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Systems modelling for effective mine water management

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ABSTRACT

Concerns about the difficulties in securing water have led the Australian coal mining industry to seek innovative ways to improve its water management and to adopt novel strategies that will lead to less water being used and more water being reused. Simulation tools are essential to assess current water management performance and to predict the efficiency of potential strategies. As water systems on coal mines are complex and consist of various inter-connected elements, a systems approach was selected, which views mine site water management as a system that obtains water from various sources (surface, groundwater), provides sufficient water of suitable quality to the mining tasks (coal beneficiation, dust suppression, underground operations) and maintains environmental performance. In this paper, the model is described and its calibration is illustrated. The results of applying the model for the comparison of the water balances of 7 coal mines in the northern Bowen Basin (Queensland, Australia) are presented. The model is used to assess the impact of applying specific water management strategies. Results show that a simple systems model is an appropriate tool for assessing site performance, for providing guidance to improve performance through strategic planning, and for guiding adoption of site objectives.

1. Introduction

The mining industry is a significant contributor to the Australian economy, representing almost 10% of the country's economic activity and around a third of all export income (Hooke, 2007). Water is integral to virtually all mining activities and access to secure water supplies is crucial to mining production. The Bowen Basin (Queensland, Australia), one of the world's important coking coal mining regions, recently experienced a prolonged regional drought that coincided with a significant rate of growth in production. It was facing difficulties in securing water supplies that could not be entirely solved through the traditional approach of developing regional water infrastructure. The drought also led the Australian coal mining industry to recognise that there was scope for improving water management.

A coal mine can consist of open-cut operations (where the coal seam is located relatively near the surface and coal can be extracted following removal of the overlying rock), underground operations (where the overlying rock is left in place and the coal removed through shafts or tunnels) or both types of operations on the same site. Many coal mines have a coal handling and preparation plant (CHPP) on site. Water is used in the CHPP (if present), for dust suppression, vehicle wash down and potable uses. Dust suppression is needed in pits, on roads and in industrial areas.

With severe droughts imposing on the mines to reduce their consumption of fresh water, alternative water sources have been sought, such as worked water, which in this paper is defined as water that has been involved in a task or has passed over (or through) an area disturbed by the mining processes. It includes runoff intercepted by mining pits, groundwater inflows, wash down residuals, and output from the various tasks, such as the water that has been used in the coal preparation plant. Some of the issues that arise from the increase in worked water use are related to water quality management, and more particularly increases in salt concentration. Worked water can potentially be used for all tasks on open-cut mines, but in practice there is a great deal of variation in the tasks to which worked water is applied. A barrier to increasing worked water use is a lack of information on its impacts. There is a requirement to balance the corrosion costs associated with using worked water with the costs of water treatment (essentially desalination) and/or importing more fresh water. For underground mining, only fresh water is used to protect the health and safety of miners and to minimise corrosion of underground equipment (Cote et al., 2007).

Sufficient water supply must be available, as production cannot proceed if there is no water available for dust suppression, the CHPP and underground operations. In addition, any water that has been contaminated through contact with disturbed areas must be stored appropriately and can only be discharged to the surrounding

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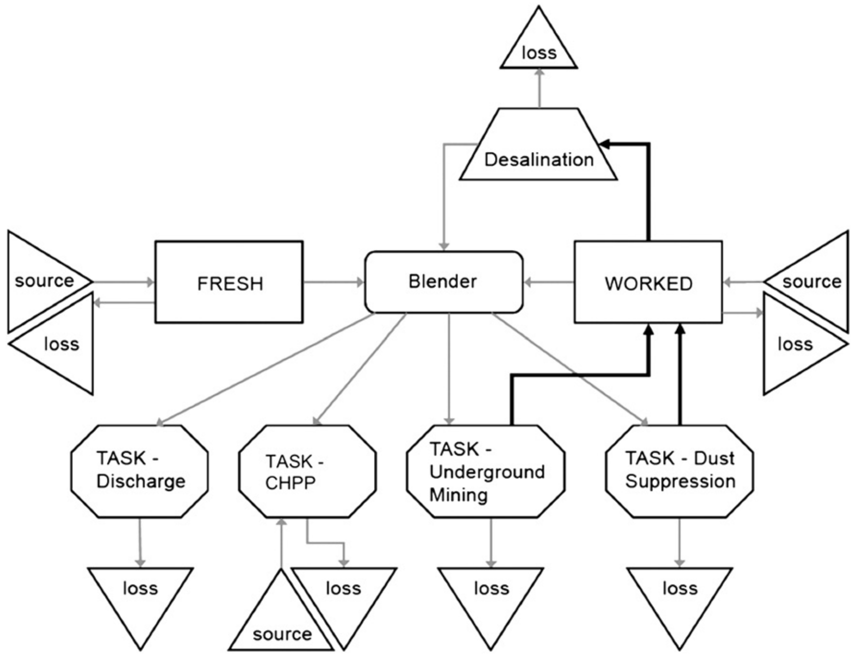

Fig. 1. System diagram of a simplified coupled salt and water balance model for a coal mine (Cote et al., 2007).

environment if it meets specific criteria, usually expressed in the form of a discharge license (Barger, 2006).

The engineered water circuit comprises collection, storage, distribution, losses and release. Water is collected from a range of sources, which often includes an allocation of fresh water, delivered via specific infrastructure such as a dedicated pipeline. Additional sources of water may be on-site runoff capture and aquifer inflows. Water is stored on-site in purpose-built dams and in the pits from where mining has ceased. Large coal mines can have a complex network of water stores. For instance, one of the mines that participated in this study had 8 storage dams and 10 old mining pits that were used for water storage, and a complex infrastructure network to transfer water among all these elements. Water quality in these storages can vary widely depending on the type of water that is collected (e.g. fresh water, runoff capture, worked water) and the condition of the medium through which it is collected.

We define an effective coal mine water management system as one that: (1) meets operational constraints, such as avoiding production losses due to water shortages and abiding by discharge license requirements, (2) maintains worked water at appropriate salt concentrations and (3) adopts novel strategies that will lead to less water being used and more water being recycled. These three elements constitute what Checkland (1981) terms the root definition of a system and this term is adopted here when referring to these elements.

As water circuits on coal mines can be complex, simulation tools are essential to assess how well a coal mine water system performs with respect to the root definition and to predict the efficiency of various management strategies. Currently, the modelling techniques that prevail in the field of mine water analysis are anchored in process-based approaches (Jakeman et al., 2006). They aim at studying in detail one isolated aspect of mining and water interactions: the impact of mining on groundwater (Younger et al., 2002) and on acid mine drainage (Banks et al., 1997; Liang and Thomson, 2009; Mayer et al., 2003; Younger, 2000); water balance modelling (Bru et al., 2008) or hydrochemical modelling (Schwartz et al., 2006) of tailings dams, where fine waste is stored; or the design of mine water dams using industry-accepted hydrological softwares (Laurenson and Mein, 1990; WP Software, 1994). None of these detailed approaches can be used to assess the performance of a mine water system and increasingly, mining companies rely on consulting engineers to develop operational models. There are as many types of these engineering models as there are consulting companies, but they are similar in structure. They represent all catchments, storages, reticulation and pumps, along with the operational rules that dictate transport rates in the distribution system. An example of such model is described in McIntosh and Merritt (2003) with runoff calculated with the Australian water balance model (Boughton, 2004).

This type of model is essential for day-to-day operations as it can provide mine management with risk-based guidelines for both securing and containing mine water inventories (McIntosh and Merritt, 2003). It can also be used for detailed planning of major changes to the site and feasibility analysis for new projects (McIntosh and Merritt, 2006). However, their structure is not well adapted to assess the performance of the water management system as it includes elements that are not meaningful at this strategic level of interest whilst it excludes elements that form part of the root definition. For instance, the maximum pumping capacity that is available to move water from one storage to another does not impact on the overall status of water stocks and thus is not meaningful to assess whether sufficient supply will be available for the life of the operation. Conversely, the salt concentration of water stored in one pit may not impact on daily water movement, but can

Table 1
Rainfall to runoff coefficients.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall/runoff coefficient	0.195	0.245	0.136	0.044	0.03	0.023	0.020	0.006	0.012	0.057	0.100	0.132

Table 2
Adopted salt return thresholds.

Location	Moranbah	Collinsville	Blackwater	Emerald	Average
Salt return threshold (mm/month)	110	129	106	105	112.5
Average daily salt return threshold (mm/day)	3.6	4.2	3.5	3.4	3.7

greatly influence the long-term sustainability of a water management strategy, which is why water quality is clearly outlined in the root definition. Another issue is that these engineering models focus on the description of water transfers but do not explicitly represent the water tasks, so that the feedback mechanisms that link the water tasks with the water stocks are not clearly identified. There is a requirement for a tool that emphasises the whole system with consideration of the main interactions, feedbacks, and functional relationships between the various parts of the whole system, without unnecessary detail.

2. Materials and methods

2.1. Development of systems model

A systems model in agreement with the root definition provided in the previous section was developed. This model is a simplified systems representation of a coal mine water circuit to assist with assessing water management performance and understanding the implications of implementing specific water management practices. It 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, which import and export water of varying and potentially constrained qualities; and (4) a desalination plant. Fig. 1 illustrates the flow of water around the mine site model.

All storages present on site are represented as two stores, characterised by the quality of the water they contain (fresh or worked). This follows from the important feature that the storage property at the scale of interest (overall water stock) arises from the interaction of the vast number of storages at the lower (engineering) level. Water enters the system either as fresh water (pipeline water from a regional water supply scheme for example), aquifer inflows or rainwater captured on site. Aquifer inflows and rainwater capture may be directed to either or both of the reservoirs. Salt is introduced to the system via each water inflow, and is represented as a concentration. 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. All water tasks are represented. The feedback mechanism related to water quantity is represented by way of rules for the fresh water reservoir, with two options: simulation of fixed volumes of fresh water being delivered or as an as-needed basis, when the water level in the fresh water store drops below a certain threshold level, selected by the model user. The feedback mechanism related to water quality is represented through use of a salt tolerance that can be set at the water intake to any task. This is described in detail in Cote et al. (2007). Water management strategies can be simulated by varying storage capacities, water imports, fraction of worked and fresh water at the intake of any task, and salt tolerances.

2.1.1. Climate

The simulation model is driven for a duration that is determined by the rainfall and pan-evaporation time-series that are provided by the user. The computational time step is daily but the model will accept daily, weekly or monthly rainfall data, and the simulations presented here used monthly rainfall data. The time step for the pan-evaporation sequence is monthly. The daily rainfall and evaporation are calculated as monthly values divided by the number of days in a given month. Evaporation from the reservoirs is computed by multiplying pan-evaporation values by a factor of 0.75, based on annual averages of local measurements.

Table 4
Salt exchange parameters.

Parameter	Unit	Value
Intercept of salt exchange function	mg/L	668.00
Slope of salt exchange function	–	−0.2696
Concentration at which salt exchange becomes constant	mg/L	15 000

2.1.2. Rainfall/runoff calculations

Runoff is computed from rainfall data using monthly values of a volumetric rainfall/runoff coefficient (Table 1), which were derived through analysis of historical values derived from regional data (Eastgate et al., 1979). For the areas which are not vegetated and where land has been disturbed (e.g. spoil, roads), this assumption yields too conservative an estimate of runoff because the regional data were biased towards natural, more-or-less vegetated surfaces. To obtain more realistic values of runoff volumes:

- The proportion of disturbed land in the catchment of each storage was computed;
- The runoff volumes generated by rainfall falling on disturbed land were calculated using the monthly regionalised rainfall runoff coefficients increased by 50% to account for the lack of vegetation; this was based on the analysis of runoff predictions from AWBM (Boughton, 2004) embedded in the engineering reports that were supplied for this study. These reports are confidential but a general description of the engineering models is available (McIntosh and Merritt, 2003, 2006).
- It was recognised, however, that not all the generated runoff would be captured by the reservoirs on disturbed land. Some water that does not infiltrate can be temporarily stored in surface depressions and microtopography from which it evaporates. A factor was introduced to account for this additional evaporation (referred to as "additional evaporation loss factor" – ADELOF), and it was calibrated on a site basis when sufficient data were available. The importance of accounting for depressional storage for runoff estimation has been known for many years (Hairsine et al., 1992). This is likely to be more important than in agriculture because of the large surface roughness and the possibility of storage at a larger spatial scale.

With the system approach, we tried to strike an appropriate balance between the required level of complexity in the model structure, the available data, and the purpose of the model, and thus tried to minimise the number of parameters that required calibration. With these runoff calculations, only one parameter had to be calibrated, which is in line with the fact that very little data was available for calibration.

2.1.3. Salt return to the worked water reservoir

Runoff from the road is collected and directed to the worked water reservoir. This runoff usually contains salt, as the water that is applied for dust suppression also usually contains salt. When the applied water evaporates, the salt is left behind to accumulate on the roads and to be flushed by the next rainfall event. Mine sites have provided the following information regarding road runoff:

- When rainfall occurs on a wet road, runoff can be collected if there is at least 25 mm of rainfall over 24 h.
- When rainfall occurs on a dry road, runoff can be collected if there is at least 50 mm of rainfall over 24 h.

The threshold for road runoff is thus on average 37.5 mm/day, setting the threshold for salt return to the worked water reservoir. To derive a monthly equivalent for the threshold value of 37.5 mm/day, daily rainfall data were obtained at four locations (Moranbah, Collinsville, Blackwater, Emerald) from the Department of Natural Resources and Mines data drill tool. The data were analysed by finding the months during which there was no daily rainfall event that would reach the daily

Table 3
Step function parameters for dynamic road watering.

Location	Moranbah	Collinsville	Blackwater	Emerald	Average
Threshold for 100% occurrence (mm/month)	110	129	106	105	112.5
Threshold for minimum occurrence (mm/month)	500	600	600	560	565
Minimum road watering occurrence (%)	57.3	54	57.3	57.3	56.4
Slope	−0.0007	−0.0006	−0.0006	−0.0006	−0.00063
Intercept	0.9517	0.9425	0.9463	0.9595	0.95

Table 5
Summary of water management characteristics at seven mines.

Parameter	Unit	Mine 1 Open-cut	Mine 2 Mixed	Mine 3 Open-cut	Mine 4 Open-cut	Mine 5 U/ground	Mine 6 U/ground	Mine 7 Mixed
Fresh water import	L/t	218	134	199	432	329	161	279
Worked water storage capacity	ML	226	16000	10000	1600	801	908	16210
Worked water storage mean TDS	mg/L	5471	8836	10103	3727	4475	4893	8014
Discharge objective – TDS	mg/L	4000			1005		1005	1340
CHPP process demand	L/t	604	386	296	2839	1065	644	299
Dust suppression demand	L/t	214	104	206	93	65	22	77
Underground demand	L/t		115			55	149	192
Total water demand	L/t	818	605	501	2932	1186	815	569
Fresh as % of total	%	17	22	40	15	27	19	49

threshold value, compiling their monthly rainfall total and selecting the lowest total as monthly threshold. Dividing this monthly threshold by the number of days in the month yielded the required model input (Table 2).

2.1.4. Dynamic road watering

The volume of water that will be applied to the roads to suppress dust is modelled as a function of the amount of rainfall received by the site. Mine sites generally do not water the roads if rainfall is at least 10 mm over 24 h.

As with the calculations of salt return thresholds, a monthly equivalent to represent the monthly occurrence of road watering had to be derived, using the daily rainfall data from Moranbah, Collinsville, Blackwater, and Emerald. The number of daily rainfall events occurring in a month and reaching the daily threshold value was calculated, and plotted against monthly rainfall. The graphs showed that these curves could be described by step-functions:

- For monthly rainfall less than the salt return threshold defined above (R1), road watering occurred every day (100% occurrence).
- For monthly rainfall greater than a certain threshold (R2), road watering was minimum, between 55% and 60% occurrence, depending on location.
- Road watering occurrence decreased linearly between those two threshold levels.

Table 3 summarises the parameter values characterising the step function at each location. As parameter values are quite similar at all locations, the average values were adopted. Dividing the monthly rainfall by the number of days in the month yielded the required model input.

2.1.5. Salt exchange in the coal handling and preparation plant (CHPP)

The water balance model recognises that salt is a constituent of each water inflow, and it is represented as a concentration associated with each of the water flows. When the water that is used in the CHPP to wash the coal contains salt, salt exchange between the coal and the water can occur. Preliminary experimental data (Cote et al., 2007) indicates that there is a close relationship between salt in fine coal product and the salinity concentration of the solution. The mass of salt exchanged decreases linearly with increasing NaCl concentration, and the parameters adopted to represent the linear relationship are summarised in Table 4.

The total volume of water held in the CHPP was assumed to be 20 ML. This was based on information provided by one mine site, and it was assumed that volumes held at other mine sites would be similar. Salt concentration is not overly sensitive to this assumption given that the water held in the CHPP is significantly less than the volume of inflow into the CHPP, which is typically in the range of 200–300 ML/month.

2.1.6. Site specific parameters

Undertaking simulations with the systems model for the seven selected mines required the input of several parameters, which are not provided in this paper. They concern the detailed description of water requirements of the mines' tasks (CHPP, road dust suppression, industry), storage characteristics (storage volume, surface area, catchment area, aquifer input) and details about water supply system (allocation volume and source). The information was sourced from existing engineering reports and directly from site staff.

2.2. Data collation

Seven mines were selected for analysis: three open-cut mines, two underground mines and two mixed mines, containing both open-cut and underground operations. Current water management at the seven mines is characterised by:

- the volume of fresh water that needs to be imported onto the site for normal mining operations to proceed;
- the storage capacity that is available (both for fresh and worked water);
- the amount of salt that accumulates in the worked water storage; and
- the volumes of water required by each task, and the associated type of water (fresh or worked).

This information is summarised in Table 5, where the volumes of water used by each task are reported in megalitres per megaton of coal production (ML/Mt), to outline the productivity of each ML of water used and to allow comparison between the various sites. Mine types are also indicated in the table, as the mine type will influence the tasks' water requirements. There is little evidence that any relationship exists between fresh water use, worked water use and coal production (Fig. 2).

From the data collection and collation, the following comments could be made regarding current water management at those mines:

- There is a wide range of water use, with water productivity varying between 570 and 3000 ML/Mt;
- The proportion of fresh water used in the CHPP varies from 5% to 67%;
- There is no obvious relationship between mine production and its storage capacity, and there is a need to investigate how appropriate the current storage capacities are; and

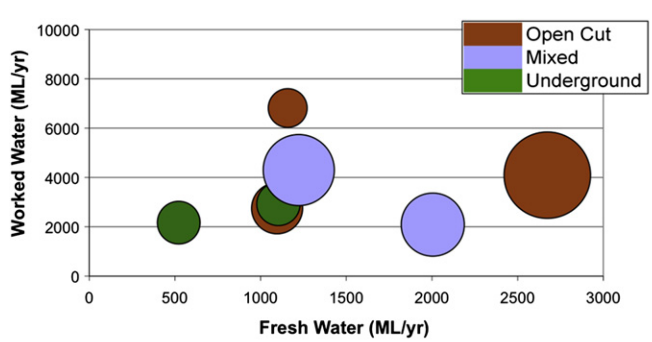

Fig. 2. Current relationship between fresh and worked water use across the 7 mine sites. The size of the bubbles indicates the coal production.

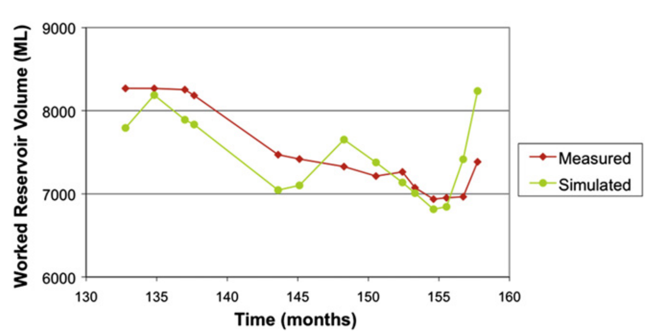

Fig. 3. Example of comparison between measured and simulated worked water reservoir volumes.

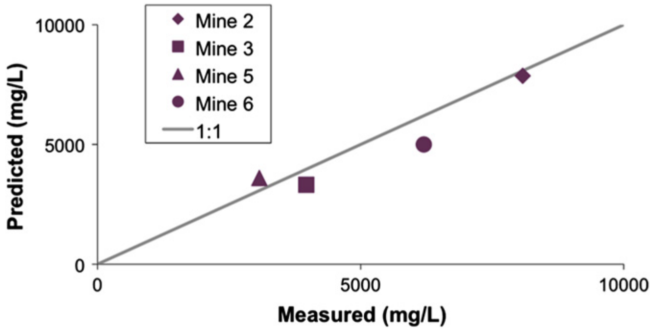

Fig. 4. Predicted and measured clarifier concentrations.

- There is considerable variation in the average salinity of the worked water stores.

Based on these results, some water management performance objectives were selected. These related to optimising the worked water storage capacity to minimise the discharge risk, minimising the use of fresh water and minimising total water use through adoption of the leading water productivity ratios.

2.3. Model calibration

Calibration was achieved by adjusting the single model variable, representing additional evaporation from depressional storages (ADELOF). When sufficient data were available, simulated results were calibrated against measured data, the measured storage levels in the largest reservoirs. A least squares method was used to determine the ADELOF factor that best simulated the storage levels. An example of model calibration is given in Fig. 3, which compares measured water levels of a worked water store and model output for the same period. When mines could not provide measurements of storage levels, default values for ADELOF were adopted, based on area of disturbed land.

The model was also checked against the salinity of the worked water (Cote et al., 2007). As the model calculates salt concentrations in the worked water store and coal preparation plant, these could be compared with measurements of salt concentration in the coal preparation plant clarifiers, when available. Comparisons were satisfactory (Fig. 4), with a correlation coefficient of 0.89 between measured and predicted salt concentrations.

3. Results and discussion

The model was used to assess the performance of each site with respect to the root definition provided in the Introduction. We undertook three types of modelling scenarios at each site: varying the storage capacity to assess its impact on avoiding production losses due to water shortages and abiding by discharge license requirements; varying the volume of fresh water being delivered to each task to simulate the impact of increased water reuse; and varying the total volume of water delivered to each task. Modelling results were also analysed for their predictions of worked water salinity.

Table 6
Wet and dry indicators for seven demonstration mines.

	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 6	Mine 7
Wet indicator (% time above 90% full)	26	35	66	20	99	15	84
Dry indicator (% time below 25% full)	33	0	0	6	0	6	0

3.1. Storage capacity to minimise discharge and supply risk

To ensure water security, surface water stores must hold minimum stocks but the mine must also have sufficient storage capacity to contain runoff during wet periods. Using the system-level tool, modelling of water volume within the worked water storage over time using long-term climate data can be undertaken to help select the most appropriate storage capacity. With such a model, only one parameter (the capacity of the worked water store) has to be changed. Results are presented as exceedance curves in Fig. 5 for the 7 mines, showing the probability that the volume stored in the reservoir will exceed a certain proportion of the available storage. They provide a visual assessment of the adequacy of storage. We also define a dryness indicator (25% full) and wetness indicator (90% full) selected to reflect the uncertainty embedded in the simulation input information and the approximate nature of the systems model (Table 6). The selection of 25% full for a dry indicator (rather than 10% full) is due to additional uncertainty over the depth of storages associated with sedimentation and questionable water quality at the bottom.

Mine 1 is a site that has a problem with being too dry too often, as the store is less than 25% capacity about 33% of the time. Mine 5 is a site with a discharge risk, as the store is almost always 90% full and is likely to quickly fill up and discharge. Exceedance curves following storage optimisation are provided in Fig. 6, with wet and dry indicators in Table 7. Results clearly show how changing storage capacity can change the behaviour of held water stocks. The selected optimised storage volumes are summarised in Table 8.

Modelling results indicate that increasing storage capacity at some mines would help decrease the likelihood of discharge occurring, but that it could also help manage the risk of running out of water. For instance, the dry indicator at Mine 1 is predicted to

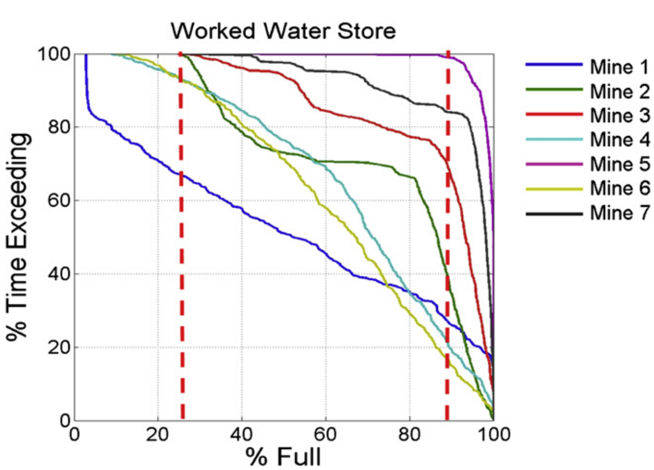

Fig. 5. Worked water store exceedance curves for seven demonstration mines.

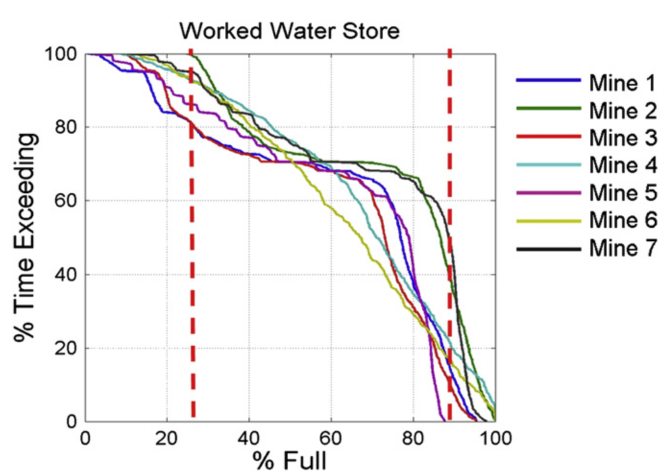

Fig. 6. Worked water store exceedance curves with increased storage capacity.

Table 7
Wet and dry indicators when storage capacity is increased.

	Mine 1	Mine 2	Mine 3	Mine 4	Mine 5	Mine 6	Mine 7
Wet indicator (% time above 90% full)	12	35	7	20	0	15	41
Dry indicator (% time below 25% full)	18	0	18	6	14	6	0

decrease with increased storage capacity because a larger volume of runoff can now be captured, leading to increased water availability. This highlights the advantage of applying a systems view to mine water circuits. The interactions between the various elements lead to results that cannot necessarily be intuitively guessed. In the case of Mine 1, results show that the worked water store is currently too small to capture large runoff volumes and thus to provide long-term water availability.

In some cases, the recommended increases in storage capacity might not be feasible or cost effective (e.g. Mine 1). An alternative to provide more storage capacity is to increase the proportion of worked water used and reducing the imports of fresh water. Exploring a range of practices would provide a more practical solution and this can be easily done with a systems model as presented here.

3.2. *Minimise fresh water use*

Site visits and discussions with operators indicated that there are few constraints to using worked water in coal preparation plants. In some plants, fresh water is required to cool vacuum pumps and this represents 5% of water requirements. Although some coal preparation plants would not require any fresh water, a minimum of 5% fresh water use was adopted as our target. There are no constraints for using worked water for road dust suppression (none of the mines had acidic water) and some mines already only use worked water for this task. Simulations were thus undertaken with 5% fresh water use in the CHPP and 0% fresh water use for road dust suppression at all mines. The resulting fresh water requirements are summarised in Table 9 and exceedance curves are provided in Fig. 7.

Implementing the practice decreased the simulated import and use of fresh water, but some mines (1, 3, 4) were at risk of running out of worked water (less than 25% full more than 60% of the time). This is because more worked water is used, and more worked water is drawn from the worked water reservoir. Increasing the capacity of the worked water reservoir as well as the amount of worked water that can be captured by the reservoir could help address this limitation.

3.3. *Adopt leading water productivity ratios*

The review of summary information showed that there was a range of water productivity values with some sites managing to use less water in their various processes and others achieving lower losses. To illustrate the impact of achieving minimum water use and minimum water losses at all mines, simulations were undertaken with leading water production and loss ratios (Table 10) imposed at all mines. The leading ratios did not include dust suppression because haul road length and dust suppression areas were not requested from mines. The proportions of fresh and worked water used in each of the processes were not modified from current practices.

Table 8
Adopted worked water reservoir storage capacity.

Mine ID	Current storage (ML)	Simulated storage (ML)	Increase factor
Mine 1	226	16000	70.8
Mine 2	16000	16000	1.0
Mine 3	10000	27500	2.8
Mine 4	1600	1600	1.0
Mine 5	801	25000	31.2
Mine 6	908	908	1.0
Mine 7	16210	40000	2.5

Table 9
Fresh water requirements with minimum fraction of fresh water use in the CHPP and for road dust suppression.

Mine ID	Current (ML/Mt)	Simulated (ML/Mt)	% Decrease
Mine 1	218	160	26
Mine 2	134	134	0
Mine 3	198	75	62
Mine 4	426	191	55
Mine 5	325	174	47
Mine 6	158	158	0
Mine 7	278	207	25

The resulting summary information characterising water management is provided in Table 11, with associated exceedance curves in Fig. 8.

With implementation of this practice, the main changes are not so much related to the worked water store behaviour but to total water use and to import of fresh water. Scenario results indicate sites could reduce their fresh water imports by up to 60%. For Mine 2, the changes in water consumption greatly improve the distribution of water stocks, with the storage displaying a low risk of either running out of water or discharging. For the other sites, the change in water consumption does not impact much on storage behaviour. The reduction in consumption also leads to a reduction in the volumes of worked water that are returned to the reservoir, and these combined changes seem to balance each other out. An exception to this is Mine 1, for which the risk of running out of water increases with the reduction in fresh water imports. This again highlights the advantage of applying a systems approach as all interactions are taken into account.

It was found that there is little technical information explaining how the leading production and the loss ratios were being achieved, and this was identified as a further research need. It is therefore hard at this stage to assess the difficulty a mine site would face in trying to meet them.

3.4. *Impact of management practices on water quality*

A feature of the model is that it includes salt as a constituent of each water flow so that the impact of any practice on water quality

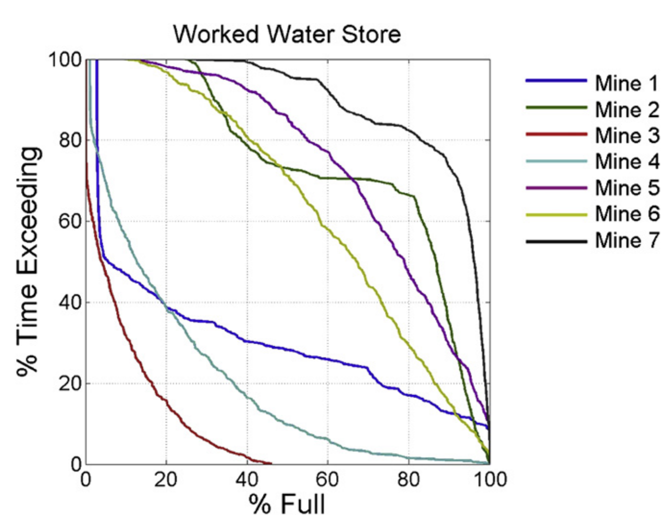

Fig. 7. Worked water store exceedance curves with minimum fraction of fresh water use in the CHPP and for road dust suppression.

Table 10
Leading water production and loss ratios.

Water ratio	Minimum value
CHPP process make-up requirements (ML/Mt)	296
Water loss from CHPP (ML/Mt)	81
Water demand for underground operations (ML/Mt)	55
Water loss from underground operations (ML/Mt)	29

can be assessed. Fig. 9 illustrates the impact of implementing the above strategies on the mean salt concentration in the worked water reservoir (as calculated by the model). Increasing the storage capacity to minimise the discharge risk is not predicted to impact on water quality, except at Mine 1, where the large increase in storage leads to more worked water being captured and less fresh water being used, leading to an increase in salinity. When simulating the minimum use of fresh water, an increase in salinity is predicted at all the mines where fresh water use has been reduced. In general, the greater the reduction in fresh water use, the greater the increase in salinity (Fig. 10). At Mine 3, the minimum fresh water use represents a 62% reduction, accounting for the larger salinity increase that is predicted. When simulating the adoption of the leading production ratios, the salinity is also predicted to increase, with the magnitude of the increase depending on the proportion of worked and fresh water used adopted at each mine.

The predicted increases in salinity are not very large, except that predicted when minimising fresh water use at Mine 3. There is a requirement to define specific objectives related to water quality that could, for instance, target the elimination of product quality compromises (too much salt in the water that is used to wash the coal can produce "salty" coal) or the optimisation of the flotation processes that are used to recover fine coal products (there is a relationship between the salt concentration and the amount of reagents that are used in flotation). The analysis could then progress from investigating the implications of moving from a position of passive acceptance of salt loads to managing according to specific objectives. This topic is discussed in more detail in Cote et al. (2007).

3.5. Environmental performance

In recent years, concerns about the sustainability and social responsibility of mining have led the mining industry to reach consensus on sustainability principles through an extensive global process known as The Mining, Minerals and Sustainable Development Project (MMSD, 2002) later implemented by the International Council on Mining and Minerals (International Council on Mining and Minerals, 2003). This process achieved the development of a sustainability framework comprising three elements: a set of ten principles, independent assurance and public reporting, for instance via the Global Reporting Initiative (GRI), which provides a suggested list of contents for corporate sustainability reports (Global Reporting Initiative, 2005). Water issues feature in the framework, through specific reporting indicators (Table 12).

Table 11
Projected decreases in total water use.

Mine ID	Current (ML/Mt)	Simulated (ML/Mt)	% Decrease
Mine 1	818	595	27.3
Mine 2	605	455	24.8
Mine 3	501	501	0.0
Mine 4	2932	389	86.7
Mine 5	1186	417	64.9
Mine 6	815	373	54.3
Mine 7	569	427	24.8

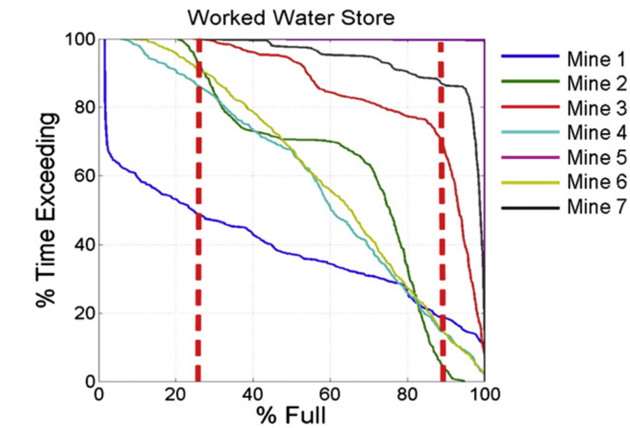

Fig. 8. Worked water store exceedance curves with adoption of leading production and loss ratios.

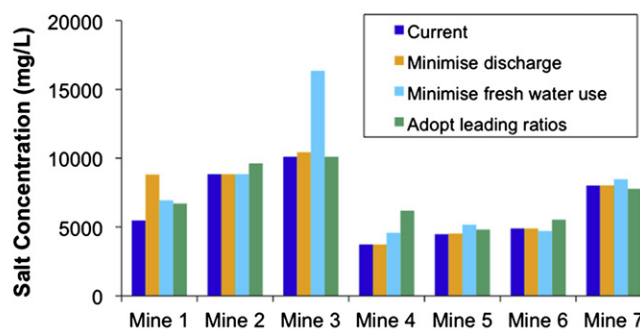

Fig. 9. Mean salt concentration in the worked water reservoir (mg/L).

The data collation that was required to run simulations with the systems model provided values for the four quantitative indicators (Table 12). Withdrawals reported here are limited to withdrawals of surface water. Note that volumes are reported in ML per megaton of coal production (ML/Mt), to facilitate comparison between sites. The discharge indicator that was selected for this study was the probability of the worked water store to be above 90% of its capacity. Given the uncertainty inherent in the simulation input information and the approximate nature of the systems model, discharges are reported as discharge risks (e.g. a store at 90% of its capacity would have a high risk of filling and discharging) rather than prescribed volumes.

A review of the sustainability reports of twenty-seven major mining companies showed that only nineteen of them reported on

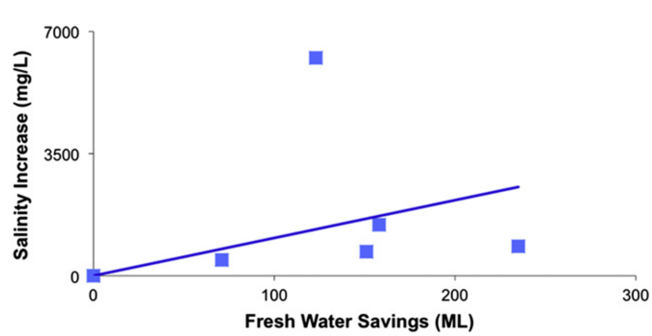

Fig. 10. Water quality impact of minimising fresh water use.

Table 12
Reporting indicators relating to water.

Mine ID	EN05 Total water use (ML/Mt)	EN12 Significant discharges to water (%time above 90% full)	EN21 Withdrawals of surface water (ML/Mt)	EN22 Total recycling and reuse of water (ML/Mt)
Mine 1	818	26	140	600
Mine 2	605	35	134	471
Mine 3	501	66	199	303
Mine 4	2932	20	432	2506
Mine 5	1186	99	329	861
Mine 6	815	15	161	657
Mine 7	569	84	279	291

indicator EN05 (total water use), six of them reported on EN12 (discharges), seven reported on EN21 (withdrawals) and nine reported on EN22 (recycling). Despite the increasing sophistication in environmental disclosure, there is still variation in reporting content (Jenkins and Yakovleva, 2006) including reporting of water management. Clearly, there is a requirement for a tool that can extract and compile the information that is required for reporting purposes. By using and applying a systems representation of a mine water circuit, all mines could report on the quantitative compulsory water indicators. Moreover, the assessment of potential water management performance objectives is directly related to a potential improvement of water indicators. Minimising the discharge risk would improve water indicator EN12, minimising the use of fresh water would improve water indicators EN21 and EN22, and minimising total water use through adoption of the leading water productivity ratios would improve water indicator EN05.

4. Conclusion

This paper has presented a systems-representation of coupled water and salt balances on coal mines. Data from engineering model systems were successfully aggregated for systems-level use, although more calibration data would be a major benefit. The model has been used to simulate strategies that could be implemented for improved management of the range of tasks that are performed on a coal mine.

The results demonstrate that a simple systems model is an appropriate tool for assessing site performance, for providing guidance to improve performance through strategic planning and for guiding adoption of site objectives. Results aggregated across a number of mines can be used to compare performance or make statements regarding leading practice and performance on the basis of a region, a company or the industry as a whole. The systems model is also particularly helpful to compile the water management information that can be reported as sustainability performance indicators. It can assist companies and their stakeholders in assessing the extent to which their production activities are contributing to sustainable development goals through a responsible use of water resources. An implementation of the model can be found at http://selkie.smi.uq.edu.au/waterminer/index.html.

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References

Banks, D., Younger, P.L., Arnesen, R.T., Iversen, E.R., Banks, S.B., 1997. Mine-water chemistry: the good, the bad and the ugly. Environmental Geology 32, 157–174.

Barger, A., 2006. Like liquid gold – towards a resource industry position on water. In: Proceedings of the Water in Mining Conference. Publication Series No 7/2006. The Australasian Institute of Mining and Metallurgy, Brisbane, pp. 151–158. November 2006.

Boughton, W., 2004. The Australian water balance model. Environmental Modelling and Software 19 (10), 943–956.

Bru, K., Guezennec, A.-G., Bourgeois, F., 2008. Numerical simulation: a performing tool for water management in tailings impoundments. In: Rapantova, N., Hrkal, Z. (Eds.), Proceedings of 10th International Mine Water Association Congress, Karlsbad, Czech Republic 2008. Technical University of Ostrava.

Checkland, P., 1981. Systems Thinking, Systems Practice. John Wiley & Sons.

Cote, C.M., Moran, C.J., Hedemann, C.J., 2007. Evaluating the costs and benefits of mine sites salt management strategies using a systems model. Mine Water and Environment 26, 229–236.

Eastgate, W.I., Swartz, G.L., Briggs, H.S., 1979. Estimation of runoff rates for small Queensland catchments. In: Q.D.o.P.I. (Ed.), Division of Land Utilisation, p. 76. Technical Bulletin.

Global Reporting Initiative, 2005. GRI Mining and Metals Sector Supplement Pilot Version 1.0 Available at. http://www.globalreporting.org/ReportingFramework/SectorSupplements.

Hairsine, P.B., Moran, C.J., Rose, C.W., 1992. Recent developments regarding the influence of soil surface characteristics on overland-flow and erosion. Australian Journal of Soil Research 30 (3), 249–264.

Hooke, M.H., 2007. CEO Minerals Council of Australia. National Press Club. http://www.npc.org.au/ Address, transcript available at.

International Council on Mining and Minerals, 2003. ICMM Sustainable Development Framework: ICMM Principles. International Council on Mining and Metals, London.

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environmental Modelling and Software 21, 602–614.

Jenkins, H., Yakovleva, N., 2006. Corporate social responsibility in the mining industry: exploring trends in social and environmental disclosure. Journal of Cleaner Production 14 (3–4), 271–284.

Laurenson, E.M., Mein, R.G., 1990. RORB Version 4 Runoff Routing Program User Manual. Department of Civil Engineering, Monash University. 1990.

Liang, H.C., Thomson, B.C., 2009. Minerals and mine drainage. Water Environment Research 49, 1615–1663.

Mayer, K.U., Blowes, D.W., Frind, E.O., 2003. Advances in reactive-transport modelling of contaminant release and attenuation from mine-waste deposits. In: Jambor, J.L., Blowes, D.W., Ritchie, A.I.M. (Eds.), Environmental Aspects of Mine Wastes. Mineralogical Association of Canada Short Course Series, vol. 31, pp. 283–302. ISBN 0-921294-31-x.

McIntosh, J.C., Merritt, J.L., 2003. Risk-based water management – practical application for serious management. In: Proceedings of the Water in Mining Conference. Publication Series No 8/2003. The Australasian Institute of Mining and Metallurgy, Brisbane, pp. 57–64. October 2003.

McIntosh, J.C., Merritt, J.L., 2006. Water management at Capcoal mine—past, present and future drivers for sustainable change. In: Proceedings of the Water in Mining Conference. Publication Series No 7/2006. The Australasian Institute of Mining and Metallurgy, Brisbane, pp. 339–350. November 2006.

MMSD, 2002. Breaking New Ground: the Report of the Mining, Minerals, and Sustainable Development Project, May 2002. Earthscan Publications Ltd, 410 pp.

Schwartz, M.O., Schippers, A., Hanh, L., 2006. Hydrochemical models of the sulphidic tailings dumps at Matchless (Namibia) and Selebi-Phikwe (Botswana). Environmental Geology 49 (4), 504–510.

WP Software, 1994. RAFTS-XP Runoff and Flow Training Simulation, User Manual, Version 4.

Younger, P.L., 2000. Predicting temporal changes in total iron concentrations in ground waters flowing from abandoned deep mines: a first approximation. Journal of Contaminant Hydrology 44, 47–69.

Younger, P.L., Banwart, S.A., Hedin, R.S., 2002. Mine Water: Hydrology, Pollution, Remediation. Kluwer Academic Publishers, Norwell, MA, USA.