Salinity and experience constraints to water reuse in coal mining

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ABSTRACT
Water scarcity is leading to increased focus on water reuse. One common assumption is that the best way to reduce fresh (raw) water use is to introduce water recycling. The amount of water thereby reused is no longer needed from an external supply. However, it is important to consider wider implications of increased water reuse. We present a generic model of a mine site to examine some limitations to water reuse in coal mining. We consider a discrete-time model of water flow around a mine site, with a single contaminant, salt. Each process is assumed to require water of a minimum quality, which limits the amount of "worked" water able to be used in each process. We quantify the substitution of worked water for raw water for a range of salt tolerances. As reuse increases the water balance becomes more closely coupled to the climate. Finally, we examine the implications of failure in various components of the water infrastructure, caused by limited skills to manage the water system, on the expected water savings. We conclude that moving to water reuse should be accompanied by careful planning to ensure the new water system is appropriately managed.

INTRODUCTION
Water management in the minerals industry is driven by the need for secure access to sufficient water, environmental protection under relevant local laws and the need to meet corporate sustainable development goals. A combination of changing water policies (governmental and corporate), increased competition for water and climate changes are resulting in increased attention to water management. In regions where water is scarce, good water management is required to ensure that production is not threatened by lack of water. Improving water management can also provide the water necessary for expansions or to support development of new operations. Water management is both an environmental and direct operational issue.
Fundamental to good water management is an understanding of water balances. A water balance is a mechanism for accounting for fluxes of water between storages of various types, the changes in the quantity of water in those storages (including any gains and losses from the system) over some time and system domain. Water balance approaches necessary for good mine planning (Chaulya, 2003) and are a commonly applied method for improving water management on existing sites. For example, Dharmappa *et al*., (2000) were able to demonstrate improved storm water management practices at a coal mine in a wet environment. One common assumption is that the best way to reduce water use is to introduce water recycling within the domain of the water balance. The amount of water thereby reused is no longer needed from an external supply (which may be located some distance from the point of use). However, reuse of water generally goes hand-in-hand with increasing contaminant loads, which must also be managed (*e.g.*, O'Leary, 1996, Sans *et al*., 1998).
In this paper, we present a generic model of a mine site to examine some issues surrounding water reuse. We consider a simple discrete-time model of water flow around a mine site, with a single contaminant, salt, which enters the water reticulation system from groundwater, coal, spoil, rain and imported fresh (raw) water. We examine the extent to which limitations of salt concentrations for various mine site water uses limit the extent to which reuse can supplement the importation of raw water. The effect of adding a desalination plant to the system is quantified for a range of plants of increasing magnitude. Due to a healthy growing economy and the current international demand for iron ore and coal, in particular, there is a shortage of skills to support mining operations in Australia. On top of this, Australia does not have an extensive desalination industry and so there is a limit on the number of experienced operators. The significance of unavailability of skills in desalination has been demonstrated in stark terms in Kuwait where, during the invasion of 1990 maintenance was neglected, requiring a significant subsequent national effort to ensure security of water supplies (Dessouky *et al*., 1999; Falah *et al*., 2001). Significant effort expended in the Middle East (Genthner, 2001) and in Indonesia (Sunaryo et al., 2001) to minimize failures with training and R&D attest to the potential significance of desalination plant down time. We model the impact of skills shortage on raw water savings and frequency of discharge of worked water to estimate the importance of the issue to the site water balance.

A COUPLED WATER AND SALT BALANCE MODEL
We develop a discrete-time difference equation model for water and contaminant flow around a mine site. Water flow is driven by both volume requirements and salinity constraints. The model is a considerably simplified representation of a mine site. It consists of: (1) two water storage facilities, one for raw 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 users, which consume and discharge water of varying qualities; and (4) a desalination plant. Figure 1 illustrates the flow of water around the mine site model.

Water enters the system in one of three ways. Either as raw water which is sourced from a pipeline, aquifer inflows or rainwater captured on site. Rain water captured on site may be directed to either or both of the reservoirs. We define *RAW(t)* to be the total amount of raw water used by the mine in time period *t,* and $capture_x(t)$ to be the amount of water captured on site, where $X \in \{R = raw, D = worked\}$. It is also assumed that each reservoir intercepts rainwater directly.

Salt is introduced to the system as a constituent of each water inflow. It is represented as a concentration associated with each of the water flows. Salt can be removed from the water circulation system by being stored on/in roads/swales, exported in the coal product and lost in seepage.

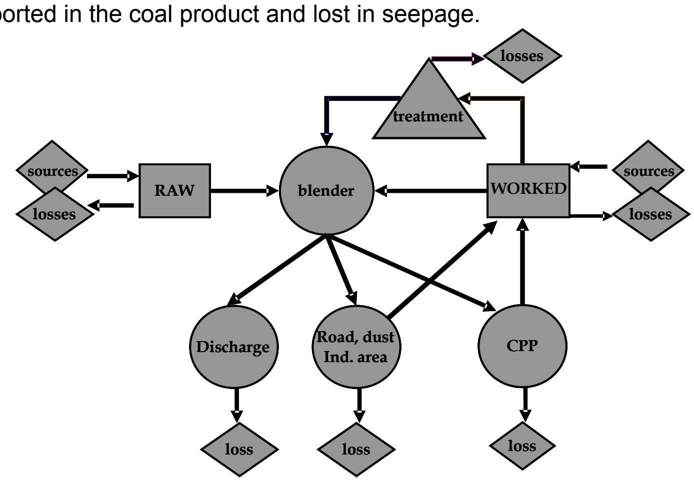

Figure 1. System diagram of a simple coupled salt and water balance model for a mine site (circles represent water using processes, rectangles are stores and diamonds losses and sources of water/salt).

Assumptions and constraints

We consider a system in which the maximum fluxes in connecting pipes, raw water intake, volume discharged and quality of water in the worked water reservoir are *not* constrained. The system is constrained by the volume requirements and concentration constraints on each user. We control the system by assuming our objective is to minimise raw water consumption. In this model, this is equivalent to maximising re-use of worked water or minimising discharge frequency.

In addition to that sourced from the pipeline, water is imported from intercepted rainfall and run-off captured on site. Implications of run-off include flushing of salt from spoil into water storages and transport of salt that has been sprayed onto roads when using worked water for dust suppression. In this model the user may specify the proportion of salt on roads that returns to the worked water reservoir (once a run-off threshold is exceeded). In the simulations reported below all salt is returned.

Mine site processes using water (the users)

We define $U_i(t)$ be the total volume of water required by user i for time period t. This water is comprised of a compulsory raw water requirement, $raw_i(t)$, and a component, $\mu_i(t)$, which is a mixture of raw, $mR_i(t)$, and worked, $mD_i(t)$, water. Each user imposes a quality constraint such that the salt concentration of the "non-compulsory" water is less than the maximum allowed by that user (MAX_i). That is,

$$[\mu_i(t)] = [U_i(t) - raw_i(t)] = [mR_i(t) + mD_i(t)], \qquad \leq MAX_i, \qquad (1)$$

where square brackets denote salt concentration. We denote water losses in user i by $L_i(t)$. Any water not lost from the system, $U_{out,i}(t) = U_i(t) - L_i(t)$, is directed to the worked water reservoir. In passing through a user salt may be added or subtracted from the water depending on the purpose of the user. Define $Y_i(t)$ to be the change in salt concentration between water entering and leaving user i.

User 0 - the coal preparation plant (CPP): We assume the amount of water required by the CPP at each time step to be constant, i.e. $U_0(t) = U_0$. We define CPP reuse as the amount of worked water used by the CPP resulting in maximising CPP reuse being equivalent to maximising $mD_0(t)$ such that Constraint 2 is satisfied. We also assume losses are constant over time, hence $U_{out,0}(t)$, the volume of water returned to the worked water reservoir from the CPP, is also constant but may vary in salinity. The CPP differs to other users as in addition to raw and worked water the CPP may also use treated water (see below). Consequently for the CPP Equation 1 is replaced by,

$$\mu_0(t) = U_0(t) - raw_0(t) \; = mR_0(t) + mD_0(t) + T_{out}(t), \qquad (2)$$

where $T_{out}(t)$ is the volume available for use from the treatment plant.

User 1 – Discharge: All water entering Discharge is lost from the system, that is, $L_1(t) = U_1(t)$ for all t. Hence, no water exiting the Discharge user enters the worked water reservoir, i.e., $U_{out,1}(t) = 0$, for all t. Water is only discharged when the worked water reservoir exceeds capacity. We assume that we can discharge as much water as is required as long as it satisfies discharge quality requirements. Consequently, to minimise discharge, we minimise $mD_1(t)$ subject to the constraint $VD(t+1) \leq VD_{MAX}$, where VD is the volume of the worked water reservoir.

User 2 – Roads: The third user represents water used for road watering for dust suppression and in the industrial area. As with Discharge, once water enters the user it is assumed to be lost from the system. That is, $L_2(t) = U_2(t)$ and $U_{out,2}(t) = 0$ for all t. In all other respects Roads behave very similarly to the CPP (user 0) in that $U_2(t) = U_2$ is constant over time.

Reservoirs

This model assumes two reservoirs for water storage. One for raw water, indexed as R, and one for worked water, indexed as D. Each Reservoir is assumed to be rectangular in shape with a fixed surface area. Water losses from each reservoir, denoted by LX where $X \in \{D, R\}$, are assumed to be of two types: evaporation, LX_{evap}, and seepage, LX_{seep}. We assume evaporation increases linearly with time until a critical volume is reached, and then becomes independent of volume but may still vary with time, allowing evaporation to be climate dependant. Let EVAP(t) be the maximum evaporation rate from a reservoir for time period t. We approximate evaporation by:

$$LX_{evap}(t) = \begin{cases} c(t) \cdot VX(t) & if \; VX(t) < VX_{critical} \\ EVAP(t) & if \; VX(t) \geq VX_{critical} \end{cases}, \qquad (3)$$

where c is a continuity constant given by $c(t) = \dfrac{EVAP(t)}{VX_{critical}}$. Seepage is approximated by the linear equation $LX_{seep}(t) = d \cdot VX(t)$, where d is the seepage rate.

Treatment

Treatment is introduced as a single desalination unit (with fixed treatment volume σ) situated between the worked water reservoir and the blender. We make a number of simplifying assumptions.

1. Treated water is only used in the CPP.
2. The decision to use treatment is made on a weekly basis.
3. Worked water is allocated to Roads before considering water available for treatment (or use in the CPP).

Define $T_{in}(t)$ to be the volume of water treated at each iteration, P_{brine} to be the percentage of treated water exported as brine and $T_{out}(t)$ to be the volume of treated water available for use. If treatment is employed then the volume treated is fixed, hence

$$T_{in}(t) = \begin{cases} \sigma & if \; treatment \; is \; employed, \\ 0 & otherwise. \end{cases}$$

Also note, $T_{out}(t) = T_{in}(t) \cdot (1 - P_{brine})$. Desalination is described as a percentage salt mass reduction in the water treated. That is,

$$[T_{out}](t) = \frac{(1-\rho) \cdot [VD(t)] \cdot T_{in}}{T_{out}}, \qquad (4)$$

where ρ is the mass reduction percentage. At each time step the treatment plant is employed if the following two conditions hold:

1. Worked water is too salty to be used directly in the CPP:

   $[VD(t)] > MAX_0$, and

2. The amount of raw water required if treatment is employed is less than or equal to that required if no treatment is employed:

$$mR_0(t) \le \tilde{m}R_0(t),$$

where $mR_0(t)$ and $\tilde{m}R_0(t)$ are the raw water requirements with and without treatment respectively. Note that Condition 2 implies that treatment will not be implemented if there is not enough worked water to be treated.

Water and salt balance

For each time period the system must satisfy a number of water balance equations. First, to ensure that the total amount of water entering and leaving the system balances, the system must satisfy

$$RAW(t) = LD_i(t) - ID(t) - T_{brine}(t) + \sum_i L_i(t) + \Delta VD(t+1)\,, \tag{5}$$

where $\Delta VD(t+1)$ is the change in volume of the worked water reservoir. (i.e., $\Delta VD(t+1) = VD(t+1) - VD(t)$), and $T_{brine}(t) = P_{brine} \cdot T_{in}(t)$. Each component must also satisfy an individual water balance equation:

Worked water reservoir:

$$\Delta VD(t) = ID(t) - T_{brine}(t) + \sum_i U_{out,i}(t) - LD(t) - \sum_i mD_i(t). \tag{6}$$

Raw water reservoir: $\Delta VR(t) = Pipeline(t) + IR(t) - LR(t) - \sum_i \left(raw_i(t) + mR_i(t)\right).$ (7)

CPP: $U_0(t) = raw_0(t) + mR_0(t) + mD_0(t) + T_{out}(t)$. (8)

Users 1&2: $U_i(t) = raw_i(t) + mR_i(t) + mD_i(t)$, for i =1,2. (9)

Blender: $\sum_i \left(raw_i(t) + mR_i(t) + mD_i(t) \right) = \sum_i U_i(t)$ for all *i*. (10)

Treatment Plant: $T_{out}(t) = T_{in}(t) \cdot \left(1 - P_{brine}\right)$. (11)

In addition to satisfying water balance equations, the model must also ensure salt mass balance is observed. That is, *salt mass in = salt mass out*. These equations are simply the above water balance equations with each volume multiplied by its concentration. For example, users 1 and 2 must satisfy the mass balance equation,

$$[U_i(t)] \cdot U_i(t) = [raw_i(t)] \cdot raw_i(t) + [mR_i(t)] \cdot mR_i(t) + [mR_i(t)] \cdot mD_i(t)\,.$$

Determining Concentrations

The following set of equations is used to calculate the concentration of the worked water reservoir; the water leaving the CPP; and the water entering each user respectively.

$$[VD(t+1)] = \frac{[U_{out,0}(t)] \cdot U_{out,0}(t) + [VD(t)] \cdot \left(VD(t) - LD_{seep}(t) - \sum_i mD_i(t) \right)}{VD(t+1)}\,;$$

$$[U_{out,0}(t)] = [U_0(t)] + Y_0\,;$$

$$[U_0(t)] = \frac{[mD(t)] \cdot mD_0(t) + [mR] \cdot (mR_{0i}(t) + raw_0(t)) + [T_{out}(t)] \cdot T_{out}(t)}{U_0(t)}\,;$$

$$[U_i(t)] = \frac{[mD(t)] \cdot mD_i(t) + [mR] \cdot mR_i(t)}{U_i(t)}\text{, for } i = 1,2. \tag{12}$$

Note that the raw water concentration, $[mR]$, is assumed to be constant over time.

Parameterisation

The model described above is driven for a duration that is determined by the rainfall sequence that is provided. The computational time step is daily with a weekly or monthly input climate sequence. Finer time scale data could be used if available. For the results below a 50 year precipitation record was used. Evaporation from reservoirs is computed using a pan factor of 0.7 (based on annual averages of local measurements) applied to each month, *i.e.,* evaporation is seasonally variable but with the same pan factor. Run-off is computed from rainfall data using an historical monthly regionalised rainfall run-off coefficient. It is expected that this will be a conservative estimate of run-off because the regional data are biased towards natural, more-or-less vegetated surfaces and our sites include some spoil and roads which are not vegetated. Given that most sites in the region harvest a relatively small amount of run-off into the reservoirs this error is considered acceptable for these broad system-level simulations.

Base information on water consumption and water inflows to the site was acquired from a number of mine sites in the Bowen Basin region in central Queensland Australia. All data presented below relate to a single mine site. The mine site is not identified by name to maintain confidentiality.

In essence, therefore, the model is being run as though calibrated. Rough testing for reasonable model behaviour was checked by comparing reservoir water levels and salinity concentrations. Whilst detailed validation data are sparse, to examine the system behaviour under a number of scenario conditions, it was felt that "reasonable behaviour" was sufficient. No specific management advice should be interpreted from the model outputs. Rather, differences in system behaviour associated with each of the scenarios examined could be used to guide detailed investigations of water management options that appear prospective for improving water management.

DESIGN MODEL SIMULATIONS

This region is currently experiencing water shortages which threaten current mining operations and limit planned and announced expansions. Therefore, the industry is interested in exploring options which might reduce the amount of water required from the pipeline. Three main issues are being discussed (here posed as questions):

1. How much raw water might be saved by increasing water reuse?
2. Would the introduction of site-based desalination plants make a significant difference?
3. Does the current lack of experience or ready availability of skills with managing desalination compromise the case for desalination?

We designed a number of model scenarios to examine these questions. Central to our approach is the mode described above. It can be misleading to assess the gross savings of water associated with a particular practice unless it is related back to the water management system as a whole (Parikh, 1986).

Water reuse was modelled by first using worked water for dust suppression on roads and the industrial area. Then any worked water remaining was gradually used as make-up water to the CPP by increasing step-wise the salinity tolerance acceptable in the CPP. Desalination was then examined by introducing water treatment between the worked water reservoir and the CPP. Consider installing a treatment plant which treats N ML of worked water per month. Based on published data, we assumed 3% of water is with the concentrated brine, and that treatment reduced the mass of salt in the water by 95%.

The skills shortage was studied by assuming that lack of skills would result in failure of the water treatment plant and/or the blender infrastructure. We incorporated the skill level of the treatment plant operator(s) by introducing stochastic treatment failure as a function of the skill level of the operator. We assumed that a particular skill level, ø, corresponds to the treatment plant failing in a given time step with probability p=ø. We further assumed that once the treatment plant was broken, it was fixed in the next time step with probability (1-p).We gradually increased ø to estimate how much of the potential savings of raw water might be lost through infrastructure down time. For the case of treatment failure, the blending infrastructure remains functional. For Blender failure, raw water only is used. Except in the case of the CPP, where blender failure is only obstructs worked water use, not the ability to use treated water. Depending on the construction of the infrastructure, this may or may not be a reasonable assumption. We further assume that each user has independent blender infrastructure which is independently subject to failure.

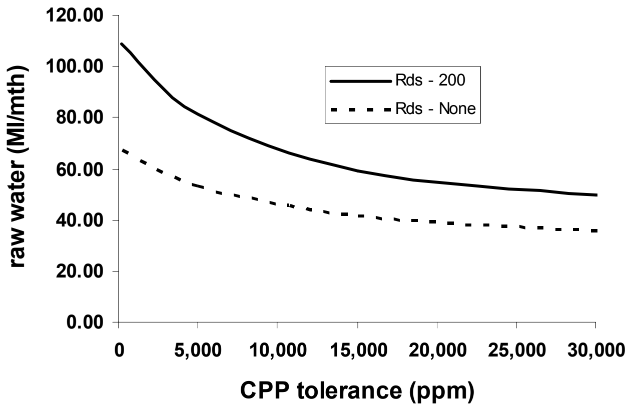

Figure 2. Raw water use with increasing salt tolerance in CPP for the case of no salt constraint for road water watering and raw water (200ppm) required for road watering.

RESULTS

Water Reuse

Figure 2 shows that there is significant scope for raw water savings by reuse of worked water on roads and in the CPP. The broken line indicates the potential raw water savings if roads are watered with raw water. The biggest gains in raw water savings are up to a CPP tolerance of ~15,000ppm. This is even more pronounced when worked water is used on roads (broken line). By ~15,000ppm there is little additional advantage in increased reuse, in this case because there is insufficient water to treat.

Desalination

In Figure 3 the effect of implementation of desalination is shown for a range of CPP salt tolerances and for a range of desalination intensities. It appears that, for this site, desalination is an effective way to reduce raw water consumption when treating up to ~0.7 Ml/d. After this point there is negligible return because there is insufficient water to treat. If considering total costs, it should also be borne in mind that the additional plant maintenance costs associated with higher salt tolerance also militate against further desalination.

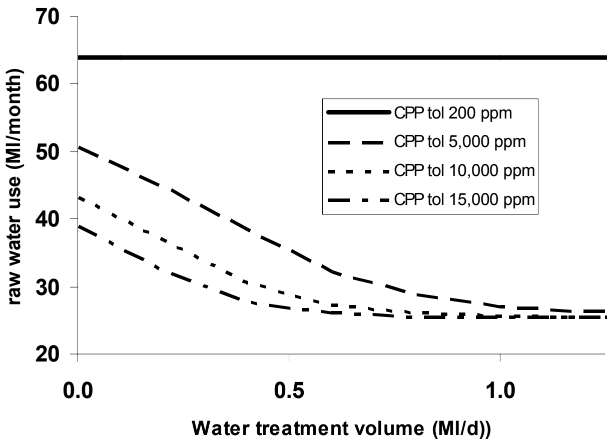

Figure 3. Raw water use with increasing water desalination volume, for a range of CPP salt tolerances.

Skills

We consider four levels of treatment: Minimum (0.2 ML/d), Low (0.5 ML/d), Medium (0.7 ML/d) and High (1 ML/d). Medium is the (approximate) lowest level of treatment which guarantees no discharges over a 50 year period when the treatment plant is fully operational. For amounts of treatment greater than this, we then find the minimum amount of treatment failure allowable before discharges begin to occur. We can equate this minimum probability of treatment failure with a minimum skill level required to avoid discharge.

Figure 4 demonstrates that failure of a treatment plant that is operating at the limit to avoid discharges from the worked reservoir begins to cost more in raw water and in discharge with only a small compromise to 100% operation. To ensure robustness, treatment at ~1 Ml/d would maintain minimum discharge and would not compromise raw water savings below ~20% failure rate – which should be achievable.

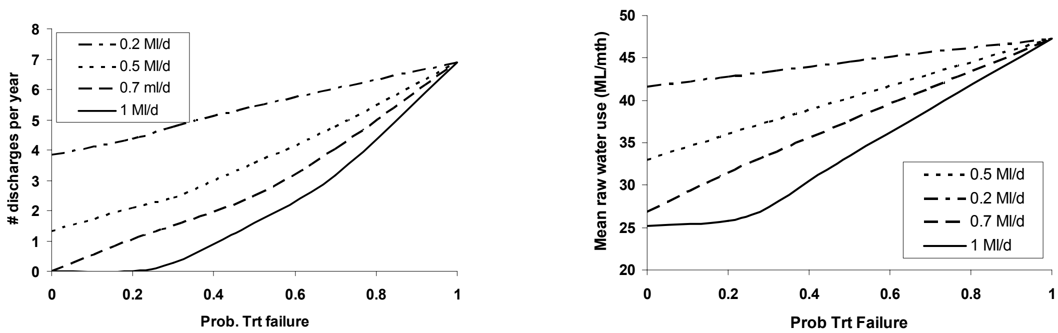

Figure 4. The effect of failure of desalination treatment on discharge (left) and mean raw water use (right) from the worked water reservoir as a function of the treatment intensity.

Figure 5 indicates that, with desalination at 0.6 Ml/d, failure of the blender infrastructure (see above for details of this) would have a greater impact on expected raw water savings than treatment failure. However, raw water savings up to ~20% failure are only modestly compromised even if both blender and treatment plant fail. Under these conditions it appears that increased frequency of discharge is a greater threat to operations than the loss of raw water savings through blender failure. Therefore, it would appear that ensuring that the treatment is of sufficient capacity and does not often fail is, perhaps, the greater priority.

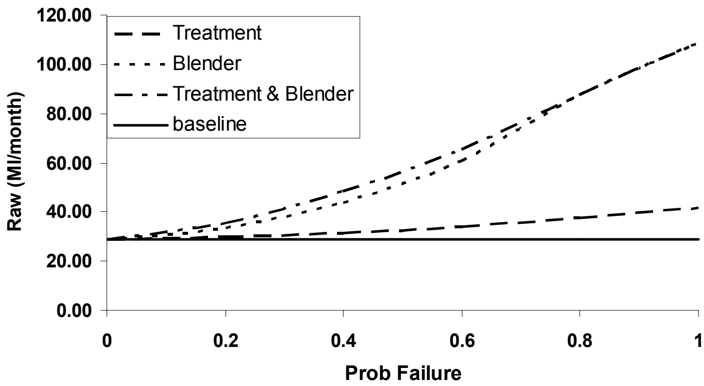

Figure 5. The effect of blender failure compared to treatment failure (treatment is 0.6 Ml/d).

DISCUSSION

The initial model outputs above would indicate that there is significant potential for savings of raw water. For sites not using worked water for dust suppression this would appear to be a relatively simple option. Implementation requires pipe and pump infrastructure with which site staff are well acquainted from pit dewatering and tailings management activities. One issue requiring careful consideration is the assumption that there is no run-off from the roads across the lease boundary. If run-off were to occur and salt was transported into surrounding and/or downstream ecosystems then this could be in contravention of the site operating license and become problematic from sustainable development and environmental regulation perspectives. Currently, in this region, there is no instrument to consider the potential trade-off between the impacts caused by harvesting the raw water and the risk of off-site salt transport. Involvement of government in policy formulation to assit with such initiatives is well documented (*e.g.*, Hilson, 2000). Therefore, dust suppression on roads using worked water requires additional vigilance that roads are internally draining within the lease boundary.

The second avenue for raw water savings is to use worked water as make-up water in the CPP. For the site studied, tailings return water is already used in the CPP which also includes a thickener/clarifier system. Therefore, the make-up water is only a modest component of the total water in circulation within the CPP. A number of sites in this region, which have moved to worked water make-up, have realised an advantage in that there has been a reduction in requirement for flotation reagent. However, some performance issues have been experienced with flotation, filtration and flocculation which are being investigated and may have to do with the nature of the salts rather than the ionic concentration alone. It is also accepted that plants using saltier water incur greater maintenance costs. This is being dealt with by gradually replacing corroded parts with more resistant materials. However, a cost does exist.

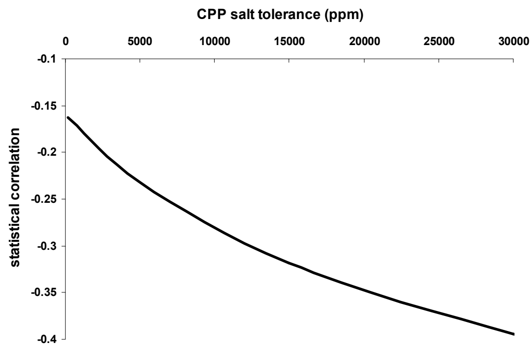

Figure 6. Correlation between climate (precipitation) and level of water reuse.

A complication, which is somewhat less easily dealt with, is the increased attention required for water management. As mentioned above, performance issues must be monitored to minimize expensive downtime (which can also consume significant quantities of raw water, to flush the plant that had apparently, been saved). As acceptable CPP salt tolerance increases, the site water system becomes gradually more closely coupled to the climate. This is indicated in Figure 6 by the increasing (negative) statistical correlation between precipitation and raw water demand as the tolerance increases. In a region of large rainfall temporal variability this is an unfortunate downside of saving the raw water and, again, requires increased vigilance to avoid running dry and allowing excess water accumulation to result in discharge events.

Our analysis of desalination can be simply converted into a cost. This has not been done here because of current (in this case unhelpful) debates about actual operating costs of desalination plants on coal mines. However, it is also worth noting that an economic analysis should also include the likely additional costs of workforce (or contractors), brine disposal and, critically, corrosion of plant and equipment (recall that salt on roads will also impact vehicle maintenance schedules). These costs should be considered in terms of the additional value that can be generated from the raw water made available rather then compared to the cost of access and delivery of the raw water. This argument holds when water scarcity threatens production or expansion or when company imperatives for meeting sustainable development goals outweigh the site costs.

CONCLUSIÓN

We conclude that use of worked water on roads for dust suppression and as make-up water in the CPP can save considerable quantities of raw water. Implementation of onsite desalination can further reduce raw water demands. The economics of desalination require a full analysis of the costs and benefits which include the value that the raw water might generate elsewhere in the business. Raw water savings can be partly jeopardized because of failure of infrastructure due to lack of skilled workers. However, the raw water losses would appear to be acceptable up to ~20% downtime. Saving raw water in these ways requires that water management is paid more attention to avoid potential problems associated with site drainage design and maintenance, corrosion, desalination plant operation and increased risk of water security associated with more reliance on weather/climate.

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