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TECHNICAL ARTICLE

Evaluating the Costs and Benefits of Salt Management Strategies at Mine Sites Using a Systems Model

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Abstract Unprecedented expansion of coal mining in Australia is occurring within the context of a severe ongoing drought. This has induced more companies to adopt improved water management strategies, such as water reuse. A direct consequence of this is an increase in the salt concentration of the water, which affects in turn the efficiency of the coal preparation processes, the quality of the coal product, and the level of required equipment maintenance. There are three strategies that can be adopted with respect to salt management: accept the elevated salt concentrations and increase spending on equipment maintenance; remove the salt by desalination; and dilute the salt by importing more water. A tool is required to predict the salt concentrations arising from water reuse and to simulate the impact of potential management strategies. This paper presents a systems approach to the modelling of coupled mine site water and salt balances to assist with understanding the implications of implementing desalination or dilution and with assessing the costs and benefits of each option.

Introduction

The Bowen Basin (Queensland, Australia) is one of the world's important coking coal mining regions and plans for unprecedented growth have been announced. The region is experiencing a severe regional drought. This has presented considerable challenges to meet current coal production requirements. Alternative water sources have been sought, such as worked water. Worked water is water that has been involved in a task or has passed through an area disturbed by the mining processes. Some of the issues that arise from the increase in worked water use (e.g. increase in water reuse) are related to water quality management, and more particularly, to an increase in salt concentration in the worked water.

Salt can be managed by accepting and managing the consequences of increased salt concentrations (living with salinity), removing the salt (desalination) or diluting it. For each of these strategies, a tool is required to predict the concentration of the worked water, and to simulate the impact of the management strategies (desalination or dilution) on the concentration of the worked water. Some tools have been developed and are available to study the impact of salt in a mining environment but they tend to deal with the management of saline discharge water or with the fate of salt after a mine has closed. For instance, a study of the long-term water quality trends in a post-mining final void was conducted in the Hunter Valley, Australia (Hancock et al. 2005). The model focused on describing the physical processes occurring in the pit and had no connection to mine site water management. With respect to the management of mine waters, several studies have been concerned with alternative ways of disposing of mine water either through irrigation, or treatment and disposal to the environment. For instance, the use of gypsiferous mine water for irrigation of agricultural crops could solve problems related to both shortage of irrigation water and disposal of effluent mine drainage. The long-term effect of irrigation with lime-treated acid mine drainage on soil properties and catchment salt load was investigated with a physically based soil water, salt balance, and crop growth model (Annandale et al. 1999, 2001). Other studies have

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addressed the issue of saline water being discharged to the environment following desalination, with the treatment process including pretreatment, reverse osmosis, and thermal plant for concentration of brine (Ericsson and Hallmans 1996; McIntosh and Merritt 2006; Turek et al. 2005). Except for the McIntosh and Merritt paper (2006), these studies do not address salt management of mine site water during the operational phase.

Though salt management can also be an issue for mine sites outside of Australia, there is no simple tool for predicting salt concentration in mine waters that could help assess potential management strategies for the mine operational phase, rather than the closure phase. This paper demonstrates how a simple systems model can assist with understanding the implications of specific water management strategies for salt balance.

Study Area

The Bowen Basin, located in Queensland, Australia (Fig. 1), is a major coal producing region containing one of the world's largest deposits of bituminous coal, including virtually all of the known mineable prime coking coal. The coal that is produced is exported to Japan, Korea, India, and Europe for steel manufacture.

Traditionally, water has been delivered by development of regional water infrastructure. This is still the case and new water pipelines and off-stream storages are being constructed. However, there is growing awareness that water management needs to be improved. This change in attitude has been brought about by a recent severe drought. Analysis of daily climate data from Moranbah, Emerald, and Blackwater for the period 1955 to 2004 shows that mean annual rainfall in the Basin is around 580 mm/year, with mean pan-evaporation around 2,100 mm/year. Rainfall is highly variable with the 10th percentile annual rainfall being 360 mm/year and the 90th percentile 870 mm/year. Dry periods are a natural part of Queensland's climate, but since 2002, dry conditions have not been relieved by substantial wet periods, and the Basin has been drought-declared for 5 years.

In the Bowen Basin, an open-cut coal mine with a coal handling and preparation plant (CPP) uses the majority of its water for coal preparation, dust suppression, vehicle wash down, and potable uses. Dust suppression is needed in pits, on roads, and in industrial areas. Coal preparation increases the quality of the coal by removing impurities. Run-of-mine coal from a modern mine may incorporate as much as 60% reject materials. There are three basic steps in coal preparation (Kirk et al. 1991): (1) the run-of-mine coal is crushed and separated into coarse coal and fine coal; (2) water is added to each fraction so that the lighter coal

Fig. 1 A regional map of the Bowen Basin, with the *grey area* outlining the coal measures

particles can be separated from the impurities using circuits adapted to the fraction size (e.g. jigs for the coarser fraction and flotation for the finer fraction); and (3) dewatering, again using a process adapted to the fraction size (e.g. centrifuges or cyclones for the coarser fraction and vacuum filtration for the finer fraction). Liquids recovered from dewatering processes are treated in thickeners or clarifiers (depending on their solid concentrations) before being exported as tailings and, on many mines, returned to the plant as worked water. The coal preparation plant uses large volumes of water, usually from 300 to 700 megalitres per megaton of coal production (ML/Mt), depending on the design of the plant and the way it is managed. An underground coal mine with a CPP uses the majority of its water for coal preparation and to support mining activities underground, such as spraying the coal seam, cooling the equipment, and suppressing dust.

Salt Issues

Worked water includes runoff intercepted by pits, ground water inflows, wash down residuals, outputs from the various tasks (such as the coal preparation plant), and water pumped out of underground workings. The salt can come from the saline materials that are brought to the surface during open cut mining, thereby producing saline runoff during a rainfall event, or from saline ground water that is pumped up into the surface water systems from underground. At many mines, the most important water reuse strategy employed has been to use worked water to suppress dust on roads and in pits. Salt is left behind when the water evaporates and can later be returned to the worked water storages. Worked water has also been used in coal preparation, despite the interactions between salt and coal not being fully understood. Worked water salt concentration needs to be monitored and managed, as it can pose challenges for mine site management.

Discharge Limitations

The Queensland Environmental Protection Agency imposes restrictions on water discharges from mine sites. Discharge licenses prescribe the location and number of discharge points, the frequency at which discharge should occur, and the quality of the water that can be discharged. For Bowen Basin mines, discharge licenses often require that the conductivity of the discharged water be between 1,500 and 3,000 μS/cm, depending on the mine's location and the sensitivity of the receiving environment. The mines must manage their water balances and water quality so that they abide by their discharge licenses.

Salt and Flotation Efficiency

Anecdotal evidence from mine sites has indicated that use of saline water for coal preparation reduces the required quantity of flotation reagents (diesel, in particular), which is supported by experimental evidence obtained under controlled laboratory conditions (Ofori et al. 2005). These laboratory experiments showed that flotation efficiency depended on the types of salt in solution, with different salts behaving differently with different coals. In general, a concentration of about 5,000 mg/L provides the maximum benefit with respect to flotation recovery efficiency.

Salt and Product Quality

When saline water is used in coal preparation processes, it has the potential to affect coal quality. Salt can cause additional costs associated with the bulk product itself (purchase of salt instead of coal) and with additional maintenance in kilns where salt is combusted. Salt in coking coal can also weaken the coke, which compromises steel quality, further devaluing the coal. It is therefore in the interest of mining companies to demonstrate appropriate management of worked water salinity, so that the issue of coal salt content does not influence price negotiations.

Preliminary experimental data indicate that there is a close relationship between salt in the fine coal product and the salinity concentration of the flotation water. Experiments were undertaken to quantify the potential extent of this exchange. Coal samples were collected at four mine sites from the CPP feed; 5 g of ground coal was placed for 6 h in 20 mL of a NaCl solution with concentration varying from 0 to 15,000 mg/L. The final salt concentration of the solution was determined by calibrating electrical conductivity with salt concentration. The difference in concentration at the beginning and end of shaking indicates an exchange of salt between the solution and the coal. The mass of salt exchanged between the coal and the solution was then calculated. Figure 2 provides results obtained at one site, for which the relationship between salt exchange and solution concentration is linear ($R^2 = 0.97$).

At low salt solution concentrations, salt moves from the coal into the solution. This implies that if the water in the flotation cells is too fresh, it is salinised by the coal. However, when the solution concentration passes a coal-specific threshold, the salt moves from the solution into the coal. In this case, high concentration solutions result in more salt in the product. For the example shown, targeting a solution concentration of about 2,500 mg/L would ensure that minimal salt would move into or out of the coal product. This threshold concentration was found to be valid for the other three sites for which experiments were undertaken.

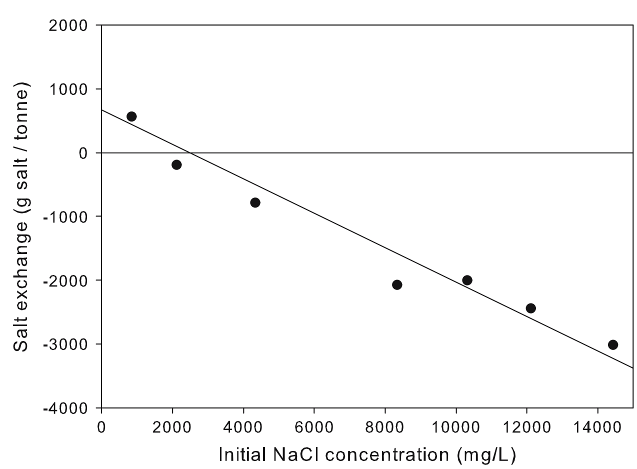

Fig. 2 Example of the relationship between background salt concentration (here NaCl) and exchange of salt into coal

Salt and Maintenance Costs

There are additional maintenance costs associated with the use of saline worked water in coal handling and preparation plants. Bartosiewicz and Curcio (2005) looked at the sources of maintenance costs, the processes involved in corrosion, and a range of mitigation techniques. Figure 3 illustrates a relationship between salt concentration in clarifier water and annual average maintenance costs. The water held in clarifiers is of a quality similar to that being used in the coal preparation plant and is relatively easy to monitor. Maintenance costs roughly increase linearly with salinity. The correlation coefficient ($R^2 = 0.58$) indicates that salinity clearly affects maintenance costs. Further work is required to analyse which additional variable (e.g. the age of the plant) would explain the remaining variation. One data point indicates that lower maintenance costs could be achieved, but the reason for such a result was not investigated in the Bartosiewicz and Curcio (2005) study. For our analysis of water strategies associated with salt management, we have excluded this data point and have assumed that maintenance costs could be described as a linear function of salinity.

It is therefore desirable, financially, to balance the corrosion costs associated with using worked water with the costs of water treatment (essentially desalination) and/or importing more fresh water.

Systems Model

A generic model of a mine site was developed to quantify the fluxes of surface water, ground water, and worked water, with salt a constituent of each flow. The model is a considerably simplified system representation of a mine site. The model consists of: (1) two water stores, one for fresh water and one for worked water; (2) a blending facility, which is a piece of "virtual" infrastructure representing all water reticulation around a site; (3) several tasks that import and export water of varying qualities; and (4) a desalination plant (Fig. 4).

Water enters the system as fresh water that is sourced from a pipeline, as aquifer inflows or as rainwater captured on site. Salt is represented as a concentration associated with each water flow. Salt can be removed from the water circulation system by being stored on roads or swales, exported in the coal product, or lost in seepage. The simulation model is driven for a duration that is determined by the rainfall and pan-evaporation sequences that are provided. The computational time step is daily. The time step for the input rainfall sequence is daily, weekly, or monthly, with the simulations presented here using monthly rainfall data. The time step for the pan-evaporation sequence is monthly.

The model calibration and its performance for representing water flows have been described previously (Côte et al. 2006; Moran et al. 2006). The model was also verified for its calculations of worked water salinity. In this case, time series monitoring data were not available so only the order of magnitude of the salinity could be checked. There is no parameter in the model that needs to be calibrated with respect to the calculations of salt concentrations. As the model calculates salt concentrations in the worked water store and coal preparation plant, these can be compared with measurements of salt concentration in the coal preparation plant clarifiers, when available. Comparisons were satisfactory (Fig. 5).

A previous study (Côte et al. 2006) presented a comparison of the modelled water balances of seven coal mines in the northern Bowen Basin in Queensland, Australia. The

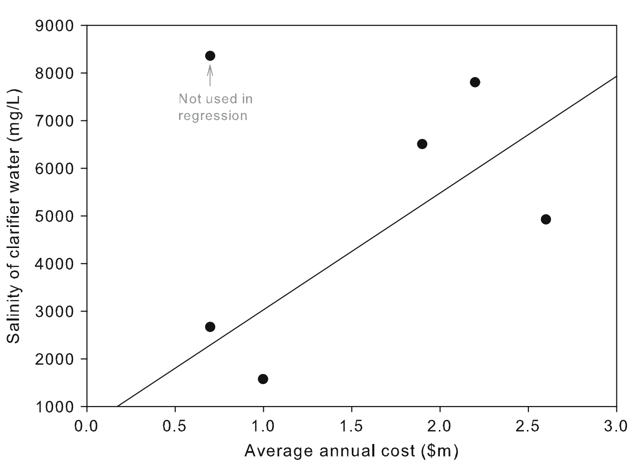

Fig. 3 Average annual maintenance costs as a function of clarifier water salinity in six mine sites

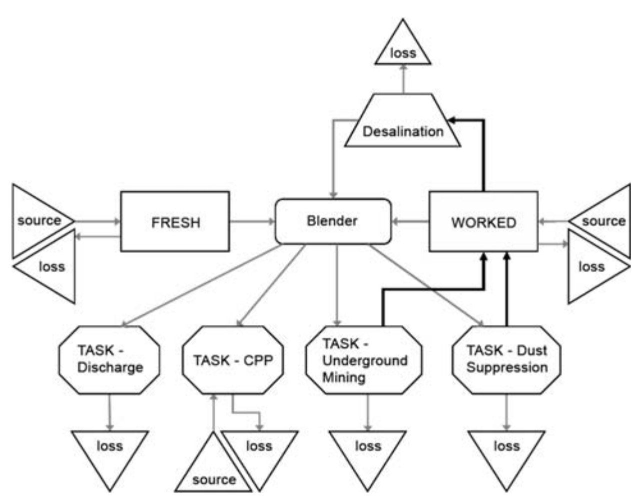

Fig. 4 System diagram of a simplified coupled salt and water balance model for a mine site, adapted from Moran and Moore (2005)

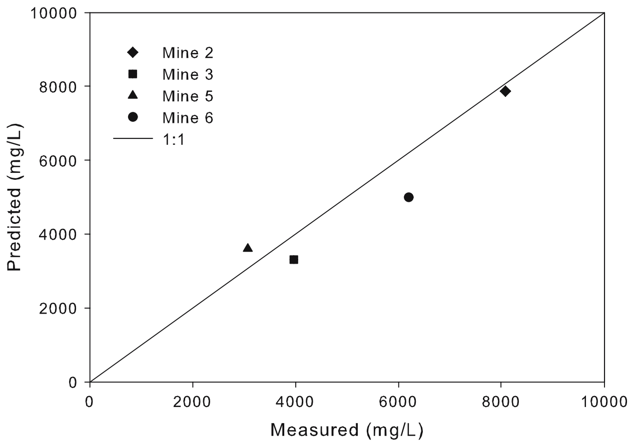

Fig. 5 Measured and predicted concentration of clarifier water

focus was on deriving a series of water management performance objectives: (1) optimising the worked water storage capacity to avoid discharge of water; (2) maximising the use of worked water (particularly in the coal preparation plant); (3) maintaining sufficient water availability; and (4) adopting leading water productivity ratios. In this paper, the model was used with the same seven example mines to explore the relative benefits of salt management strategies. Salt can be managed by accepting and managing the consequences of increased salt concentrations (living with it and increasing maintenance spending), by removing the salt (desalination), or by importing additional freshwater and diluting it. The concentrations that were adopted as simulation targets were selected based on the effect salts can have on flotation efficiency and coal product quality, as discussed. The target in each case was to limit the clarifier salinity to respectively

1. 2,500 mg/L to eliminate product quality compromises.
2. 5,000 mg/L to get some benefit of reagent savings from salt water flotation.

The systems model was designed so that a salt tolerance could be set at the water intake to any process. When the worked water concentration becomes greater than this tolerance limit, freshwater is imported to dilute it until the worked water meets the specified tolerance limit. Dilution is easily simulated by lowering salt tolerances so that the maximum salinity of the water entering the CPP is equal to the selected targets (2,500 or 5,000 mg/L). The salinity may, of course, be less if the salinity of the worked water is less than the target.

The systems model also includes a desalination plant, located between the worked water store and the blender. When simulating this option, desalination is activated when the concentration of the worked water reaches the set salt tolerance. If there is no worked water available to be desalinated, fresh pipeline water is used as makeup water. As for dilution, this ensures that water entering the CPP cannot have a salinity higher than the tolerance limit. The salinity of the worked water may be lower than the tolerance limit, in which case the desalination plant is not activated. It was assumed that the desalination process removed 90% of the salt and that 10% of the water remained with the separated salt as brine.

It was also necessary to select the appropriate desalination plant capacity for each site and for each concentration objective. The capacities were selected by looking at: (1) the trade-offs between the amount of desalinated water versus the potential volume (i.e. how often the plant could operate because water was available and sufficiently saline to warrant desalination); and (2) the impact of desalination on the overall stock of worked water. The latter ensured that desalination did not compromise site water supplies or cause discharge in excess of the discharge limitations. The full procedure is described for each site in Moran et al. (2006).

Results and Discussion

Imports of Pipeline Water

The effect of desalination or dilution on imports of pipeline water are summarised in Table 1. This table does not include additional fresh water supplies such as rainwater capture, which, in the model, is used in preference to importing pipeline water. The full fresh water usage, including evaporation from the dam, is greater than the import of pipeline water.

At Mines 2, 6, and 7, a dilution management strategy would increase the import of pipeline water. At these mines, the concentration of the worked water is above 5,000 mg/L (see also Fig. 9) and dilution to either 2,500 or 5,000 mg/L would require additional pipeline water. At Mines 1, 3, 4, and 5, dilution to 2,500 mg/L would require additional pipeline water but dilution to 5,000 mg/L would not. This is because at these mines, the current worked water salinity is lower than 5,000 mg/L (Fig. 9). When simulating dilution to 5,000 mg/L, a slight increase in worked water use is predicted. The impact of desalination on pipeline water imports varies from mine to mine depending on current worked water salinity and current worked water use.

Costs of Salt Management Strategies

One method for comparing these simulated scenarios is to calculate the cost of implementation and to compare it with

Table 1 Calculated fresh water imports for current situation, dilution, and desalination strategies

	Current	Dilution to 2,500 mg/L	Dilution to 5,000 mg/L	Desalination to 2,500 mg/L	Desalination to 5,000 mg/L
Mine 1	140	144	134	136	135
Mine 2	134	268	199	138	134
Mine 3	199	223	167	155	145
Mine 4	432	602	264	455	252
Mine 5	329	568	179	178	179
Mine 6	161	357	179	197	168
Mine 7	279	401	313	208	208
Mean	239	366	205	210	174

the cost of using the untreated saline water. As discussed previously, using saline water can have direct financial consequences since it can undermine coal quality, thereby reducing its value, and can induce additional maintenance costs due to corrosion. Three cost components were taken into account: (1) maintenance costs associated with the CPP salt concentration (Fig. 3); (2) cost of fresh water supply estimated at AUD$1,600 ML^{-1}; and (3) cost of desalination using electrodialysis and estimated as AUD$1,200 ML^{-1}. The latter cost is based on the amortised capital cost and operating cost, including brine transport and sea disposal, as estimated in a previous study (Firth 2005). Electrodialysis was selected from the options examined by Firth (2005) because it is the most well proven of the options. In all calculations, the sale price for coal was assumed to be AUD$120 t^{-1} of saleable coal product.

Results are summarised in Fig. 6. There is considerable variation in the cost of the current water supply, with the maximum (1.08 AUD$M/Mt) being 2.7 times greater than the minimum (0.40 AUD$M/Mt). Similarly, there is considerable variation in the estimated cost of the salt management strategies. For instance, the maximum cost for implementing dilution to 2,500 mg/L (1.23 AUD$M/Mt) is 3.5 times greater than the minimum (0.35 AUD$M/Mt).

There is little average cost difference between desalination and dilution (Table 2). This underscores the potential importance of water price in determining whether water should be purchased for dilution or whether a technological solution such as desalination should be adopted. Small changes in the relative costs of purchasing and delivering water could tip the business case argument for one solution (dilution) over the other (desalination).

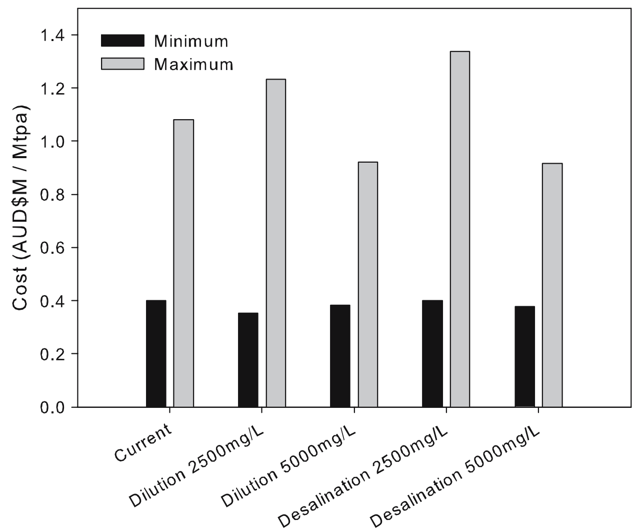

Fig. 6 Estimated costs of water and salt management strategies

Value of Salt Management Strategies

Beyond cost considerations, desalination uses less pipeline water (Fig. 7). With a target of 5,000 mg/L, it is predicted that the desalination option can use up to 30% less pipeline water than the dilution option. With a target of 2,500 mg/L, desalination can use up to 65% less pipeline water than dilution.

Desalination offers the advantage of providing some risk mitigation against regional water scarcity. In addition, water that is not used by dilution has other potential values. One obvious financial benefit is to sell the water as a temporary trade, and water markets exist in this region to do so. It may also be of considerable benefit to a company to have the water available for town use, for instance to irrigate parks, gardens, and sporting facilities. In the dry environment of the Bowen Basin mines and the associated towns, this could have considerable value when there is strong competition to find and retain workers and their families during a skills shortage. Water that is not used can also form part of the supply needed for a new mine. This value, referred to as opportunity revenue, can be calculated by estimating the amount of money that can be made from each megalitre of water. As an illustration, we have computed the opportunity revenue by only considering the cost of water:

Table 2 Cost in AUD$M of dilution and desalination

	Target = 2,500 mg/L		Target = 5,000 mg/L	
	Dilution	Desalination	Dilution	Desalination
Mine 1	1.658	2.045	2.033	2.115
Mine 2	4.655	5.591	4.529	5.150
Mine 3	5.560	5.394	5.163	5.087
Mine 4	3.354	3.358	2.506	2.492
Mine 5	3.829	4.542	2.587	2.587
Mine 6	2.655	2.599	2.487	2.472
Mine 7	5.366	5.201	5.176	5.089

$$\begin{aligned}\text{Opportunity revenue} &= \text{revenue} - \text{cost of water}\\ &= (\text{coal production} \times \text{coal price})\\ &\quad - \text{cost of water}\end{aligned}$$

Annual opportunity revenues were computed for the seven mines and the average of these seven annual revenues is presented in Fig. 8. The opportunity revenue of desalination is much greater than that of dilution. If a new project is limited by partial unavailability of water, the cost of desalination on an existing site to make the water available for a new project is small compared to the value it will create.

These results illustrate that if only the purchase price of water is considered, the benefits of water management strategies, such as desalination, will be underestimated. Mining operations located in water-scarce environments should manage water as a key asset with business value, thereby reducing risks that would be associated with a lack of recognition of the social, environmental, and economic values of water. Adopting a strategic approach that takes into account the true value of the water should provide business opportunities and risk protection.

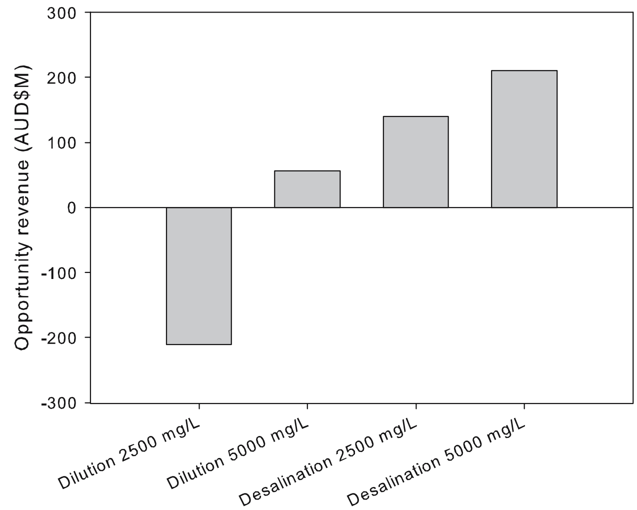

Fig. 8 Opportunity revenue of the salt management strategies, based solely on the cost of water

Managing both Water Quantity and Quality

The systems model was used to simulate a water management strategy that would meet a series of objectives (Côte et al. 2006): (1) optimising the worked water storage capacity to avoid discharge of water, (2) maximising the use of worked water (particularly in the coal preparation plant), (3) maintaining sufficient water availability, and (4) adopting leading water productivity ratios. Meeting these multiple objectives involves changes to the status of overall water stocks and changes to the use of fresh and worked water. Results from a scenario simulating implementation of various strategies to meet these objectives predict large increases in salt concentration at the coal preparation plant, more particularly the clarifier water (Fig. 9). The magnitude of the change is governed by how closely each mine meets the water quantity management objectives.

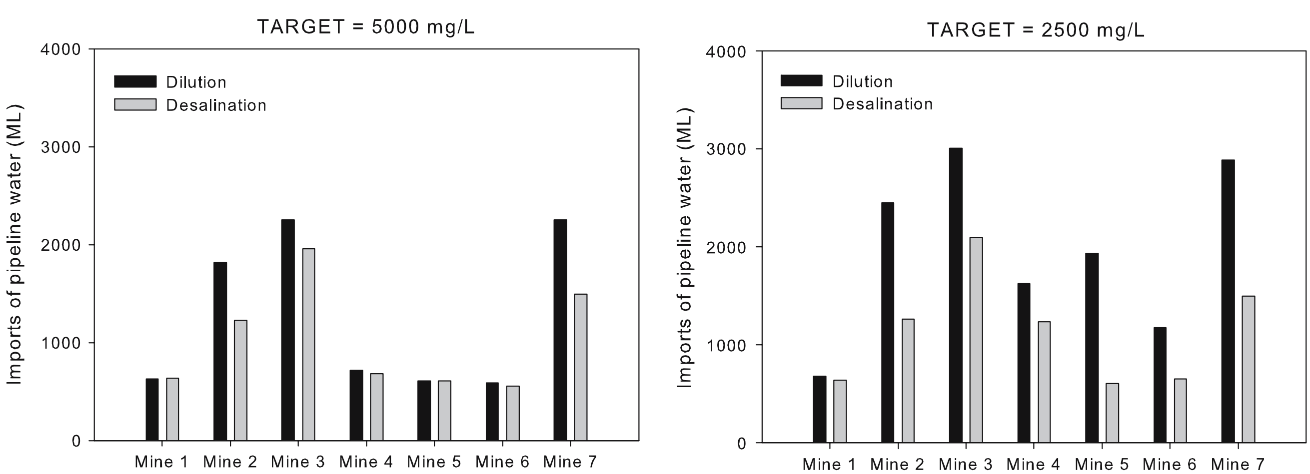

Fig. 7 Comparison between imports of pipeline water for dilution and desalination, for a target of 5,000 mg/L (*left*) and a target of 2,500 mg/L (*right*)

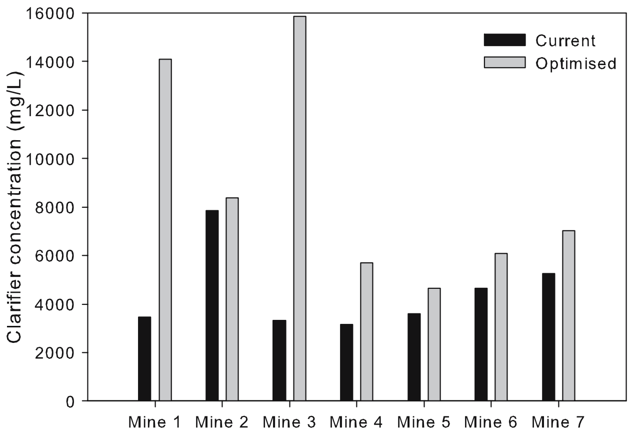

Fig. 9 Meeting the multiple water quantity objectives is expected to impact on water quality

This paper has shown that a coal mine water system is complex and consists of various elements that are interconnected. Selecting a salt management strategy poses several challenges and its implementation will likely affect various elements of the system. For instance, desalination will affect the overall stock of worked water and may expose a site to an increased risk of running out of water or of discharging. To define strategies that will meet both water quality and quantity objectives, iterative modelling will be required. The systems model presented here provides a suitable tool to try and address those challenges.

Conclusion

A systems model representing water and salt balances on a mine site was used to assess the advantages of two major salt management strategies: dilution and desalination. The model enables estimation of salt concentration in the mine water and quantification of the fresh water savings that may be achieved with each option. It also provides preliminary design criteria for assessing the cost of implementation of a selected strategy. However, it is argued that if only the purchase price of water is considered, the benefits of water management strategies, such as desalination, will be underestimated. Mining operations located in water-scarce environments should manage water as a key asset with business value; not recognizing the social, environmental, and economic values of water will expose them to risks. Adopting a strategic approach that takes into account the true value of water should provide business opportunities and risk protection.

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