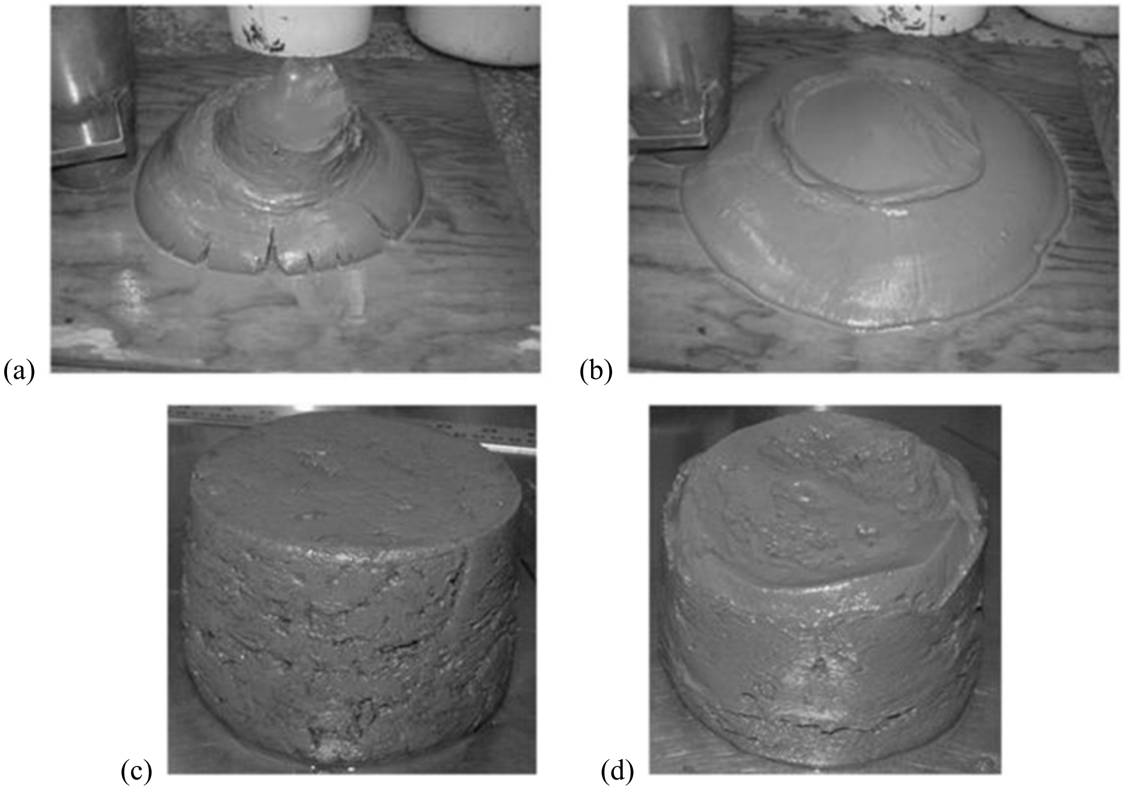

Figure 6 (a) Blend at 175 mm at 64.1 wt% solids; (b) blend at 250 mm at 62.7 wt% solids; (c) unsheared 125 mm slump; (d) sheared – 175 mm slump

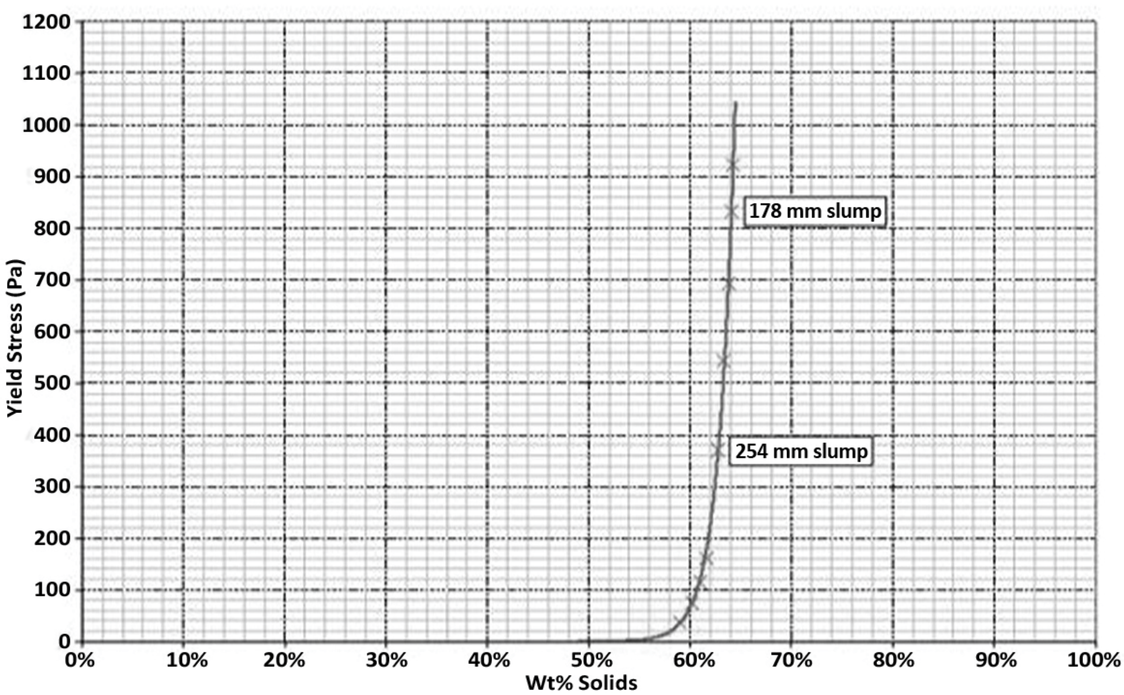

Figure 7 Yield stress versus wt% solids – blend

As seen in the above photographs, the PEO provides considerable structure and strength, well beyond typical flocculant and/or coagulant, which must be understood with respect to the potential dewatering equipment selection, pumping system and disposal operations.

For the samples tested in beakers, the ultra-fines proved difficult to settle and to consolidate; even after a few weeks of sitting idle, the ultra-fine remained in suspension. To obtain a clear overflow particle charge modifiers (coagulants) were required.

2.3 Laboratory tests results

The main findings from the laboratory testing of the Salitre tailing samples are summarised in Table 1.

Table 1 Rheological properties

	Salitre (75:25 Blend)	
Increasing Solids Content	**Wt% Solids**	**Yield Stress (kPa)**
High rate thickener	41–43	<25 kPa
Paste thickener	45–55	<35 kPa
Slump 250 mm	63	370
Water bleed at 250 mm slump (% of total contained water)	0%	
Slump 175 mm	64	835
Water bleed (175 mm slump) (% of total contained water)	0%	
Vacuum filtration	49	
Centrifuge	60	

Generally, paste material is defined as a non-segregating material having a measurable slump, i.e. less than or equal to 250 mm. In the case of Salitre, the blended tailings sample would need to reach approximately 63 wt% solids, well above of the values obtained by centrifuge dewatering, which is typically defined as the limit of what can be achieved by gravitational means.

Therefore, achieving a paste consistency with the Salitre tailings will be difficult and costly; especially when one considers that increasing the wt% solids is further limited by the fine nature of the tailings (65 wt% passing 20 microns). This high concentration of fine material led to poor cake loadings and blinding of the filter cloth when using vacuum filtration and further limits the wt% solids that can be achieved by conventional means.

Typically for tailings, the wt% solids observed in the 175–250 mm slump range are less than the values obtained using centrifuge dewatering. This is the main reason why water bleed can typically be observed for tailings in the paste range; leading to further consolidation following deposition to a surface impoundment. For the samples tested, the ultra-fines proved difficult to settle and to consolidate; even after a few weeks of sitting idle, the ultra-fine remained in suspension. To obtain a clear overflow particle charge modifiers (coagulants) were required.

2.4 Lab testing conclusions

Based on the results of the laboratory testing program on the Salitre pilot plant tailing samples, it was determined that:

- The Salitre tailings are very difficult to dewater. Through the use of conventional reagents and dewatering equipment it would be possible to produce only thickened tailings, not paste.
- The ultra-fines found in the sample do not settle readily and will require the use of coagulants in order to achieve a clear thickener overflow.
- The blending of the two tailing streams (RT and LT) and dewatering them to that of a non-segregating thickened tailings consistency prior to disposal, indicated that there could be definite advantages as:

   - a reduction in the surface area (footprint) required for disposing of the tailings
   - a reduction in the risk of potential impact of the tailings impoundment in the event of dam failure (smaller volumes of water being stored)
   - an increase in water recovery at the mill and decrease in fresh water use
   - a possible reduction in energy consumption by reducing the volume of water being pumped to and from the tailings impoundment and fresh water reservoir.

Therefore, three alternatives, looking at different degrees of dewatering the blended tailings, formed the basis for the trade-off/conceptual study.

- Alternative 1: Thickened tailings to 35 wt% solids and a deposition slope of 1%.
- Alternative 2: Thickened tailings to 45 wt% solids and a deposition slope of 2%.
- Alternative 3: Thickened tailings to 65 wt% solids and a deposition slope of 10%.

3 Project description

The options evaluated for the trade-off/conceptual study regard to the design of the tailings dewatering plant and tailings management facility where based on:

- the need to handle a 850 t/hr of tailings
- the need to consider a single full plant tailings stream
- the dewatering and rheological properties of the tailings obtained from laboratory testing
- the location and physical layout of the processing plant
- the disposal of the tailings into the same area selected for slurry disposal (base case).

3.1 Tailings dewatering plant

The following three alternatives were evaluated:

- Alternative 1: Single stage process – thickening (clarification). Dewatering to 35 wt% solids, using a particular flocculant PEO.
- Alternative 2: Two stage process – thickening and clarification. Dewatering to 45 wt% solids, using MF 1011 flocculant.
- Alternative 3: Multiple stage process – thickening. Dewatering to 65 wt% solids, using PEO followed by filtration (belt press filter).

Clear overflow was not a requirement of the project to a significant degree as it does not affect the process nor discharge requirements. The flotation circuit water quality is improved with fresh make-up water. However, during the tests preliminary evaluation was considered.

Process flow sheets developed for the conceptual project are presented on Figures 8–10, for each of the alternatives 1, 2 and 3 respectively.

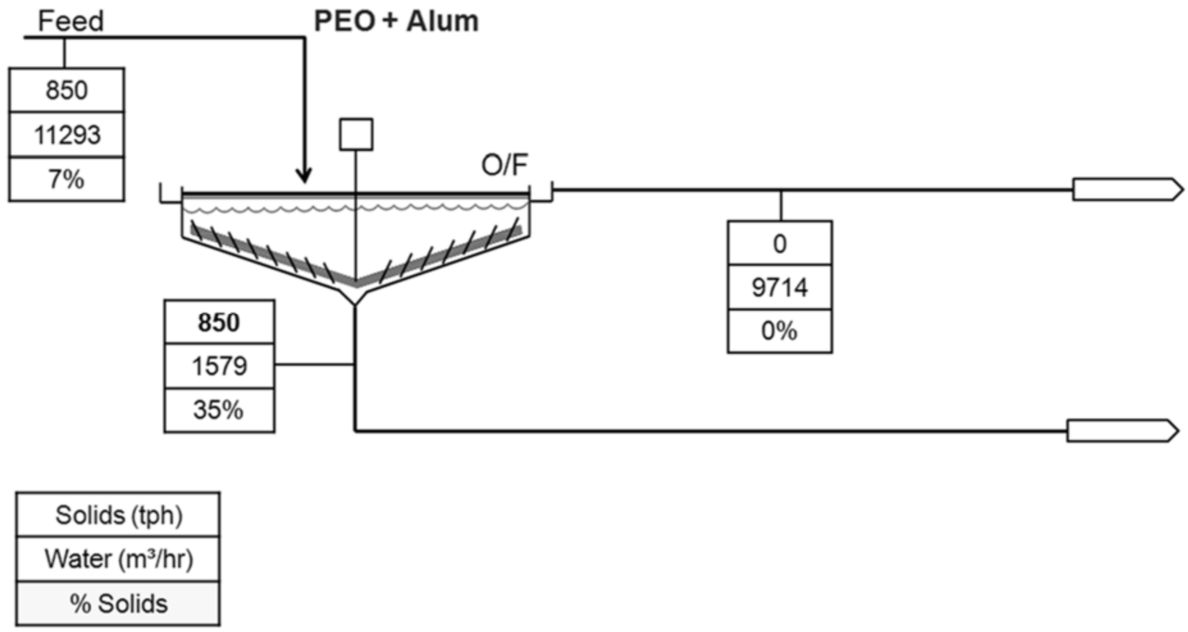

Figure 8 Salitre Project simplified flow sheet – alternative 1

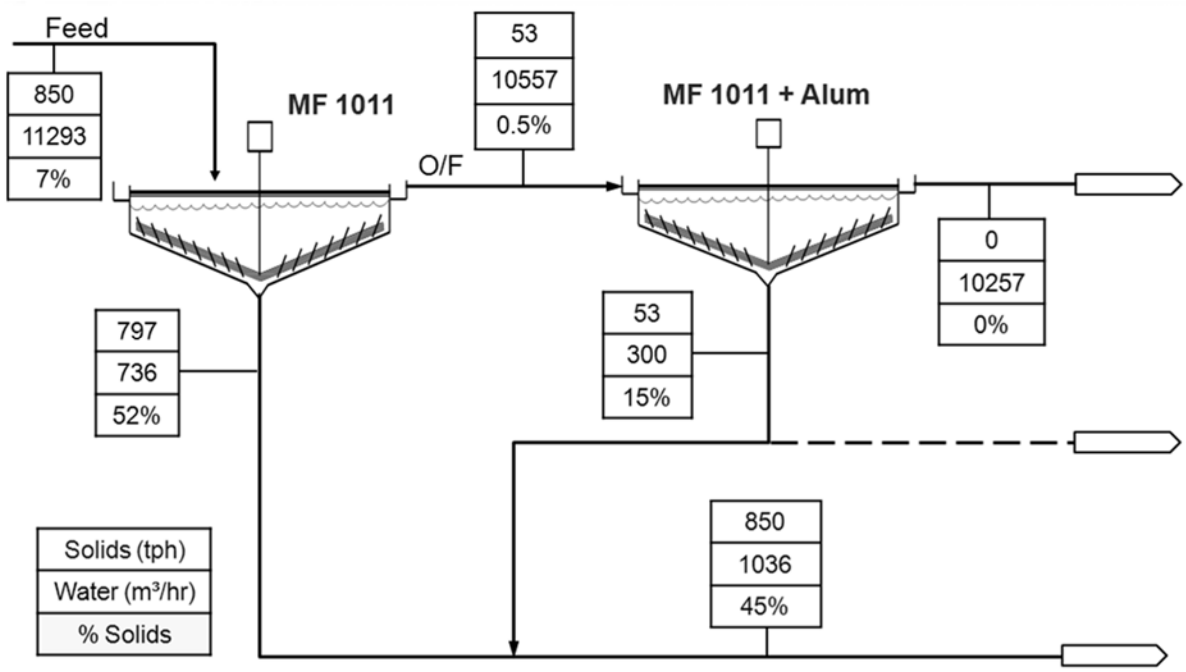

Figure 9 Salitre Project simplified flow sheet – alternative 2

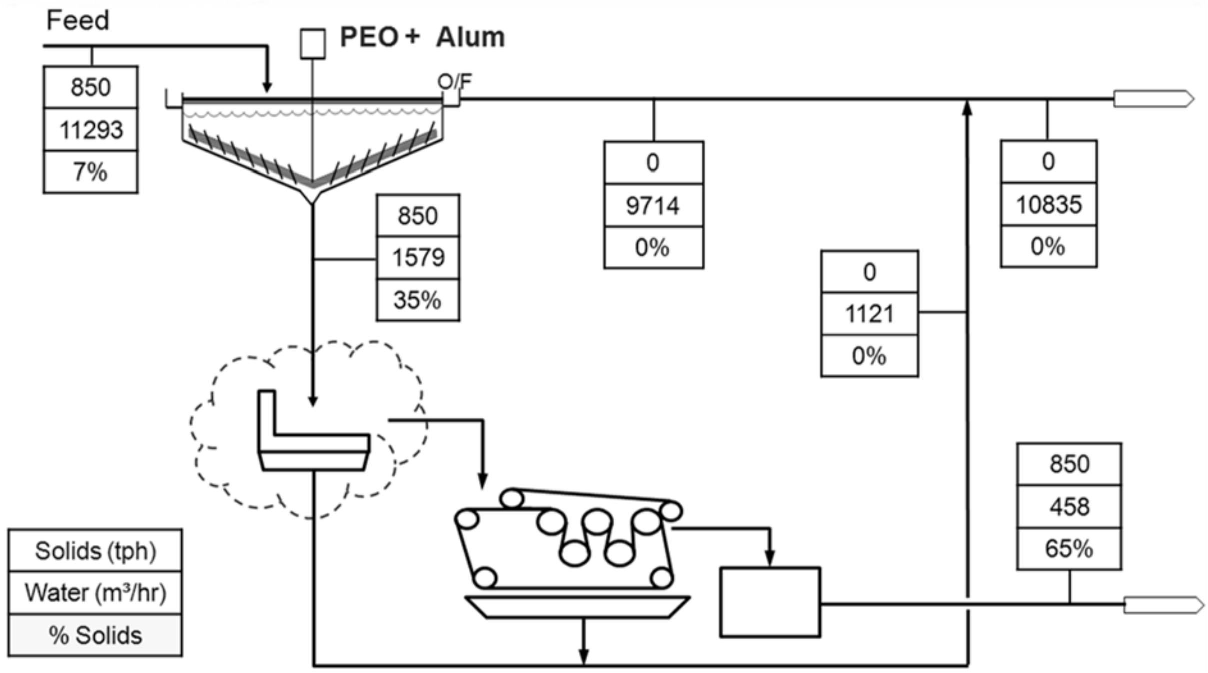

Figure 10 Salitre Project simplified flow sheet – alternative 3

3.2 Tailings disposal system

The tailings disposal systems for each of the alternatives evaluated were developed based on the climatic data, the operating data and the local hydrology, which was used to model the tailings dam needed for containment after three and 20 years of operation. The project included the tailings management facility (TMF) containment structures (including water recovery, dykes, diversion channel, etc.) as well as the closure costs. The followings deposited slopes were adopted for each alternative:

- Alternative 1: Tailings deposited slope 1%.
- Alternative 2: Tailings deposited slope 2%.
- Alternative 3: Tailings deposited slope 10%.

The operational management of the tailings disposal system considered in situ dewatering by evaporation and consolidation to allow the tailings to develop greater strength. A model of thin-layer desiccation was recommended, such as is practiced at Barrick Gold's Bulyanhulu Mine in Tanzania. This strategy is fundamentally opposite to that which occurs in the conventional dilute slurry impoundment, the latter requiring extensively long periods to reach final consolidation. With significant amount of water locked up in the interstitial voids of the particles, closure of the facility will be delayed.

The base case considers tailings disposal as slurry containing 20 wt% solids and deposited with a slope of 0%. Table 2 shows a comparison of the predicted recovered process water at the plant and from the tailings dam for each alternative, including base case:

Table 2 Process water recovered at the process plant and disposal area

Year	Base Case			Alternative 1			Alternative 2			Alternative 3		
	Qb	Qr	Qt	Qb	Qr	Qt	Qb	Qr	Qt	Qb	Qr	Qt
	L/s											
1–3	465	959	1,424	260	1,189	1,449	250	1,251	1,501	150	1,326	1,476
4–20	920	1,856	2,776	495	2,401	2,896	375	2,549	2,924	165	2,713	2,878

Where:

Qb = Average flow rate of water recovered from the tailings disposal area.

Qr = Average flow rate of water recovered at the process plant and dewatering plant.

Qt = Qb + Qr.

Table 3 presents a summary of the TMF characteristics such as impoundment, dykes and perimeter channels for the year three and 20 of the tailings disposal system, considering the same area selected for the base case.

Table 3 Summary of the TMF characteristics

Year	Base Case			Alternative 1			Alternative 2			Alternative 3		
	Vd $M\text{-}m^3$	Ad $M\text{-}m^2$	Vp $M\text{-}m^3$	Vd $M\text{-}m^3$	Ad $M\text{-}m^2$	Vp $M\text{-}m^3$	Vd $M\text{-}m^3$	Ad $M\text{-}m^2$	Vp $M\text{-}m^3$	Vd $M\text{-}m^3$	Ad $M\text{-}m^2$	Vp $M\text{-}m^3$
3	5.8	1.1	0.41	5.6	1.2	0.49	5.3	1.4	0.27	5.3	1.1	0.24
20	81.4	3.9	4.52	77.9	4.0	3.36	74.4	3.7	1.73	60.5	3.4	0.24

Where:

Vd = Volume of tailings deposited.

Ad = Area disturbed by tailings deposited.

Vp = Volume of basin to contained tailings deposited.

The disposal system arrangements developed at the conceptual level are shown in Figures 11–14, for each of alternatives 1, 2, 3 and base case, respectively.

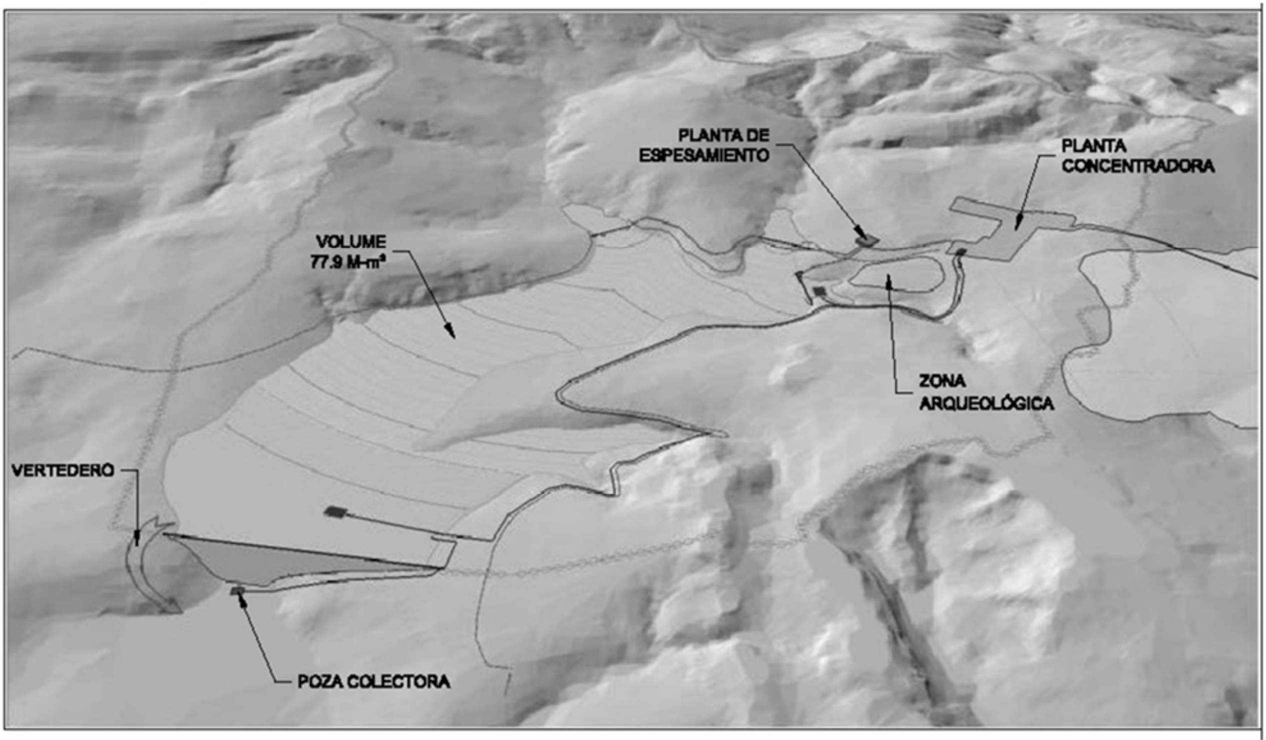

Figure 11 Salitre Project disposal system – alternative 1 (year 20), dykes and dam volumes: 3.7 $M\text{-}m^3$, channels: 13 km, water recycled: 600 L/s, area: 4.0 km^2

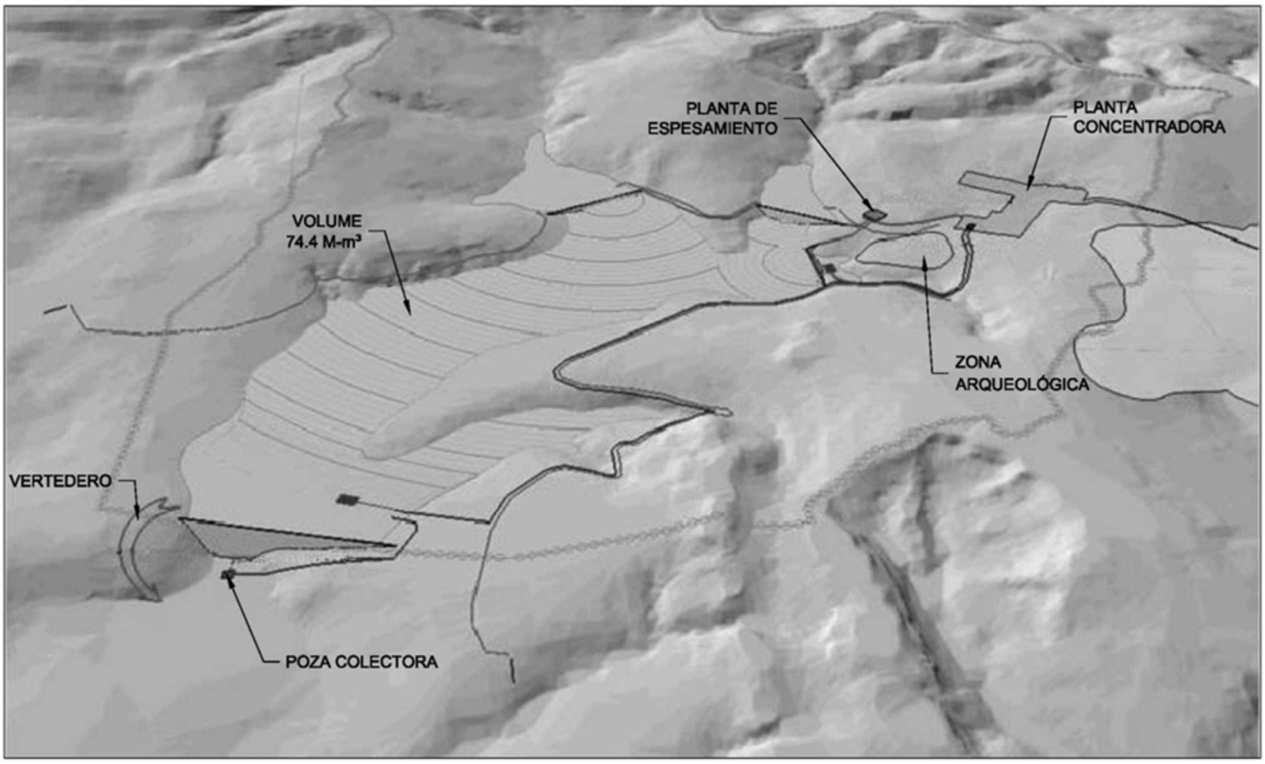

Figure 12 Salitre Project disposal system – alternative 2 (year 20), dykes and dam volumes: 3.0 M-m^3, channels: 11 km, water recycled: 375 L/s, area: 3.7 km^2

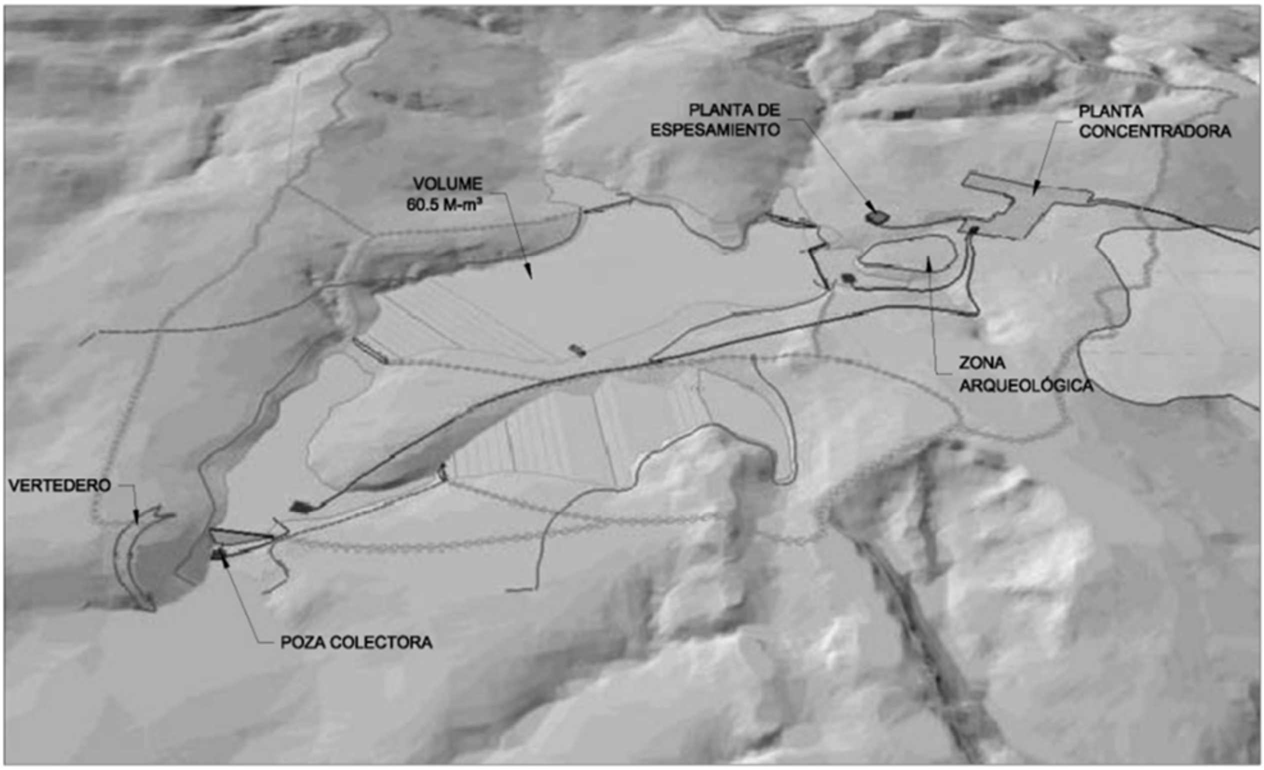

Figure 13 Salitre Project disposal system – alternative 3 (year 20), dykes and dam volumes: 1.3 M-m^3, channels: 15 km, water recycled: 300 L/s, area: 3.4 km^2

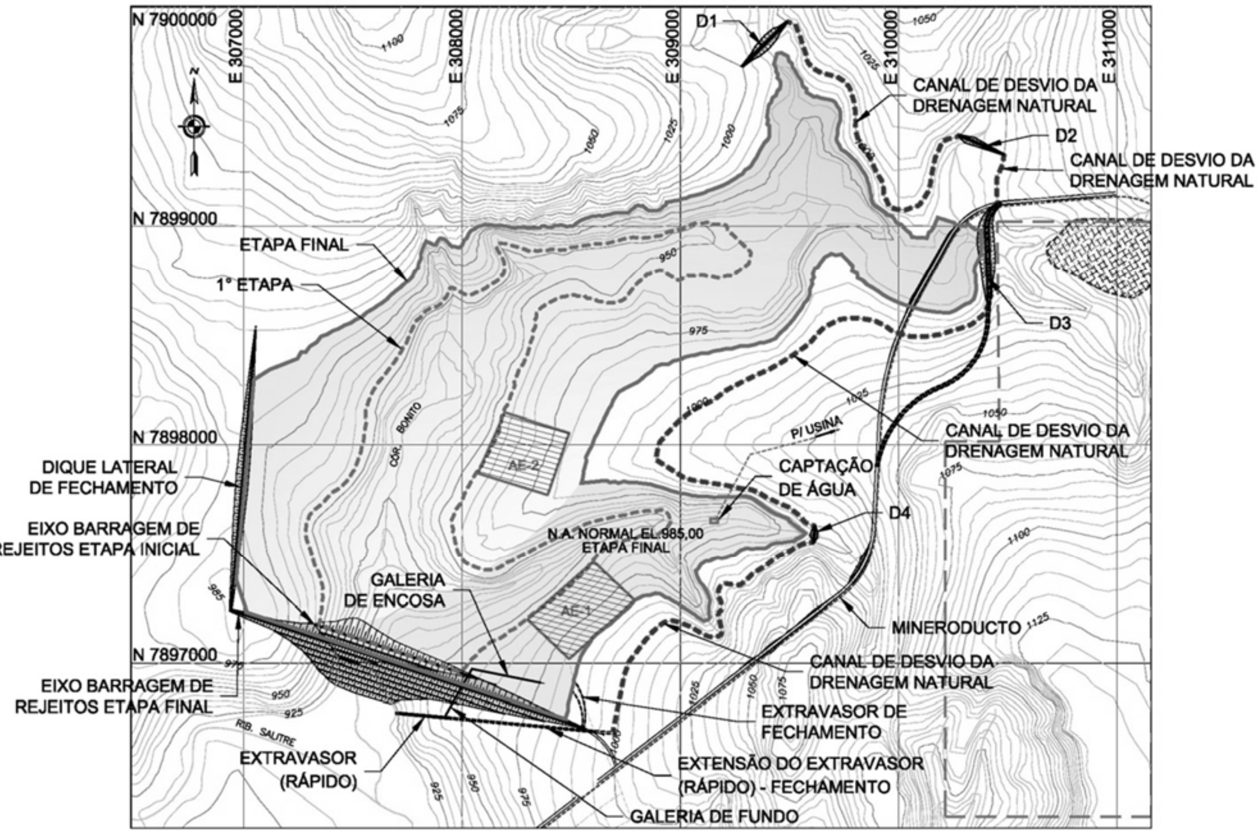

Figure 14 Salitre Project disposal system – base case (year 20), dykes and dam volumes: 5.3 M-m^3, channels: 7 km, water recycled: 920 L/s, area: 3.9 km^2

3.3 Discussions

Alternatives 1 and 3: For both alternatives the tailings process dewatering is carried out in a single stage (thickening and clarification simultaneously). However, alternative 3 includes belt press filtration. In a case where clear overflow is needed, it would be necessary to use a coagulant, such as alum, followed by a particular flocculant (PEO). By using this flocculant it was possible to achieve a dewatered material with high shear strength characteristics. With the addition of PEO, flocculation reached a point where the individual flocculants consolidated and moved as highly viscous gelatinous mass. The PEO forms strong flocculants, allowing the material to be further dewatered using dewatering equipment such as a belt filter press. The dewatered material has the consistency of putty (play dough). It was possible to obtain a clear overflow using alum and MF 1011. However, for alternative 3, the material did not produce an underflow which could be further dewatered by filtration without blinding the filter cloth leading to very low cake loadings.

Alternative 2: Two stage dewatering (thickening and overflow clarification) was carried out in two distinct operations besides clear overflow be not a requirement of the project. The advantage of such an approach is that it greatly reduces the cost of reagents required to achieve sufficiently high underflow density and reasonably clear overflow. While well-dewatered tailings can be obtained in the flow sheet option, the approach was excessively expensive and operationally more difficult. The use of PEO appears to better retain the ultra-fine which would most likely reduce the surface area within the TMF required for sedimentation.

It is important to note that for typical tailings it is possible to achieve different wt% solids ranging from thickened slurry to a wet filter cake using different process equipment. In the case of the Salitre tailings it was also required to use different reagents in order to change the physical properties of the tailings.

Table 4 illustrates the volume of slurry (tailings and water) being discharged based on the outcomes of each of the alternatives.

Table 4 Comparison between alternatives at 850 t/hr tailings

	Base Case (Vale Fertilizantes Data) (No Thickening (NT))	Base Case (Vale Fertilizantes Data) (Partial Thickening (PT))	Alternative 1 Thickening (1 Step Process)	Alternative 2 Thickening and Clarification (2 Step Process)	Alternative 3 Thickening and Filtration
Discharge (solids)	7.0 wt%	24.6 wt%	35.0 wt%	45.0 wt%	65.0 wt%
Volume of discharged slurry (m^3)	11,532	2,845	1,818	1,278	697
Volume reduction of discharged slurry (ref: NT) (%)	0%	75%	84%	89%	94%
Volume reduction of discharged slurry (ref: PT) (%)	-	0%	36%	55%	75%

3.4 Key findings

Each of the three alternatives resulted in increased capital and operating costs over and above the base case. However, alternative 2 was identified as most attractive strategy. Alternative 2 was revised to focus on producing non-segregating thickened tailings with a solids concentration greater than 45 wt% and clarification of only 2,000 m^3/h required for the flotation circuit. For the rest of the recycled process water clarity was not an issue. This modified alternative 2, with only partial water being clarified was named alternative 2a, is illustrated on Figures 15 and 16 that show the flow sheet and disposal system arrangement, respectively.

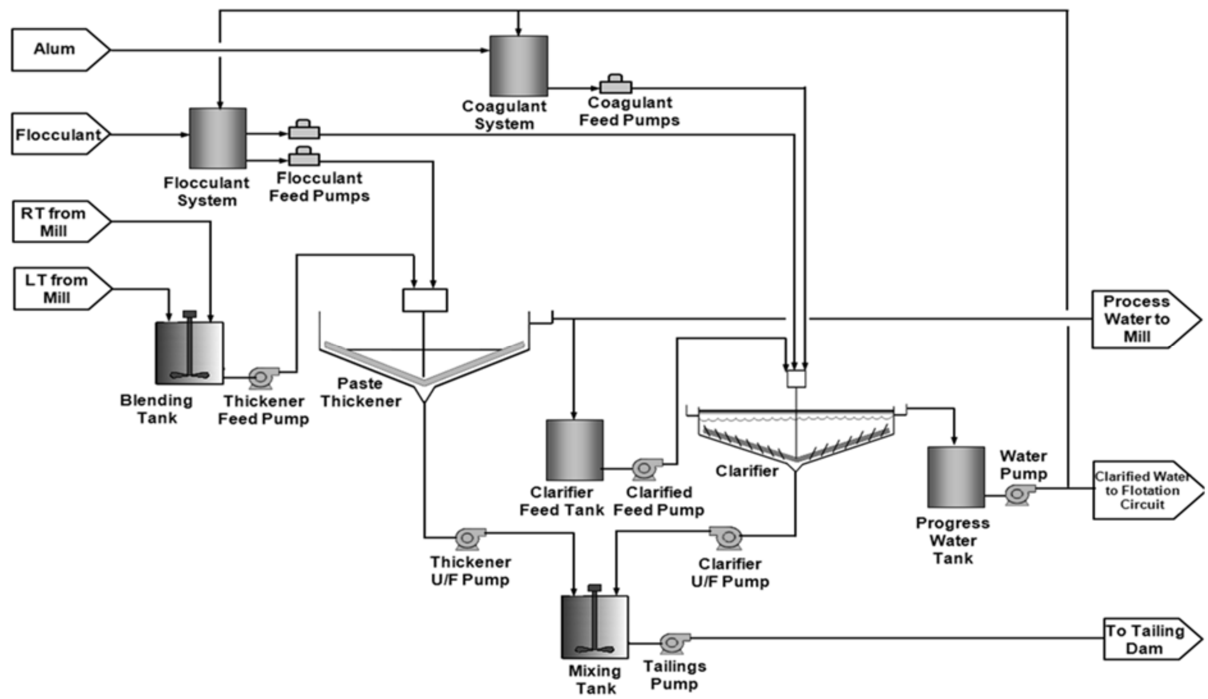

Figure 15 Salitre Project simplified flow sheet – alternative 2a

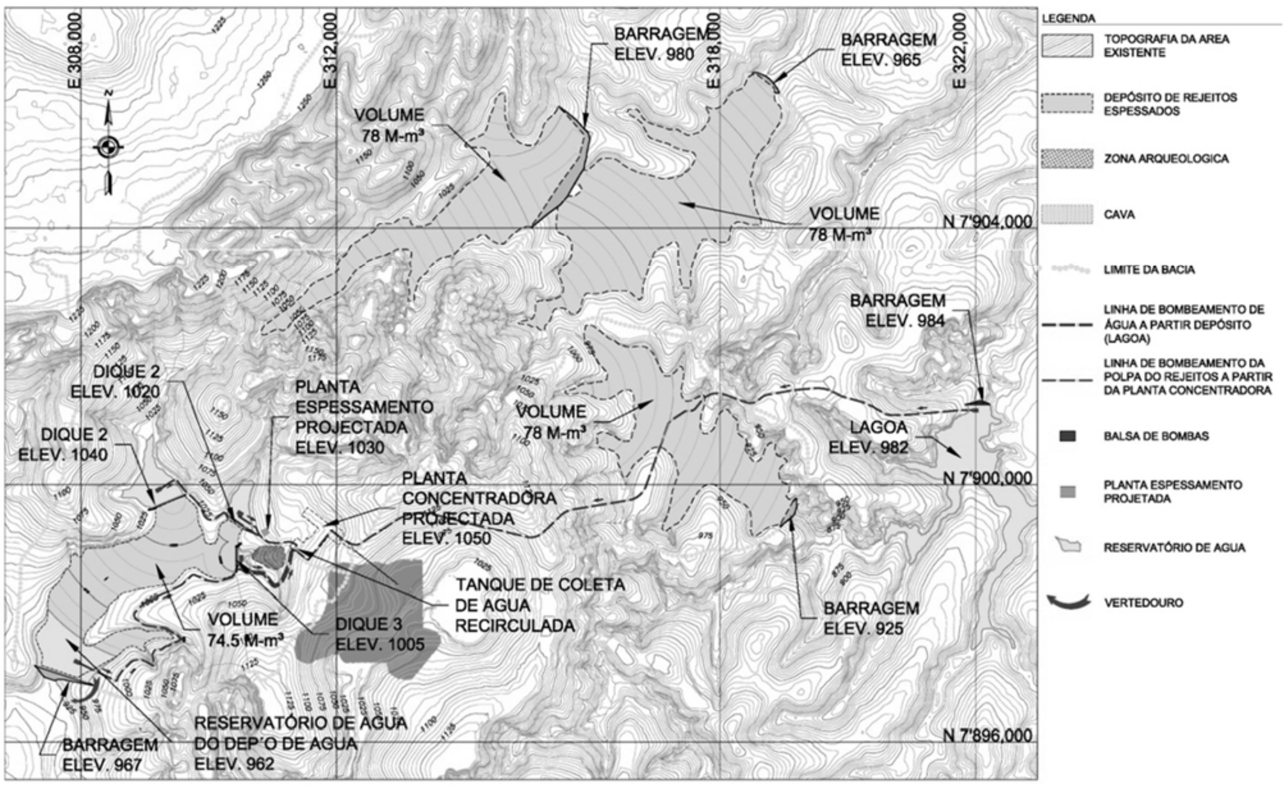

Figure 16 Salitre Project disposal system – alternative 2a (year 20)

It was identified that there are several potential areas worth further investigation. One potential area of improvement to the project is the possibility to increase the amount of fresh water collected from dykes 1 and 2. Based on a normal hydrological year, between 300–400 L/s can be recovered. Combining this with alternative 2a it results in a significant reduction, around of 70% less, of fresh water coming from the

Ribeirão Fortaleza catchment basin, located 16 km far from the plant. In this scenario the total cost of the water recovery system could be 30% lower than in the base case, illustrated in Figure 14.

4 Conclusions

- The dewatering of the Salitre tailings is difficult because of the amount of ultra-fines. Getting a clear overflow is especially difficult. However, since only the flotation circuit requires low suspended solids concentration it does offer some flexibility in the design of the dewatering circuit.
- Dewatering to a reasonable degree with mechanical equipment to such a degree that thin-layer disposal with desiccation in a surface impoundment is possible appears to be most favourable technically and economically.
- Of the different alternatives evaluated, alternative 2a was selected as more attractive to the project. It involves two stages of dewatering, with the thickening and clarification step carried out in two distinct operations.
- The capital and operating costs for alternative 2a were estimated to be US$76.9 M; i.e. US$20 M for the dewatering plant and US$0.9/t of tailings produced. However it should be highlighted that these costs include the cost of the clarification of 2,000 m^3/h that is needed for the flotation circuit.
- The capital and operating costs for the base case were estimated to be US$49.4 M and US$0.5/t of tailings, respectively. No allocation was included for water clarification.
- Alternative 2a demonstrates the impact of achieving low levels of suspended solids (high clarity) in the process water can have on the capital and operating costs. It demonstrates the necessity to confirm the quantity and quality of the water required within the process, as well as the need to test other potential reagents.
- The study considered the same disposal area selected for the base case. Identification of a less shallow area in which to deposit non-segregating dewatered tailings could further reduce the area impacted by tailings disposal.

5 Recommendations

To support the project moving forward, the following approaches are recommended:

- To pursue a system to dewater the tailings to obtain a thickened non-segregating material over 45 wt% solids which would support a thin layer desiccation model for tailings management. If solids deposition can be well managed it should facilitate a higher level of tailings consolidation, possibly resulting in the solids forming a dry stack, thus minimising footprint for the TMF and potentially extending the life of the TMF beyond 20 years. The process water would need to be managed separately.
- To perform supplemental onsite testing on the tailings samples as they are being produced by the beneficiation pilot plant for the different ore grades, so as to:
  - Better understand the variability in tailings composition (including amount of ultra-fines) due to differences in ore grade and associated changes in the beneficiation process.
  - Perform larger scale on-site test work using a pilot plant to confirm laboratory test results and to better define scale up values.
  - Perform flow loop pumping tests and flume deposition tests to evaluate pumping requirements and the behaviour of the dewatered material at different wt% solids with regard to thin layer deposition.
- Obtain a better understanding of process water requirements:
  - To better understand the water quality requirements, with regard to suspended solids, hardness and possibly other parameters and the volume of water needing treatment to maximise the amount of process water that can be recycled back to the process.

    - To identify appropriate treatment options for softening and clarifying a portion of the process water to meet plant process water requirements which could facilitate recycling a portion of the water used into the flotation circuit.

- While a decision has been made to proceed with thickened tailings with a solids concentrations of >45 wt% solids there may be opportunities to further reduce the overall surface area of disturbed land, such as:

    - To examine other sites as possible options for tailings disposal aiming to identify an area more adequate to non-segregating dewatered tailings disposal in order to allow footprint reduction.

    - To examine the possible use of an integrated waste approach (e.g. co-disposal of tailings and saprolite waste rock).

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