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A process-based simulation model for strategic mine water management

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Abstract: Substantial expansion of the mining sector in Australia has resulted in increasing demand for freshwater. The increasing demand is set within the background of augmenting water allocations to environmental flows and changing climate. Such situations have forced the mining sector to improve its water resource management. Scientific tools are urgently needed to predict outcomes from new management options that affect water supply security, water use efficiency, water use cost, and risks associated with discharges.

We present a new system model that integrates a water use process for assessing complicated mine water use strategies. The operation rules of mine water management strategies can be placed on model objects and process states. Its implementation follows the water accounting framework for the minerals industry.

A case study in the Bowen Basin in Queensland, Australia is included to illustrate the benefits of such a model, and a set of mine water use strategies are also assessed and compared. The results show that a process-based model is an appropriate tool to provide guidance on improving mine water use management.

Keywords: *mine water management, modelling mine water use, water strategy evaluation, water resources management, mining*

1. INTRODUCTION

The mining industries in Australia are going through a rapid expansion era. The substantial expansion of mining projects has resulted in an increasing demand for freshwater. In Australia, the competition for water among water use sectors is intensifying, especially when surface water and groundwater are already highly allocated (Gao et al., 2013). Such situations have placed an obligation on the mining sector to secure water use for mineral production through improving mine water management strategies. However, applying alternative strategies requires water resource managers to weigh carefully trade-offs among a variety of outcomes. This process becomes even more challenging when resource managers do not have access to scientific tools to assess the impacts of alternative management actions (Gao and Hailu, 2013).

Mine water managers used to rely on traditional engineering models for their decision making process. However, these models are not designed to assess water management strategies. Recently, focusing on the whole system, Côte *et al.* (2010) built a system model called SiteMiser for evaluating mine water management performance. The model abstracts a mine water system as a few water entities: a worked water store, a raw water store, several water tasks, a blending facility, and a treatment plant. However, due to the lack of water use details, SiteMiser cannot be used to evaluate complicated water management strategies between worked and raw water stores, which is important to improve efficiencies in mine water use. Another shortcoming of SiteMiser is its implementation does not follow object-oriented paradigm so that it is hard to integrate it with other software capabilities.

This paper proposes a new system model that includes a water use process for mine water management strategy evaluation. The operation rules of mine water management strategies can be placed on model objects and process states. We developed the system model by following an object-oriented programming paradigm and the water accounting framework for minerals industry (Sustainable Minerals Institute, 2012). The rest of paper is organized as follows. Section 2 introduces the architecture of the proposed system model. A coal mine is used as a case study in Section 3. Results from the case study are presented in Section 4. The final section concludes the paper.

2. ARCHITECTURE

In the object-oriented architecture, one *Region* object includes one or more *Site* objects. Each *Site* object has a few sub-objects, such as *WaterStore*, *WaterTask*, *TreatmentPlant*, *WaterInput*, and *WaterOutput*. These sub-objects are the five basic elements in the water system concept model for accounting purposes (Sustainable Minerals Institute, 2012). These sub-objects can be linked together through a model object called *WaterFlow* that stands for water fluxes and contains water quantity and quality values. *WaterStore* is a facility object, representing a water storage on site. Every water store, such as *RawWaterStore*, *WorkedWaterStore*, and *TailingStore*, must inherit from *WaterStore*. *WaterTask* represents a kind of activities that consume water for a particular purpose. *TreatmentPlant* is a facility object that stands for a treatment on the site for improving water quality. *WaterInput* and *WaterOutput* objects are water inputs to the site from external sources and water outputs to external destinations from the site, respectively. Some of the five basic objects are mutually coupled, for example a *WaterStore* object associates multiple *WaterInput* objects and *WaterOutput* objects. The base objects can be used to implement complex model objects.

To enable the system model to explore complex water use strategies, a process of water use is incorporated. The pseudo-code for mine water use process is described in Table 1. The process begins with reading climate time series data and the information of model objects. Then model objects are created, parameterized, and connected in terms of the predefined topology information. The default simulation time step is daily step, but it can be reset to weekly or monthly step with minor modifications. The system model firstly updates water quantity and quality caused by flow exchange between exteriors and water stores. Then it examines whether the stores exceed their storage limits and determines whether a discharge occurs. Next, water demands for all water tasks are calculated and a water extraction schedule is created for different priority water use. Before extracting water, both water quantity and quality in stores are examined. If there is not enough water in stores, a failure record will be created in the simulation logbook. In terms of water quality, a treatment (such as desalination, dilution, or both) method can be used to produce acceptable water. If water cannot be accepted by water tasks even though the treatment approach is employed, a failure record will be added. If no failure record is created, water tasks are able to extract water from stores and consume it. Finally, water returns to worked water stores are calculated and water quantity and quality in worked water stores are updated. A success record is added to the simulation logbook once a daily operation is successful. If the simulation termination conditions are not met, another daily step starts.

Table 1. Pseudo-code for mine water use process.

Algorithm 1: Mine water use process

```
Initialize a Region object R with n Site objects
For each Site object i in R
    Read local rainfall sequence
    Create sub-objects and set object parameters
    Connect sub-objects
End For
Connect Site objects
While the simulation termination conditions are not met
    Calculate water gain and loss in water stores
    If (salt returns from roads to water stores with a rainfall event)
        Update water quality in stores
    End If
    If (storage exceeds)
        Discharge
    End If
    Calculate water demands of all tasks
    If (not enough water for extraction)
        Report a failure to the logbook
    Else
        If (water quality is satisfied)
            Extract water from water stores
        Else
            If (a treatment is employed to obtain acceptable water)
                Extract water from water stores
                Treat water in a treatment plan
            Else
                Send a failure report to the logbook
            End If
        End If
    End If
    Water tasks consume water
    Calculate water loss and return to worked water stores
    Update worked water quantity and quality
    Send a success report to the logbook
End While
```

3. CASE STUDY

We used the process-based model to simulate water management options in a large open-cut coking coal mine in Queensland, Australia. The water uses in the case study mine site are aggregated to three water tasks: coal handling and preparation plant (CHPP), dust suppression, and underground operations. In addition to the water tasks, the system model still includes a worked water store, a raw water store, and a desalination plant. The related data of this case study mine is reported by Côte *et al.* (2008) as mine 3.

Next, we introduce how a series of simulation experiments are conducted to assess the impacts of different water use strategies between raw and worked water stores. We first built a *baseline* or "business-as-usual" strategy in which the model is calibrated against measured data presented in the literature (Côte et al., 2008). The model is calibrated with the input climate data during the period from 1st July 1977 to 30th June 2007, which is determined according to the fact that some indicators available for calibration are reported during the period. The model is calibrated against a bunch of objectives and the calibration performances is shown in Table 2.

Table 2. Calibration performance of mine site 3.

Calibration objective	Reported	Calibrated	Relative error
Failure rate	0	0	0
CHPP supply (ML/Mt)	777.478	777.478	0
CHPP raw water proportion	0.41	0.41	0
CHPP loss (ML/Mt)	461.714	461.714	0
Dust suppression supply (ML/Mt)	155.073	155.073	0
Dust suppression raw water proportion	1	1	0
Underground supply (ML/Mt)	15.0723	15.0723	0
Underground loss (ML/Mt)	0	0	0
Median Worked Water Reservoir % Full	30	30	0
Mean salt concentration	4843	4843	0
Discharge (ML/Mt)	0	0	0

Based on the parameter setting in the *baseline* strategy, we designed six water use strategies as follows.

(1) *Worked-first*: This strategy first consumes water in the worked water store and only after using up water in the store, the water in the raw water store can be used. A failure message will be sent to the simulation logbook if supplied water is not acceptable. (2) *Worked-first-plus-desalination*: This strategy adds a desalination plant to the *worked-first* strategy. The unacceptable worked water can be considered to go through a desalination treatment. (3) *One-store*: In this strategy, if water in the worked water store is not acceptable, one can use water in the raw water store. The water is either from the worked water store or the raw water store. This strategy does not use mixed water from the two water stores. (4) *One-store-plus-desalination*: A desalination plant is added to the *one-store* strategy. If the water quality is not acceptable, a desalination treatment can be applied. (5) *Optimal-mixture*: This strategy aims to optimal water mixture between the worked and the raw water stores through minimising water use cost. The optimisation is subject to acceptable water quantity and quality and water availability in the two stores. (6) *Optimal-mixture-desalination*: A desalination plant is added to the *optimal-mixture* strategy. Thus, the optimal water allocation is expected among worked water, desalination water, and raw water. The desalination capacity is also considered as one of constrains in the optimisation.

4. RESULTS AND DISCUSSION

This section presents the simulation results from the baseline and the above six strategies. Four indicators are proposed to assess the seven strategies. The first indicator is failure rate of supplying acceptable water, which represents how many times a water use strategy cannot supply acceptable water required by a water task against total demand times. The other three indicators are water use cost, the amount of raw water use, and unregulated discharge per unit coal production. The unregulated discharge here refers to the overflow from the worked water store. Table 3 shows the four indicators under the seven strategies. The simulation experiments cover a period from 1st July 2008 to 30th June 2012.

Table 3. Performance indicators of the seven mine water management strategies.

Strategy Name	Failure rate	Cost ($M/Mt)	Raw water use (ML/Mt)	Unregulated discharge (ML/Mt)
Baseline	0	0.823	481	0
Worked-first	42%	0.139	15	0
Worked-first-plus-desalination	33%	0.146	15	0
One-store	1%	0.509	275	0
One-store-plus-desalination	0	0.425	211	0
Optimal-mixture	0	0.202	57	0
Optimal-mixture-desalination	0	0.200	44	0

As shown in Table 3, *worked-first*, *worked-first-plus-desalination*, and *one-store* strategies lead to supply failures. At more than one third of simulation time, in two *worked-first* strategies, the water quality in the worked store is not accepted by water tasks, even if after a treatment process (in the *worked-first-plus-desalination* strategy). The *one-store* strategy also results in a small failure rate due to the fact that stored raw water is nearly used up and at the time stored worked water is not acceptable. However, this situation can be addressed by employing a desalination plant. Here, we only consider the water use cost as a sum of raw water supply cost, desalination cost, and CHPP maintain cost. Since the economic penalty of supply failure is not considered in this study, the two *worked-first* strategies lead to the minimum cost when producing one unit of coal product. The *baseline* strategy performs the worst in terms of water use cost due to its neglect of reducing unnecessary raw water use. The two *one-store* strategies outperform the *baseline* strategy in both decreasing raw water use and water use cost. Ensuring water supply security, the two optimisation strategies (*optimal-mixture* and *optimal-mixture-desalination* strategies) perform the best among all strategies. Compared with the *baseline* strategy, they save more than 75% of the water use cost and 88% of the raw water use when producing a unit of coal product. Also, they are able to avoid production losses caused by unacceptable water supply. The *optimal-mixture-desalination* strategy requires less raw water than the *optimal-mixture* strategy. The seven strategies do not result in any unregulated discharge and this is also proven by storage adequacies under these strategies, as shown in Figure 1.

Figure 1 presents the storage adequacy and water quality (salt concentration) dynamics of the worked water store for the seven management strategies. Figure 1(a) demonstrates a visual assessment of the probability that the worked water volume will exceed a certain proportion of the storage capacity. Figure 1(b) shows the changes in salt concentration of worked water for the seven water use strategies.

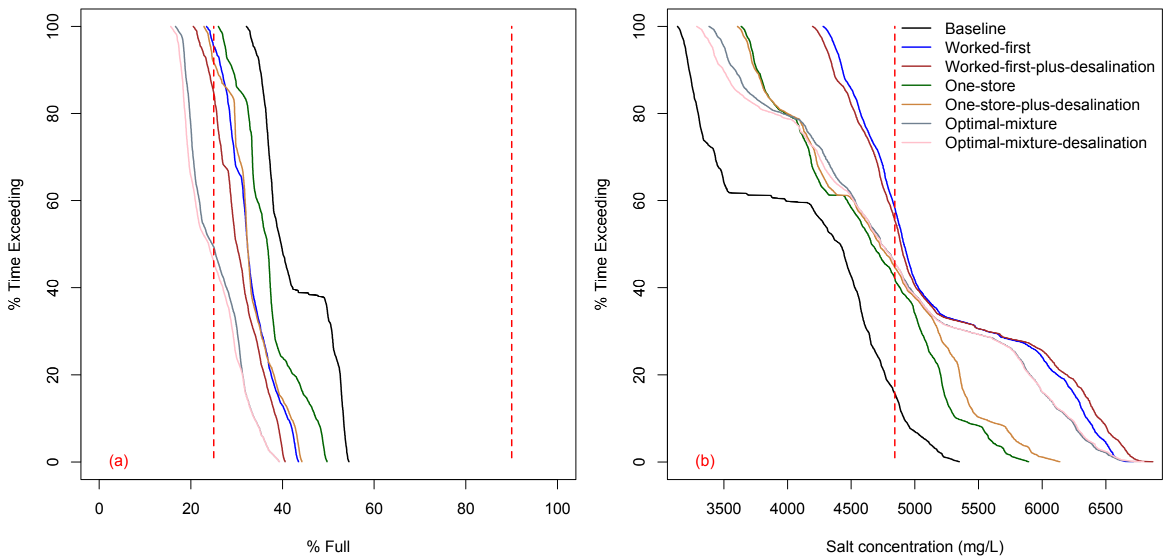

Figure 1. (a) Store exceedance curves and (b) salt concentration dynamics curves in the worked water store.

As shown in Figure 1(a), over all simulation time, the least store adequacies for the seven strategies range from15% to 35%. We selected 25% full of the storage capacity as a dryness indicator and 90% full as a wetness indicator. All simulated storage capacities are around the dryness indicator and can be grouped to "dry" category. In the *baseline* strategy, the store level is frequently higher than those in the other strategies. It proves that the *baseline* strategy consumes more raw water to secure water supply for coal production. The optimisation strategies consume more worked water, and in them, the store is less than 25% about 50% of the time. Although the two strategies provide satisfactory water supply during the simulation period with lower costs and raw water use, the worked store under them is experiencing a higher risk of running out the water.

In terms of salt concentration dynamics, the concentration in the *baseline* strategy is below the reported mean value (4843 mg/L) more than 80% of the simulation time. This is because the simulation period (1st July 2008 to 30th June 2012) has more large rainfall events per year than the calibration period from 1st July 1977 to 30th June 2007. While salt concentrations in those strategies without supply failure rates, are more than the reported mean value more than 50% of the time. This is because the four strategies consume more worked water and less raw water, so the returned water to the worked water store contains more salts, in turn, results in higher salt concentration of worked water.

5. CONCLUSIONS

This study provides the structure of a process-based model for simulating mine water use and evaluating water management strategies. An application of the system model in a open-cut coal mine demonstrates that mine water management can be based on water use process-based simulation that reflects the trade-offs among multiple management objectives, such as water security for production, water use cost, raw water use per unit of product, and unregulated discharge. There is little substitute for good scientific modeling and simulation in designing good strategies for managing complex mine water system. Future work includes encapsulating such a mine site-scale simulation model as an agent (Gao et al., 2012; Gao and Hailu, 2012), and then build a worked water trading market (Gao et al., 2013) for exploring mine water management strategies at a basin scale.

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