Addressing decreasing water availability for the mining industry using cost-benefit analysis

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Abstract

Freshwater use in the mining industry is currently one of the key issues to address within the sector as water scarcity is becoming increasingly problematic in many of the World's important mining regions. This paper investigated five scenarios to replace freshwater with seawater for a simulated mine in the north of Chile. For each scenario the net present value was calculated to compare cost-effectiveness. Near sea level, the use of raw or lime precipitated seawater was favored, however, at elevations above a few hundred metres, the use of seawater plus investments in water saving technologies was most cost-effective.

Introduction

The issue of water availability is having a profound impact upon how the mining industry is developing and, in many cases, may affect its future competitiveness. The mining regions of north Chile, which are famously some of the driest areas on the planet (Valdés-Pineda et al. 2014), are perhaps the best examples of this. As a result of the extreme dry climate in these regions, there is a limited amount of freshwater available for human appropriation which is having an impact upon local industries, particularly agriculture and mining. Furthermore, the situation is expected to worsen with predicted reductions in levels of rainfall and water storage as a result of climate change, and increased consumption in all sectors (OECD 2013). Water remains an essential part of the copper mining industry regardless of the ore type being extracted. In open cast mining, water is necessary for dust suppression, ore processing, washing machinery and for domestic consumption. It is highly important that mining operations have access to a consistent water supply with adequate quality to ensure continual production. Traditionally, mining operations have been reliant upon local freshwater sources either from surface water or more commonly from groundwater. These sources, however, are becoming increasingly under threat due to low availability and overuse (Aitken et al. 2016), and increasing recognition and protection through regulation of their socio-environmental value. As a result, many mining companies have been considering alternative options such as the use of seawater and reducing demand through improved water management.

The use of seawater is an attractive option as the resource is effectively infinite and many mining operations in Chile are relatively close to the coastline. Indeed, the use of seawater in mining operations in Chile is becoming relatively common place and was recently projected to increase by about 400% over the next 10 years (Castillo Dintrans, Hernandez Meza, and Cantallopts Araya 2015). It has been demonstrated that raw seawater can be substituted for freshwater in many mining processes, indeed, there are various mines in Chile using almost only raw seawater for their operational requirements (COCHILCO 2008). Nevertheless, it has also been demonstrated that the use of raw seawater can reduce recovery rates of copper and can considerably reduce molybdenite recovery due to the presence of magnesium and calcium ions at high pH levels (Laskowski, Castro, and Ramos 2013). The subsequent low recovery rates of copper but more importantly molybdenite, can greatly affect the economic viability of an operation (Laskowski, Castro, and Ramos 2013). Desalination of seawater can produce pure water that can be used in any mining process without adverse impacts to the operational productivity (COCHILCO 2008). Desalination, nevertheless, remains an expensive option due to the high capital cost of desalination plants and equipment, and the high energy costs for water pumping and removal of the waste stream. A further option is the precipitation of Mg hydroxide, Ca and Mg sulfate, and Ca and Mg carbonates via conditioning of the seawater with lime at a pH greater than 10 (Concha, Castro, and Vergara 2016). This allows the removal of the ions inhibiting molybdenite flotation using solid/liquid separation. This technique has the potential to allow seawater to be used in the processing without the costly desalination process. Given the high elevations of many of the mine site in Chile, however, the use of seawater regardless of its treatment requires high levels of investment.

Efficient water management in the mining industry is another important area in terms of reducing dependence upon freshwater sources. Much of the water used in copper mining is recycled but water losses still need to be replaced and are often considerable. Gunson et al. (2012) conducted a water footprint of a typical copper sulphide mining operation, the results demonstrated that around 89% of total water losses can be attributed to the tailings management facility where the water is entrained, seeps into the ground and evaporates. Tailings can typically be dewatered to increase the solids concentration, allowing water to be recycled, beach and pond sizes to be reduced, and a reduction in the structural risk associated with the tailings facility. Without any form of dewatering, copper sulphide tailings tend to have a solids content of about 30-35% (Norwest Corporation 2015), the disposal of tailings with such a low solids contents requires large areas and typically a dam to retain the water. The tailings storage facilities tend to be expensive and a risk to the mine operators. Conventional tailings dewatering strategies, such as the common sedimentation technologies, typically dewater the tailings to about 50-60% (Minson and Williams 2001) however more advanced techniques such as paste thickening and filtration can increase solids contents up to around 87% with the potential to greatly reduce overall water consumption and eliminate the need for a tailings dam (Watson 2010). The remaining majority of water losses in the model of Gunson et al. (2012) were calculated to be in road dust suppression, accounting for 9% of total losses. The application of synthetic road dust suppressants (salts, polymers, organic stabilisers) that are capable of binding dust particles with limited water application are considered an effective solution for the high water losses (Aitken, Rivera, and Godoy Faúndez 2016).

It is extremely important for the mining industry in many regions globally to implement freshwater use reduction strategies in a cost-effective manner to allow continued operation. This paper, therefore, aims to compare the cost effectiveness of five scenarios to replace freshwater consumption in the mining industry, using a simulated mine, representative of north Chile. The scenarios are: 1) the substitution of freshwater with desalinized seawater; 2) the substitution of freshwater with raw seawater; 3) the substitution of freshwater with seawater precipitated with lime, 4) the implementation of tailings thickening and synthetic road dust suppression alongside substitution of freshwater with (a) desalinized seawater, (b) raw seawater and (c) seawater precipitated with lime, and 5) the implementation of tailings filtration and chemical road dust suppression alongside substitution of freshwater with (a) desalinized seawater, (b) raw seawater and (c) seawater precipitated with lime. For each scenario the required daily volume of water was calculated and the cost of sourcing the water was determined by calculating the net present value of the necessary technologies.

Methodology

A process diagram of the scenarios that were compared in the study can be observed in figure 1 below.

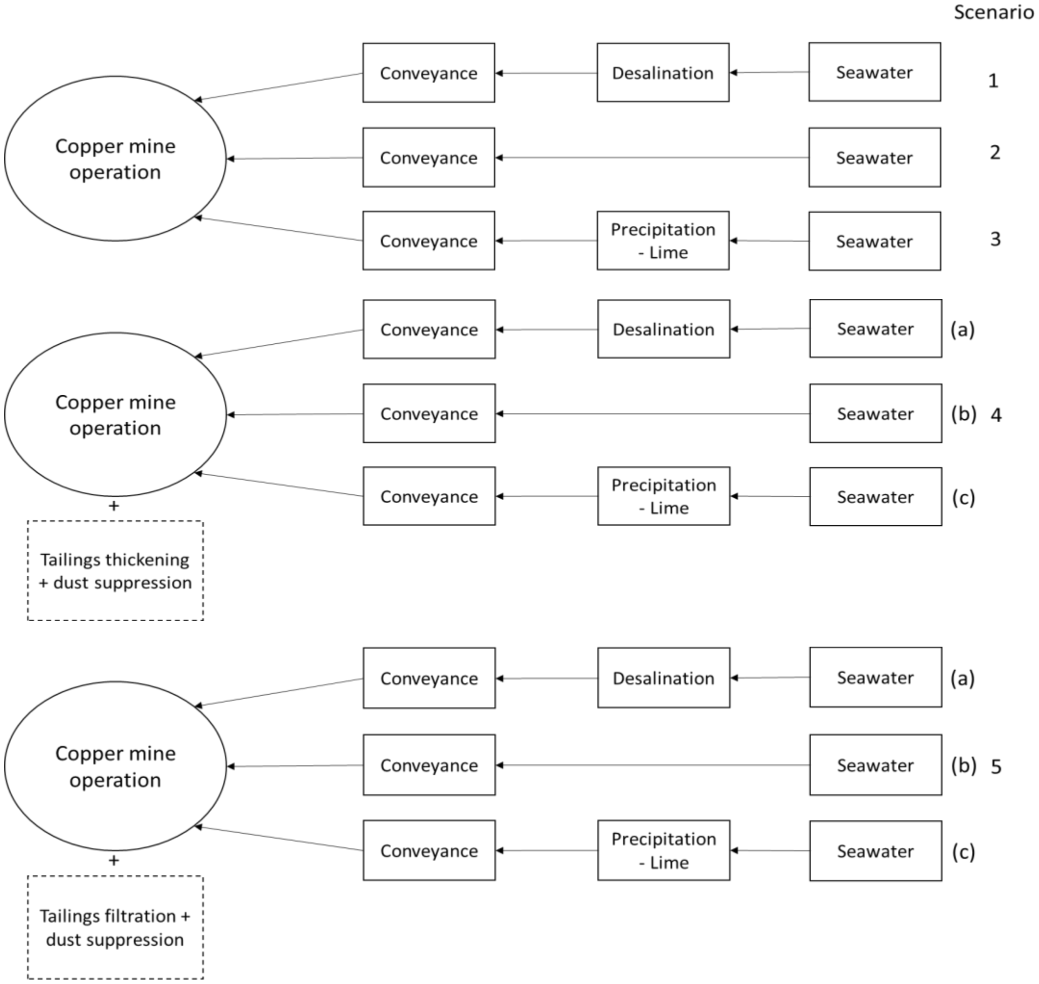

Figure 1. Process diagram of scenarios to supply the model mine with seawater

A water balance model for a copper sulfide mine was produced to first determine the freshwater requirements of the operation. The model was adapted from that developed by Gunson et al. (2012). To account for the large operational sizes in Chile, the daily ore throughput for the model was assumed to be 150,000 tpd. The base case model assumed typical processes from collection of ore from an open pit using haulage trucks, ore crushing, milling, flotation of the ore and concentration of the copper with the tailings being sent directly to a storage facility without a dewatering step. A process diagram of the model operation can be observed below as figure 2.

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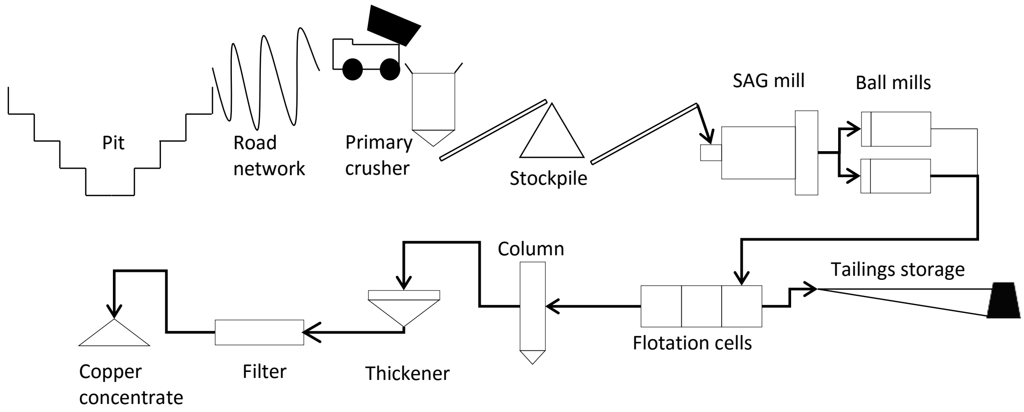

Figure 2. Process diagram of the model operation considering the basic units

The water requirement of the model operation is equal to the water losses. The water losses were calculated using the same assumptions in the model of Gunson et al. (2012) but were scaled up accordingly. The solids content of the tailings following flotation was assumed for the base case to be 32%, the tailings storage characteristics and losses were calculated based on the Wels and Robertson model (Wels and Robertson 2003). The Wels and Roberston model allows the calculation of water losses from tailings based on the losses due to entrainment of moisture in the tailings, evaporation from beach and pond areas, and the seepage from the tailings and pond. The daily losses were calculated over a 30 day period as losses vary daily in such a dynamic system, the average values of the 30 day period were used as the input values. For the specific method, please refer to Wels and Robertson (2003). When the water balance was positive it was assumed that the surplus water could be recycled back into the operation. The total process water requirement per day was calculated to be 108,558 m^3 based on the losses of each process.

For scenarios 1, 2 and 3, the total water loss of the base case was used as the value to be replaced by seawater. The net present values (NPV) were then calculated using the capital and operating costs. As the gross revenue for each scenario was assumed to be the same (the product sales are the same in all cases), the net present value accounts for only the expenditures meaning the net present value effectively represents the net present cost of supplying water in each scenario. High values therefore represent high cost or low cost-effectiveness. For scenario 1, the capital and operating costs of desalination of seawater were obtained from a report examining the costs of a desalinization plant for domestic water use in the province of Copiapó in the north of Chile (Aqua Advise 2012). The project report was produced for a flow rate of 100,000 m^3/day. The capital costs of desalination were therefore scaled using the "0.6 rule" (Tribe and Alpine 1986) and all costs were adjusted for inflation. The capital cost of the pipe network was similarly scaled up but a corrector value was used as following discussion with industrial contacts, the reported values were considered too low. As the NPVs for each scenario were calculated for different elevations of operation, from 0 m to 4,000 m, the capital cost was scaled for each increase in elevation by the ratio of power potential. The operational cost of conveyance was calculated using the pump power calculation for each elevation, the equation used can be observed below (Chadwick, Morfett, and Borthwick 2013).

Equation 1:

$$P = \frac{Q\rho g h}{e}$$

Where:

P = Pump power (kW)
Q = Flow rate (1.26 m^3/s)
g = The acceleration of gravity (9.81 m/s^2)
h = Total head, elevation and frictional head (m)
e = Pump and motor efficiencies (85% and 95%, respectively)

The frictional head was determined using a design velocity of 1.75 m/s and a roughness factor of 0.061 for a stainless steel pipe. As no extra dewatering of the tailings was assumed, the net present value of non-dewatering tailings disposal was calculated using capital and operational costs obtained from a report produced for the Ajax copper and gold mining project in Canada (Norwest Corporation 2015). The report compares the technical issues and costs of various tailings dewatering alternatives for the Ajax project which has a proposed throughput of 65,000 tonnes of ore per day. The cost data of the un-thickened option was scaled up using the “0.6 rule” and the net present value determined. The total net present value of the desalination scenario was therefore calculated by adding the desalination, conveyance and tailings disposal values together. A life span of 25 years and a discount rate of 8% was applied based on current economic analysis (Norwest Corporation 2015).

The net present value for scenario 2 was calculated with the same method but the desalination costs were replaced by the costs of simple filtration of the seawater. The values used were a capital cost of USD 0.23/m^3 and an operation cost of USD 0.07/m^3 (Concha, Castro, and Vergara 2016). For scenario three, in which seawater was precipitated with lime, the capital cost was assumed to be USD 0.35/m^3 with an operational cost of USD 0.13/m^3. For both scenarios, the conveyance costs were calculated using the same method as scenario 1 and the net present values were calculated using the same variable values.

The development of the base case model allowed the calculation of the total water required to be replaced as well as allowing the calculation of the impact of implementing the water saving strategies on the total water losses. The water use reduction strategies with the greatest effectiveness in terms of total water saved have been identified previously as tailings dewatering and optimization of road dust suppression (Gunson et al. 2012; Aitken, Rivera, and Godoy Faúndez 2016). These two strategies were therefore the focus of this study for scenarios 4 and 5. For tailings dewatering, the costs and water saving potential of conventional thickening and pressure filtration were investigated. Water savings were calculated based on the final total solids concentration after dewatering. The values of final total solids concentration were obtained from the technology assessment report produced for the Ajax copper and gold mining project (Norwest Corporation 2015). The final solids content post thickening was assumed to be 60% and 83.5% for pressure filtration. For each method the water recovery was calculated, the tailings storage model used for the base case was applied and the losses and recovery from the tailings pond calculated. As the moisture content of the tailings post filtration was assumed to be 15%, all the moisture was calculated to remain entrained in the tailings and was therefore effectively lost. For the thickening scenario, the evaporative losses from the thickeners were calculated for a thickener of 97 m diameter and an evaporation rate of 7 mm/day, the diameter of the thickener was determined by scaling the areal requirement stated in the Ajax project report (Norwest Corporation 2015). The operational and capital costs of both techniques were obtained from the report, the capital cost was scaled up using the economies of scale “0.6 rule”. To allow the comparison of costs, the net present value was calculated using the variable values mentioned earlier. The total water losses for scenarios 4 and 5 were calculated which provided the value for substitution with seawater (desalinated, raw or lime precipitated). Using the same method as described for scenarios 1 to 3, the net present values of substituting with seawater were calculated and added to the net present value of the water saving techniques to provide a total value.

For the road dust suppression, the base case considered a spray rate of 1 L/m^2 ten times a day for haul roads and four times a day for service roads. In the study of Gunson et al. (2012) it was assumed that a mine with a throughput of 50,000 tonnes per day would have 10 km of haul roads at a width of 32 m and 10 km of service roads at a wide of 8 m. Scaling these values to the base case, a water loss of 10,560 m^3 was calculated. The application of a polymer dust suppressant was applied to the model, the application rate of the suppressant was input as 0.0525 L/m^2/month at a cost of USD 1.7/L (Karsas 2015, Personal Communication). This application allows for a reduction of normal water application of 1 L/m^2/day three times per day. The net present values were determined for its use in scenarios four and five. Finally, each NPV for was for scenarios four and five were summed to provide a final value and allow comparison between all scenarios.

Results and discussion

The total water loss values were calculated for each scenario providing the replacement flow values for each scenario. For scenarios 1 to 3, the water losses were the base case with no strategies considered to reduce water consumption. For scenarios 4 and 5 the water losses were reduced as a result of the tailings dewater strategies (thickening for scenario 4 and filtration for scenario 5) and the use of road dust suppression with a synthetic suppressant in both scenarios. The water losses for each process and scenario can be viewed below in table 1.

Table 1. Water losses for each process and all scenarios

Process	Scenarios 1, 2 and 3 Water losses (m^3/day)	Scenario 4 Water losses (m^3/day)	Scenario 5 Water losses (m^3/day)
Road dust suppression	10,560	1,620	1,620
Human consumption	174	174	174
Raw water evaporation	6.6	6.6	6.6
Process water tank evaporation	10.2	10.2	10.2
Primary crusher	1080	1080	1080
Stockpile	360	360	360
Flotation cell	20.1	20.1	20.1
Concentrate thickener	3.6	3.6	3.6
Final concentrate	267	267	267
Tailings storage facility	96,076	78,036	29,164
Tailings thickener	-	52	-
Total losses	**108,558**	**90,570**	**32,706**

Using the water losses as the replacement flow values, the net present values were calculated for each scenario. Figure 3 below displays the net present values calculated for scenarios 1 to 3 for each level of elevation.

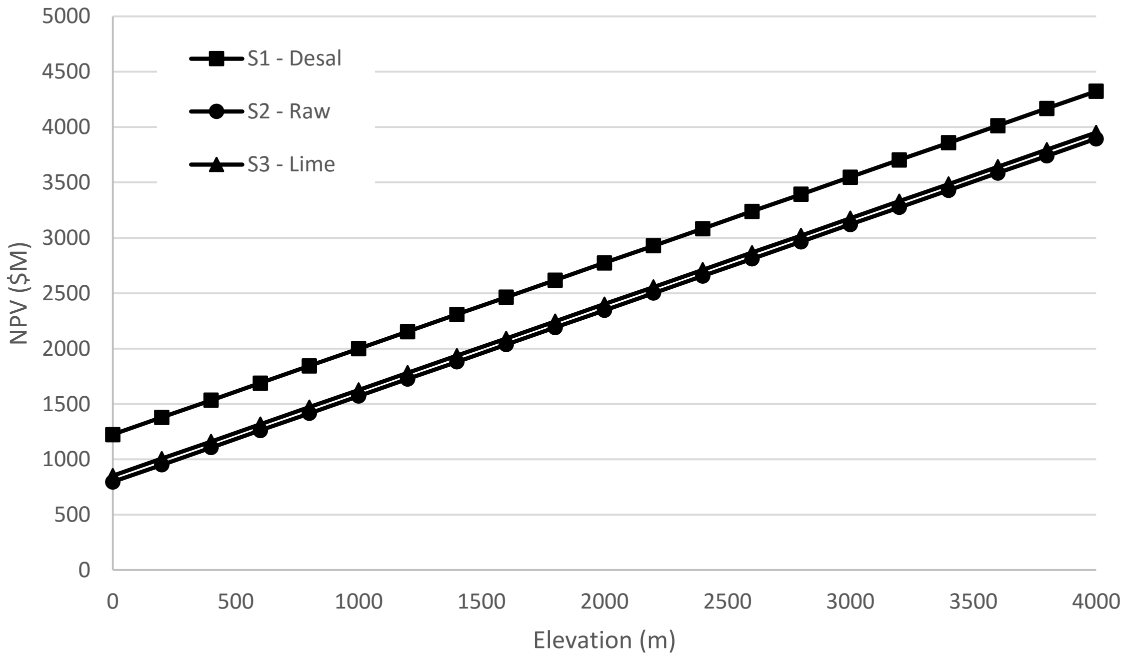

Figure 3. Net present values for scenarios 1, 2 and 3 for different levels of elevation

For scenarios 4 and 5, the replacement flow was reduced due to the impact of the water use reduction strategies. For both scenarios, replacement with (a) desalinated seawater, (b) raw seawater and (c) lime precipitated seawater was also analyzed. The net present values of each of the scenarios for the different levels of elevation and water treatment type can be observed in figure 4 below, the values without the water use reduction strategies are also included for comparison.

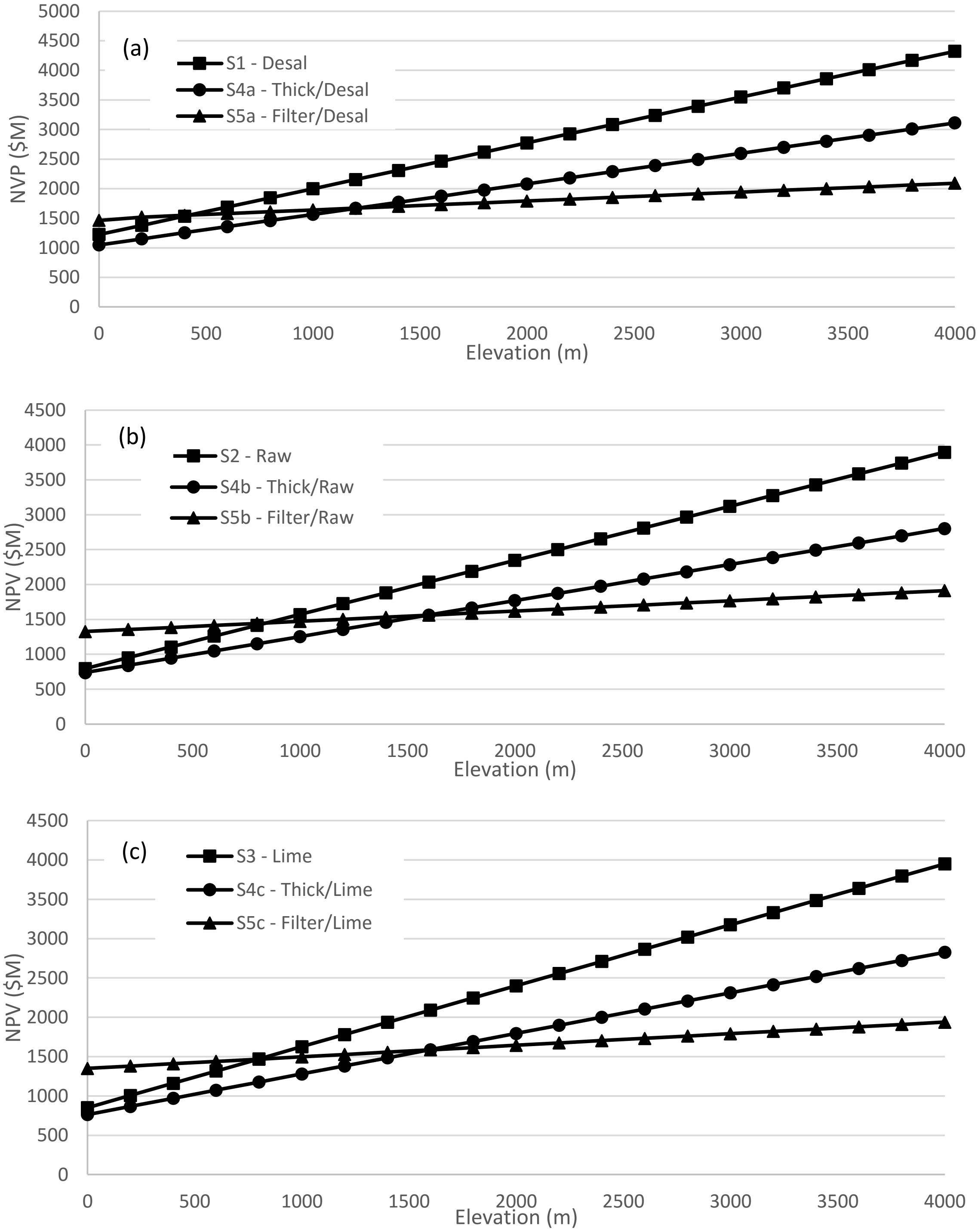

Figure 4. Net present values for each scenario using (a) desalinated seawater, (b) raw seawater and (c) lime precipitated seawater

When no water saving strategies were considered (Scenarios 1, 2 and 3), the replacement of freshwater with seawater was least cost effective when the seawater was assumed to be desalinated. Compared to the very low treatment costs of raw seawater, the desalination process, being highly capital and energy intensive, increased the net present value considerably. At sea level elevation, the difference in the net present value was calculated to be USD 427M. The use of lime precipitation increased the net present value slightly above that of the raw seawater mainly due to the operating costs of supplying the lime. At sea level, NPV of scenario 3 was USD 852M compared to USD 796M for scenario 2. For each scenario, the NPVs increased at higher elevations due to the piping requirements and more significantly the pumping requirements. At an elevation of 4,000 m (an elevation at which a number of mines in Chile are located), the NPV for scenario 1 was USD 4.3 bn and USD 3.9 bn for raw seawater.

When scenarios 4 and 5 were compared with the alternative scenarios, at low levels of elevation, thickening of the tailings (scenario 4) proved to be the most cost-effective solution having a slightly lower net present value than the use of raw seawater only. Filtration proved comparatively expensive at low elevations because sourcing seawater at around sea level or slightly higher was determined to be relatively inexpensive compared to the high capital and operating costs of tailings filtration. At higher elevations, however, the low savings of thickening relative to filtration led to scenario 5 providing the most cost effective solution as lower flows of replacement water were required. In figure 4, it is possible to observe that at a certain elevation, filtration becomes the most cost-effective scenario for each of the water types. For desalinated water, that point is at 1,200 m, for raw water it is 1,600 m, a higher value because the cost of producing the seawater is less. For lime precipitated water, this point was also at 1,600 m.

For both scenarios 4 and 5, road dust suppression with a polymer was also considered in the previous analysis. It is interesting to compare the cost-effectiveness of the dust suppression strategy with the dewatering strategies. For each strategy the ratio of the net present value for the annual volume of water saved was calculated. The results can be observed below in table 2.

Table 2. A comparison of the net present value to water saving potential of the water saving strategies

	Dust suppressant	Tailings thickening	Tailings filtration
Water saved (m^3/day)	8,940	235,574	315,208
NPV ($M)	13.7	458.6	1,191.9
NPV/m^3 ($/$m^3$)	0.17	0.21	0.41

The results in table 4 demonstrate that the use of the dust suppressant provides the most cost-effective of the three techniques suggesting that dust suppression with a polymer suppressant or similar product should be considered as a good method to reduce water use at a relatively low cost. The tailings thickening was also calculated to provide a lower cost to water saving ratio but because the filtration techniques saves more water, at high elevations where replaced water must be pumped, it provides better cost-effectiveness as shown in Figure 3.

There are some key assumptions made in the analysis that require discussion. The results suggest that raw seawater, lime precipitated seawater and desalinated seawater hold the same value. This is not the case as desalinated seawater contains far fewer contaminants than raw seawater that can affect the operating processes. As mentioned previously, the presence of certain ions can reduce the recovery of copper and molybdenite in the copper flotation process thus reducing profitability. This was the reason for the inclusion of the scenario that considers lime precipitation which has the potential to retain high copper and molybdenite recovery without the use of desalination (Laskowski, Castro, and Ramos 2013). It is unlikely that raw seawater would be used for all processes for this reason but it is also possible that a small volume of the raw seawater could be desalinated on site for use in sensitive processes such as froth flotation.

Sensitivity analysis

The results were based on assumptions of effectiveness of the tailings dewatering scenarios. To test the sensitivity, the effect of using low and high values of effectiveness was tested. For the thickening a low value of 55% total final solids was used and a high value of 70%. For the filtration, a low value of 80% and a high value of 85% was used. These values were the ranges considered in the Ajax project report (Norwest Corporation 2015). Figure 5 below displays the results for the low and high values of each different scenario.

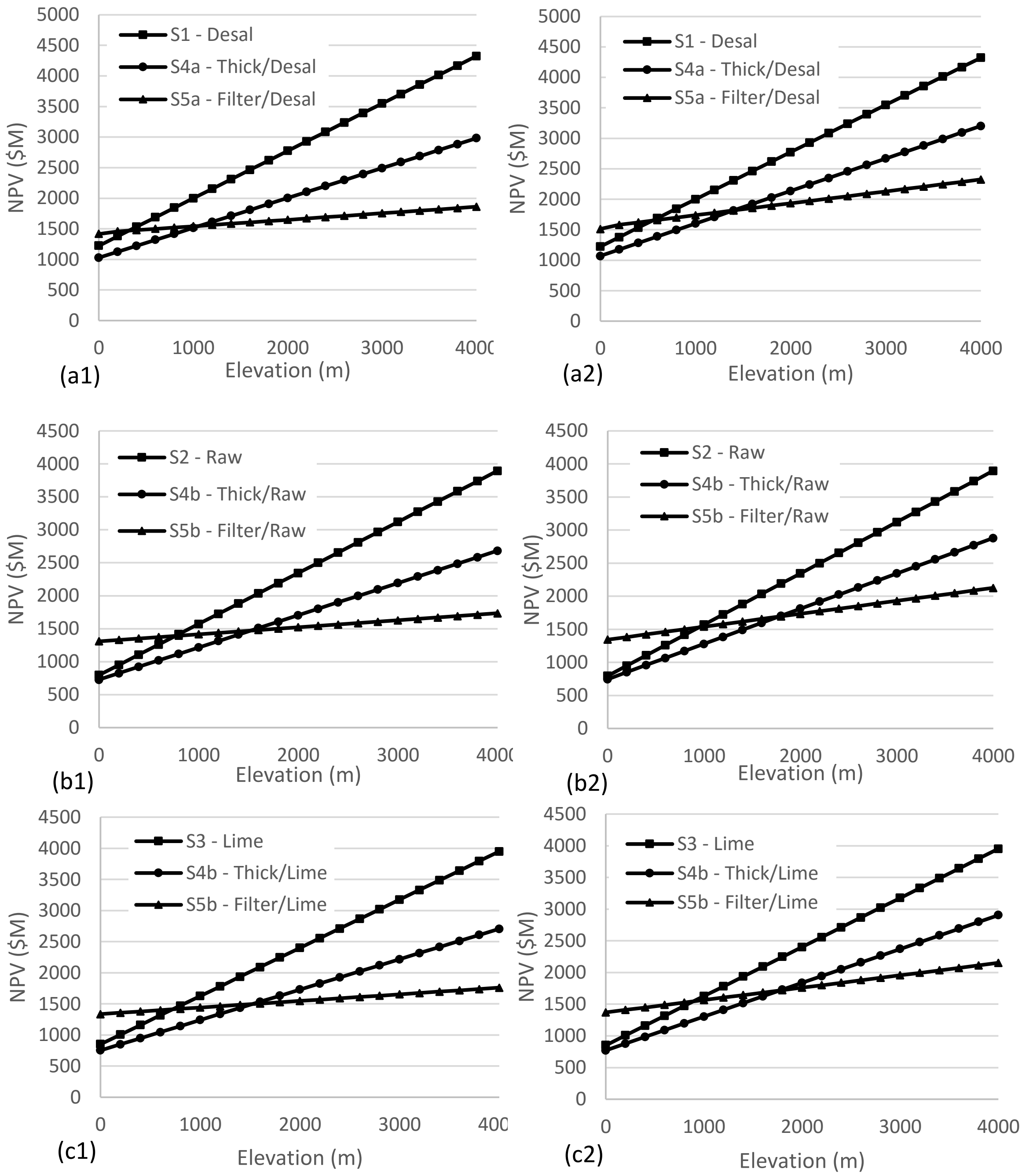

Figure 5. Sensitivity analysis of tailings dewatering effectiveness for (a1) Desalination – max, (a2) Desalination – min, (b1) Raw seawater – max, (b2) Raw seawater – min, (c1) Lime precipitated – max, and (c2) Lime precipitated - min

The impact of changing the values of dewatering effectiveness does not appear to have a large bearing on the overall results. Where the minimum values are used and the desalinated water was assumed, filtration of the tailings became the preferred option at 1,200 m of elevation instead of 1,400 m for the base case. Conversely, when maximum values of effectiveness were assumed, filtration performed less well and becomes the preferred option at 1,800 m of elevation with raw seawater and lime precipitated seawater instead of 1,600 m for the base case. Aside from these points, the impact of the maximum and minimum values is very limited on the results.

Sensitivity analysis was also conducted for the life span of the operation (20 and 30 years) and the discount rate (4% and 12%) for calculating the net present value, negligible impact upon the results was calculated.

Conclusions

This study aimed to determine the most cost-effective method to substitute freshwater abstractions with seawater in copper sulfide mining in Chile, using a case study of a representative, model mine. The study considered: 1) complete substitution with desalinated water, 2) complete substitution with raw seawater, 3) complete substitution with seawater precipitated with lime, 4) and the implementation tailings thickening alongside each of 1-3, and 5) the implementation tailings filtration alongside each of 1-3. At low elevations, the use of tailings thickening with raw seawater was calculated to be the most cost-effective option. The use of raw seawater may however be limited due to the sensitivity of some operations to its use. The use of seawater precipitated with lime was calculated to be only slightly more costly. At higher elevations above 1,600 m, however, the implementation of filtration of the tailings was determined to be the most cost-effective scenario due to the large reductions in pumping requirements, piping infrastructure and desalination where applicable. The analysis also demonstrated that the use of road dust suppression with a polymer product was a cost-effective method to reduce on-site water consumption and the associated costs. This study shows the importance of water saving techniques such as thickening and filtration of tailings as a way to reduce the high investment of using seawater in mining operations at elevations above a few hundred meters.

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