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Synergising water and energy requirements to improve sustainability performance in mine tailings management

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ABSTRACT

Mining is a water and energy intensive industry, and reducing water and energy consumption are two important issues in the quest for more sustainable industrial production. The aim of this paper is to assess the correlation between water and energy requirements in various tailings disposal strategies (on a per cent solids-based analysis). Two main methods are used: rheology testing and a system modelling approach. A coal mine site in Australia was chosen as a case study to apply five tailings disposal options. These five options are differentiated by the percentage of solids in the tailings ranging from 30% to 70%. The rheology analysis indicated that the coal mine tailings with 65–70% solids are not pumpable and these two options are beyond the scope of this study. The results of the analyses show that the optimal scheme process in terms of water saving, water management, and energy consumption involved tailings with 50% mass solids. The implementation of this option resulted in both lower water transport (15,532 ML/y) and energy consumption (34.7 TJ/y). This option also reduced the overall flows of water to the Tailings Storage Facility by 30%.

1. Introduction[1]

1.1. Background

Mining operations cannot exist without sufficient and secure supplies of both water and energy; without these, problem may arise including production chain interruption, and increase to remediation costs (Nguyen et al., 2014). Water is typically used within a broad range of activities including haul road dust suppression, mineral processing, metal recovery, water cooling, tailings and concentrate transport, and worker requirements. These water demands are met by both surface water and groundwater sources. The volume of water withdrawn by mining operations across the globe was approximately 20.1 million m^3 per day in 2010 (Jain et al., 2016) with the ABS (2016) recording that mining in Australia consumed 141 GL of water between 2013 and 2014. Total water usage can vary depending on some factors including the size of the mine, the mining and processing methods used, and associated with water conservation practices. Gunson et al. (2012) provided a hypothetical analysis for water consumption based on the requirement of processing 50,000 ton per day (tpd) of low grade copper ore in an arid region (Table 1).

On a global scale, the mining industry is not the largest consumer of water; for example mining consumes about 1% of total freshwater withdrawals in the United States (Miranda and Sauer, 2010), and mine water consumption in Australia, Chile, and South Africa accounts for only 2–4.5% of national water demand (Gunson et al., 2012). However, on a local scale, mining operations can have a significant impact on the water supply of adjacent communities. Firstly, the primary source of direct water consumed by mining often comes from surface and groundwater. Secondly, mining operations often significantly affect the water quality of local resources, e.g., acid mine drainage, and heavy metal pollution of water resources in Southern Africa (Mccarthy, 2011; Ashton et al., 2001), Baia Mare, Romania (Bud et al., 2007), and Wadi Queh, Egypt (Abdalla and Khalifa, 2013).

In addition, the mining industry is considered to be one of the five largest consumers of global energy, with energy used not only for mining and processing but also ancillary services such as water treatment, wastewater management, and generating camp

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[1] TSF: Tailings Storage Facility, P&T: Paste and Thickened Tailings, HSM: Hierarchical Systems Model, ROM: Run-of-mine, CHPP: Coal Handling and Preparation Plant.

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Table 1
Water usage in copper mining.

Process	Usage (m^3/d)
Flotation with 30% mass solids	115,646
SAG mill cooling	4100
Ball mill cooling	4100
Compressor cooling	4100
Road dust control	3520
Froth wash	2880
Pump glad seal water (GSW)	1440
Reagent dilution	720
Dust control in primary crusher	358
Dust control in ore stockpile	121
Domestic water	58

Source: Gunson et al. (2012).

electricity. Mining utilized 20% of Chile's total electricity consumption in 2013 (Simpson et al., 2014), 20% of South Africa's total electricity generated in 2006 (Johnson and Fourie, 2012), and 9% of Australia's net total energy consumed between 2012 and 2013 (BREE, 2014). Energy consumption is also a critical component in mining production costs and typically contributes between 14 and 30% of total production costs (Simpson et al., 2014; ABB, 2012). Energy consumption also generates greenhouse gas (GHG) emissions through both the purchase of energy and direct burning of fuel.

Consequently, water and energy should be appropriately managed to enhance the sustainability of mining operations. Initiatives presented in Table 2 have already been implemented by mining sites across the world in an effort to reduce water and energy consumption.

Tailings transport is an important component of mining operations that involves both significant water and energy consumption. The largest water sink at most mining sites is the Tailings Storage Facility (TSF) (Gunson et al., 2012). In TSF operation, the relationship between water and energy is significant and determines the tailings management strategies. The Castle Valley flow as shown in Fig. 1 describes an example of water and energy interaction in a coal mining. The thickener facility was built to process fine coal, where tailings generated from the underflow thickener consist of 30% solids. As an illustrated, the water required to transport these tailings equals 0.7 ton for 1 ton of tailing slurry.

As a water sink, the TSF generally receives water from runoff, rainfall, and tailings entrained from the mine processing plant. The processing plant produces solid residue (tailings) which is generally transported to the TSF as slurry by a pipeline. This transport process requires energy and generates emissions. Energy is also needed when water is recycled from the TSF and pumped back to the processing plant's water supply. Therefore, the interconnection between water and energy consumption in terms of water reduction, energy efficiency, and associated environmental impacts becomes an important factor in sustainable tailings management.

1.2. Objectives

Research to date has assessed the relationship between water and energy use in mining operations including Gunson et al. (2010), Nguyen et al. (2014) and Moolman and Vietti (2012). A linear programing algorithm was used by Gunson et al. (2010) in comparing some possible options for supplying water to a copper mine and mill. In addition, Nguyen et al. (2014) discussed two types of water and energy relationships including potential synergies and trade-offs. The relationships were represented by two criteria: net water available volume and net operational demand. Three case studies from three different mine sites were discussed which included a copper mine (Chile), a coal mine (Australia), and a gold mine (Australia). Moolman and Vietti (2012) detailed the connection between water conservation and energy costs in tailings management for a platinum project in South Africa. The results of this study revealed that the thickened tailings option generated the lowest total cost per tonne of tailings discharged. Studies until now, however, have not considered rheology or water and energy trade-offs in different coal tailings management strategies. Therefore, this study attempts to fill the gaps and discover the novelty of synergising water and energy in coal mine tailings management.

The aim of this paper is to assess the nexus between water and energy requirements across various tailings disposal methods (using a percent mass solids-based analysis) that could further improve the sustainability of coal tailings management. Four research questions are being assessed:

- How much energy is required in pumping the tailings from the processing plant to the TSF after water and energy use for different concentrations?
- What is the water balance during tailings transport for various tailings mass solids concentrations?
- What is the relationship between water and energy consumption for different tailings disposal methods?

Table 2
Examples of water and energy reduction initiatives in the international mining industry.

Mine site	Initiatives	Goals	Achievement
Minera Esperanza, Antofagasta, Chile	Implementing thickening tailings method; Using seawater.	Ensuring the usable water supply to mine operations; Optimizing water use.	Water use reduction up to 600 L/s.
BHP Billiton, Olympic Dam, Australia	Establishing water saving project; covering open site water storage, increasing the volume of wastewater usage.	Minimizing water use from the Great Artesian Basin (GAB).	Water use reduction approximately 450 ML/year.
Argyle Diamond Mine, Western Australia	Capturing and recycling water seepage from tailings; dewatering underground mine.	Reducing water use from surface water sources.	Reduction on water supply from Lake Argyle up to 300 ML
Barrick Gold Corp.	Grinding improvement by put some changes including change the profile of cone crusher liner, use gearless drive.	Reducing energy, GHG, and Cost.	Reducing on 20% net grinding energy and 43,000 tonnes CO_2/year.
The Teck Coal Elkview, BC	Installing Variable Frequency Drive (VFD) on the dryer exhaust fan	Reducing energy consumption	Total electric saving $ 105,079/year
Anglo American Group, Platinum Mining	Energy conservation through some methods including the installation of compressors, ventilation fan, and optimization of smelter.	Saving energy and cost	In 2012 total saving approximately $75 Million
	Implementing the Plant Information (PI) system infrastructure	Reducing overall energy cost	15% reduction in power consumption by 2015

Sources: ICMM (2012), Buckingham et al. (2011), Durocher and Putnam (2013), Ryan (2014), Bascur and Soudek (2014).

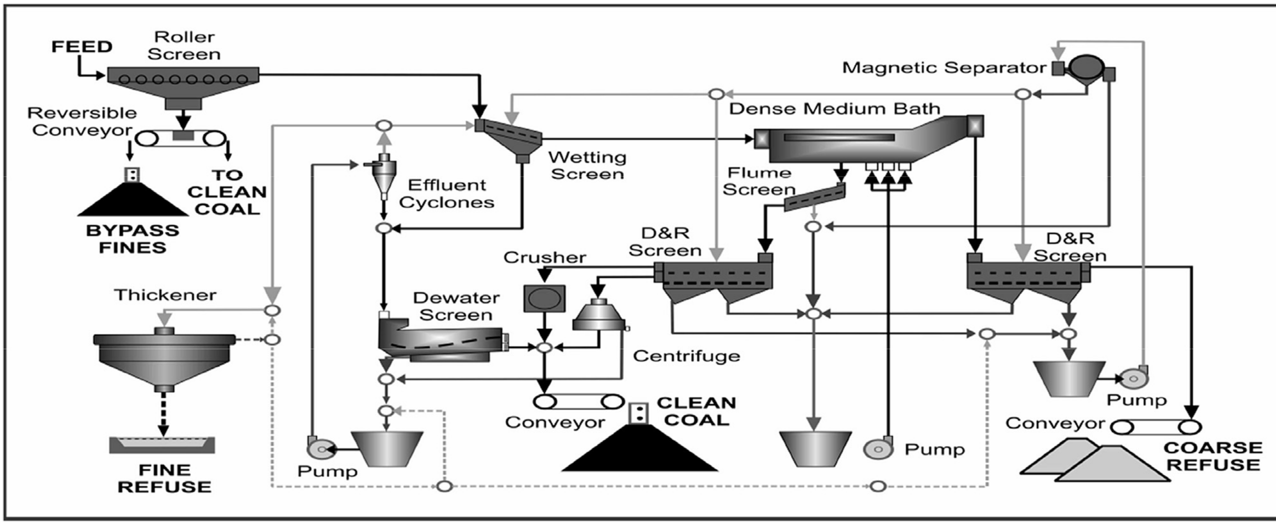

Fig. 1. Castle valley plant (Bethell, 2012).

- What is the most suitable option for transporting coal mine tailings to the TSF in terms of the water and energy nexus?

In order to understand these questions, a rheology test for coal mine tailings samples was completed. In addition, a system modelling tool known as the Hierarchical Systems Model (HSM) (Keir and Woodley, 2013) was used to analyse the relationship between water and energy use for a coal mine site at the Bowen Basin in Central Queensland, Australia as presented in Section 5.3. The following outlines current discussions relating to water and energy consumption in mining. Section 3 describes some basic rheology concepts and their relationship with mine tailings solid concentrations. Section 4 presents the material and methods used in the laboratory work and data analysis. Lastly, Sections 5 and 6 present the laboratory results and analyses the interrelation of water and energy for each option.

2. Improving sustainability of mine water and energy use

Over the past two decades, mining operations have become more sustainable with initiatives being developed through the Mining, Minerals and Sustainable Development project (MMSD) starting in 2002. The MMSD project was initiated by nine of the world's largest mining companies as a two-year independent project of research and consultation; the International Institute for Environment and Development was selected as the project leader (MMSD, 2002). In addition, the establishment of the International Council of Mining and Metals (ICMM) in 2001 was seen as a commitment by the mining and minerals industry toward the development of more sustainable operations. This commitment was embodied in the ten principles of the ICMM sustainable development code (ICMM, 2003) as shown in Table 3. The ten principles are based on issues that emerged in the MMSD and are comparable to available international sustainable management standards including the Rio Declaration, Global Reporting Initiative, World Bank Operational Guidelines, the ILO Conventions, and the Voluntary Principles on Security and Human Rights (ICMM, 2003).

These ten principles cover many issues related to sustainability including the spirit of equity and fairness (found in the ICMM sustainability codes) which shapes the interaction between mining, environment, and social outcomes. The ICMM has also developed position statements on mine closure, partnership for development, transparency on mineral resources, mercury risk management, indigenous people and mining, and protected areas and mining.

Continual improvement to environmental performance including re-use, recycling, and waste disposal is a key factor in mining sustainability. One reporting system, known as the Global Reporting Initiative (GRI), includes energy (EN3–EN7), water (EN8–EN10), emissions, effluent and waste (EN16–EN25) in their sustainability factors. Three of these aspects are described by Northey and Haque (2013) in their paper assessing the environmental footprint of copper mining activities in Australia, Chile, Peru, Laos, Papua New Guinea, South Africa, the USA, and Canada. This paper is based on the sustainability report published by each copper mine. The results show the rates of consumption of energy and water, and production of GHG emissions for each country. The average rates of these three components per ton of copper produced were as follows: 22.2 GJ of energy intensity, 2.6 ton CO_2-e of GHG emission production, and 70.4 kL of water used (Northey and Haque, 2013). Other studies revealed that 260,000 ton of water and 200,000 GJ of energy were required for every 1 ton of gold produced (Prosser et al., 2011; Norgate and Haque, 2012). In addition, Gunson et al. (2012) noted that conventional copper mines consumed water at approximately 0.34–2.07 m^3 per ton of ore processed. These figures indicate that water and energy are two critical components in mining operations. However, it is also important to considering how these two components interact to determine where the most efficient points of water/energy use are in terms of sustainability outcomes.

Several efforts have been made to assess the relationship between energy and water use in mining operations (Gunson et al., 2010; Norgate and Haque, 2012; Nguyen et al., 2014). Other studies have focused solely on mine water management without considering energy consumption (Cote et al., 2010; Gunson et al., 2012). The significance of water and energy consumption in mining operations is captured in some modelling systems such as the Mine Water Network Design (MWND) and the Hierarchical System Model (HSM) (Gunson et al., 2010; Nguyen et al., 2014). The MWND focuses on the estimation of energy consumed to supply water from specific water sources to consumers. Gunson et al. (2010) noted that there are five procedures that should be included to identify the energy/water nexus: 1) develop a site water balance; 2) identify all potential water sources; 3) identify all water consumers; 4) develop the energy demand matrices; and 5) utilize linear

Table 3
Sustainable development principles of ICMM.

The ten principles
1. Implement and maintain ethical business practices and sound system of corporate governance
2. Integrate sustainable development considerations within the corporate decision-making process
3. Uphold fundamental human rights and respect cultures, customs and values in dealings with employees and others who are affected by our activities
4. Implement risk management strategies based on valid data and sound science
5. Seek continual improvement of our health and safety performance
6. Seek continual improvement of our environmental performance
7. Contribute to conservation of biodiversity and integrated approaches to land use planning
8. Facilitate and encourage responsible product design, use, re-use, recycling and disposal of our products
9. Contribute to the social, economic and institutional development of the communities in which we operate
10. Implement effective and transparent engagement, communication and independently-verified reporting arrangement with our stakeholders

Source: ICMM website, 2003.

programming to minimise energy demand. However, the MWND has some limitations in analysing the existing mine water system and is only applicable for designing new mine water systems (Nguyen et al., 2014). There are many opportunities to improve energy and water efficiency in mining including more energy efficient processes, renewable energy use, water reuse and recycling, and increasing the percentage of solids in concentrates and tailings (Buckingham et al., 2011; Gunson et al., 2012; Mclellan et al., 2012). Some companies, such as Newmont and BHP Billiton, have published their sustainability reports showing their commitment to improving their water and energy efficiency (Newmont, 2013; BHP-Billiton, 2014). However, only a few studies have investigated the interconnectedness between water and energy or the synergy in reducing water and energy consumption in tailings management. One study used an example from a platinum tailings management project conducted by Moolman and Vietti (2012). The two main parameters were the need for maximizing water recovery and minimizing power costs. Using a coal mine as its reference point or base, another study, used the Hierarchical Systems Model to assess this water/energy dynamic (Woodley et al., 2013), as discussed in Section 4.2.3. The synergies of these two components can be used as a starting point in preparing water and energy strategic plans as discussed by Nguyen et al. (2014) which can help to prevent deleterious outcomes such as water and energy shortfalls.

Currently, there are three main methods for managing tailings: conventional tailings dams, paste and thickened tailings (P&T), and direct disposal (Franks et al., 2011). The conventional tailings management system and direct disposal method require more water in transporting tailings to the TSF or final discharge compared with P&T tailings. This is due to the difference in the amount of mass solids contained in the tailings. Conventional tailings typically consist of 30% solids and P&T consists of up to 70% solids (Fourie, 2012). Some of the advantages of P&T tailings are identified by Jones and Boger (2012), and Boger (2013) including maximizing density of tailings in the TSF, minimising the TSF footprint and reclaiming water, processing reagents, and energy. However, further analysis is required to investigate the P&T tailings process and the nexus/trade-offs between water use, and energy consumption in tailings management.

3. Rheological concepts and their application to mine tailings management

Tailings management aims to protect the environment and society from the potential impacts that might be caused by mine waste (tailings). One of the biggest problems related to TSF management is the high volume of water used. Increasing the percentage solids of tailings is the most obvious way to reduce overall water use in tailings management (Boger, 2013). In terms of rheology as presented in Fig. 2, Boger et al. (2012) consider various parameters for improvement to tailings management. These parameters include safety, environmental, and cost factors embedded in the selection, design, and testing stages. When determining disposal method in the selection stage, two questions should be considered: 1) the method appropriate to minimise environmental impacts; and 2) capital and operational costs. In addition, safety factors, such as the potential of dam failure and dam overtopping, present significant technical and design considerations. An understanding of the rheological characteristics of mine tailings is a key factor in determining tailings disposal systems. Boger et al. (2012) provides a flowchart (see Fig. 2) on how rheology can be used as a tool to determine an appropriate disposal system in the planning phase of tailings management (“rheological-based decision”).

Rheology plays a crucial role in designing mine tailings systems because it determines the flow behaviour of fluids during the transporting process and is known as a study of the deformation and flow of matter (Barnes et al., 1989; Morrison, 2001; Boger et al., 2012). The main parameter used to differentiate these two fluids is the viscosity (η). The resistance to flow (viscosity) is defined as the ratio of the shear stress (τ) to the shear rate ($\dot{\gamma}$) where the more resistant a fluid is to flow (viscous) the more pumping energy is required to transport it. The correlation between viscosity and shear stress (the force applied per unit area) shown in Fig. 3 describes two behaviours of non-Newtonian fluids. These two behaviours are shear thinning (pseudoplastic) and shear thickening (dilatants). Pseudoplastic behaviour is shown when increasing the shear stress results in decreasing in the viscosity. Dilatant or shear thickening fluids are relatively rare in mineral suspensions and show an increased shear stress with increasing viscosity (Sofra et al., 2015; Goodwin and Hughes, 2008; Barnes et al., 1989).

At sufficiently high solids levels, suspensions of mine tailings contain an apparent yield stress, which is the minimum shear stress required for flow to occur (Boger et al., 2012). These are commonly characterised by the Herschel-Bulkley Model shown in eq. (1), where τ_y is the yield stress, K is the consistency index, and n the power-law index. Table 4 shows examples of yield stress values for different tailing suspensions, including alumina and lead-zinc tailings that have a yield stress ranging from 22 to 265 Pa (Boger et al., 2012; Sun et al., 2013).

$$\tau = \tau_y + K\dot{\gamma}^n \tag{1}$$

The study of rheology in mine tailings management has brought many changes to the development of thickener technology (Schoenbrunn, 2011) and pumping systems (Paterson, 2012). Furthermore, it has created an opportunity to reduce the water content in tailings during transport to the TSF, helping to reduce the risk of tailings dam failure, minimise TSF footprints, and reclaim energy (Boger, 2013). Many mining operations apply rheological assessments to their mine tailings management systems including

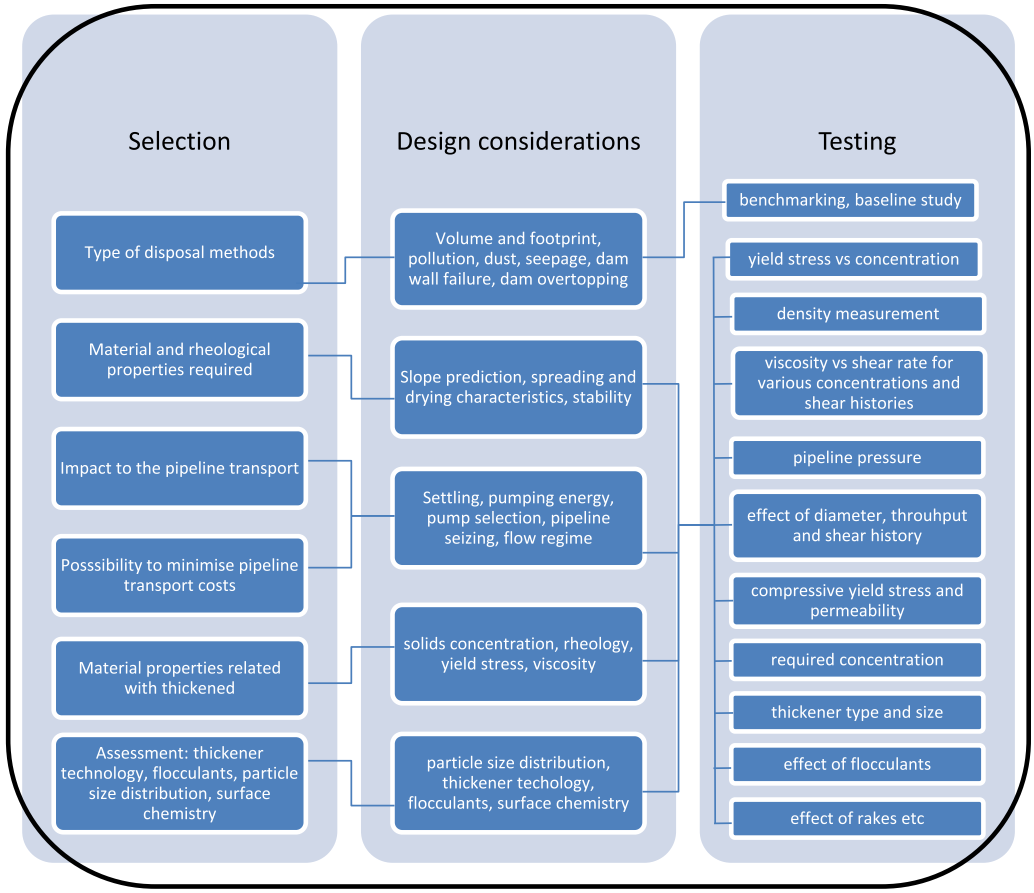

Fig. 2. Rheology-based decision flow adapted from Boger et al. (2012).

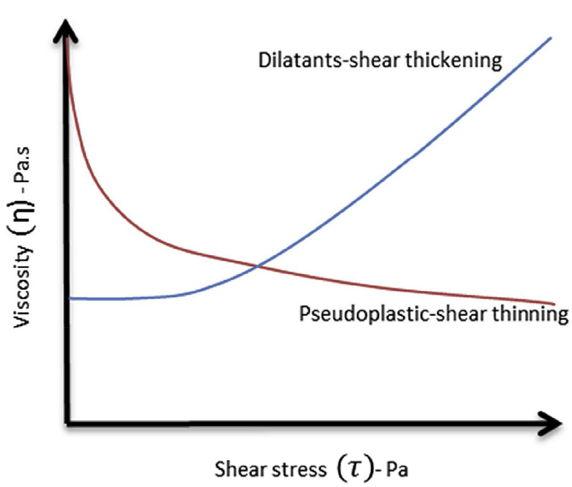

Fig. 3. Non-Newtonian fluids behaviour.

Table 4
Examples of yield stress values for mine tailings.

Substance	Yield stress (Pa)
Thickened tailings disposal (alumina)	30–100
Tailings paste (lead-zinc) various solids concentration	22–265
Mine stope fill	250–800

Alcoa bauxite production as presented in Adiansyah et al. (2015). Alcoa in Western Australia has been altering their disposal management system from wet to dry tailings. This enables Alcoa to reduce the total volume of waste and recycled water, and to recover caustic materials with total saving costs of approximately A$ 10 M/year (Cooling, 2007; Boger, 2009, 2013). Other examples of rheology benefits in mine tailings operations include Sunrise Dam, a gold mine in Western Australia which was able to reduce their mine tailings operational costs by approximately A$ 0.28 per ton when applying Thickened Tailings (TT) (Fourie, 2012). The Chihong mine in China was able to produce cemented paste backfill based on rheological experiments by increasing percent solids up to 80% (Yin et al., 2012), and the Sangan iron mine project in Iran recovered 0.87 Mm^3 of water when applying paste thickening technology (Rashidinejad and Naraghi, 2011).

4. Materials and methods

A rheological test was chosen to represent the behaviour of the coal tailings sample during the transporting process. The estimation of energy consumption during transport was based on generated rheology data. Different scenarios provided insight into the correlation between the water and energy used in tailings management. These scenarios were divided into five options including a conventional method (tailings slurry), and a non-conventional method (thickened and paste tailings).

A modelling analysis is also used to estimate the water and energy consumption in different tailings management scenarios. These two steps (rheology and modelling) were mentioned in

Adiansyah et al. (2015) as part of a framework for achieving sustainable mine tailings management.

4.1. Materials

The tailings samples in this research were provided by the Centre for Mined Land Rehabilitation (CMLR) at The University of Queensland and were taken from a coal mine site in the Bowen Basin of Central Queensland, Australia.

Tailings samples were prepared into five different solids concentrations as presented in Table 5.

Tailings were dried in the oven (50 °C) overnight and water was then added to meet the solids concentrations for each option (equation (2)).

$$\%\ \text{solids} = \frac{Ms}{MsL}\cdot 100 \tag{2}$$

where M_s = mass of solids in the sample and M_{sL} = mass of slurry in the sample.

A rheometer type AR-1500ex was used in this study to evaluate the coal tailings behaviour in a variety of solid mass concentrations. This unit has a drag cup motor drive system with torque range from 0.1 μN m to 150 mN m, an air bearing mounting for the measurement system, and an optical encoder for measuring displacement (Semancik, 2014).

The vane geometry was chosen with the standard vane dimensions of 11.0 mm for stator inner radius, 22.50 mm for the outer rotate radius, and 15 mm for the cylinder immersed height. Utilization of a vane-in-cup device can eliminate the measurement slip and generate more precise measurements from a single-point determination (Nguyen and Boger, 1998; Boger, 2013).

4.2. Methods

The Bowen basin coal mine in Central Queensland, Australia was taken as the case study. This site has 6.05 Mt/year run-of-mine (ROM), the fine rejects from Coal Handling and Processing Plant (CHPP) are transported by pipe (diameter 0.45 m) to the TSF as 30% mass solids.

4.2.1. Rheological test

Tests were carried out on samples of coal tailings with solid content by mass from 30% to 70% w/w in order to investigate the behaviour of tailings during dewatering and transporting.

All the samples with different solids concentrations were tested using the rheometer AR-1500ex. The rheometer calibration with zero gaps approximately 11,000 μm. The container was then filled with the sample and the sensor was lowered until the vane was immersed. Steady state flow steps were applied to obtain the main parameters including shear rate, shear stress, and viscosity. The test was set as a shear stress test with ranges from 0.01 to 1000 Pa and the maximum time per point was 1 min.

4.2.2. Energy estimation

The results obtained from the rheology test were used as the primary input to estimate the linear pumping energy required for transporting the tailings. The primary inputs included a consistency index (K), flow behaviour (n), and yield stress (τ_y) as presented in eq. (4). The interaction between these three rheology parameters with field data (velocity described as slurry flow speed (m/s), and pipe diameter and length) resulted in the energy pumping estimation for transporting the mine tailings as shown in eq. (3). The linear energy estimation trend is compared with the energy pumping requirement resulted from HSM as shown in Section 5.3.

Table 5
Sample preparations – mass solids concentration.

Mass solids (%)				
Option 1	Option 2	Option 3	Option 4	Option 5
30	50	60	65	70

The estimation of the linear pumping energy requirement is calculated based on the pressure loss (Pa) and the slurry flow (m^3/s) in eq. (3).

$$E = \Delta P\cdot Q \tag{3}$$

where: E = energy (watt/m) and Q = flow (m^3/s).

The calculation of pressure loss involves the rheology test results together with other parameters including velocity, pipe diameter, and pipe length. The resulting equation for the pressure loss is presented in eq. (4) (Chilton and Stainsby, 1998):

$$\frac{\Delta P}{L} = \frac{4K}{D}\left(\frac{8V}{D}\right)^n\left(\frac{3n+1}{4n}\right)^n\left(\frac{1}{1-X}\right)\left(\frac{1}{1-aX-bX^2-cX^3}\right)^n \tag{4a}$$

$$X = \frac{4L\tau_y}{D\Delta P} \tag{4b}$$

$$a = \frac{1}{(2n+1)};\ b = \frac{2n}{(n+1)(2n+1)};\ c = \frac{2n^2}{(n+1)(2n+1)} \tag{4c}$$

where: ΔP = pressure loss (Pa); K = Herschel-Bulkley consistency index (Pa.s^n) generated from the rheology test; n = Herschel-Bulkley flow behaviour index generated from the rheology test; V = velocity (m/s) was calculated as a function of the flow rate and pipe diameter; D = pipe diameter (m); L = pipe length (m), and τ_y := yield stress (Pa) generated from the rheology test.

4.2.3. Using HSM in water and energy nexus analysis

The experimental and analytical results were incorporated into a computer-based model called Hierarchical System Model (HSM) for synthesis and final analysis. The HSM is graphical, user-friendly software that allows users to build models of mine site water, energy, and emissions networks at arbitrary levels of detail. The typical application of HSM is for developing simplified systems-level models of mine site water and energy networks, in which the complex topology can be simplified to a level that is more easily comprehensible for management purposes, but still retains essential behaviours (Woodley and Keir, 2014; Woodley et al., 2014).

The HSM represents water and energy interactions using six basic components: (i) water inlets that represent water entering the system; (ii) water outlets that represent water leaving the system; (iii) energy/emissions inlets that represent energy and/or emissions entering the system; (iv) energy/emissions outlets that represent energy and/or emissions exiting the system; (v) stores that represent where water is held within the system; and (vi) tasks that represent where water and/or energy are used within the system. The relationships between these components within a coal mine context are shown in Fig. 4.

The HSM was developed by using a Modelica Integrated Development Environment (IDE) which is an equation based modelling language that has the ability to model complex and interconnected systems (Woodley and Keir, 2014). This modelling language was supported by data taken from field mine sites, and

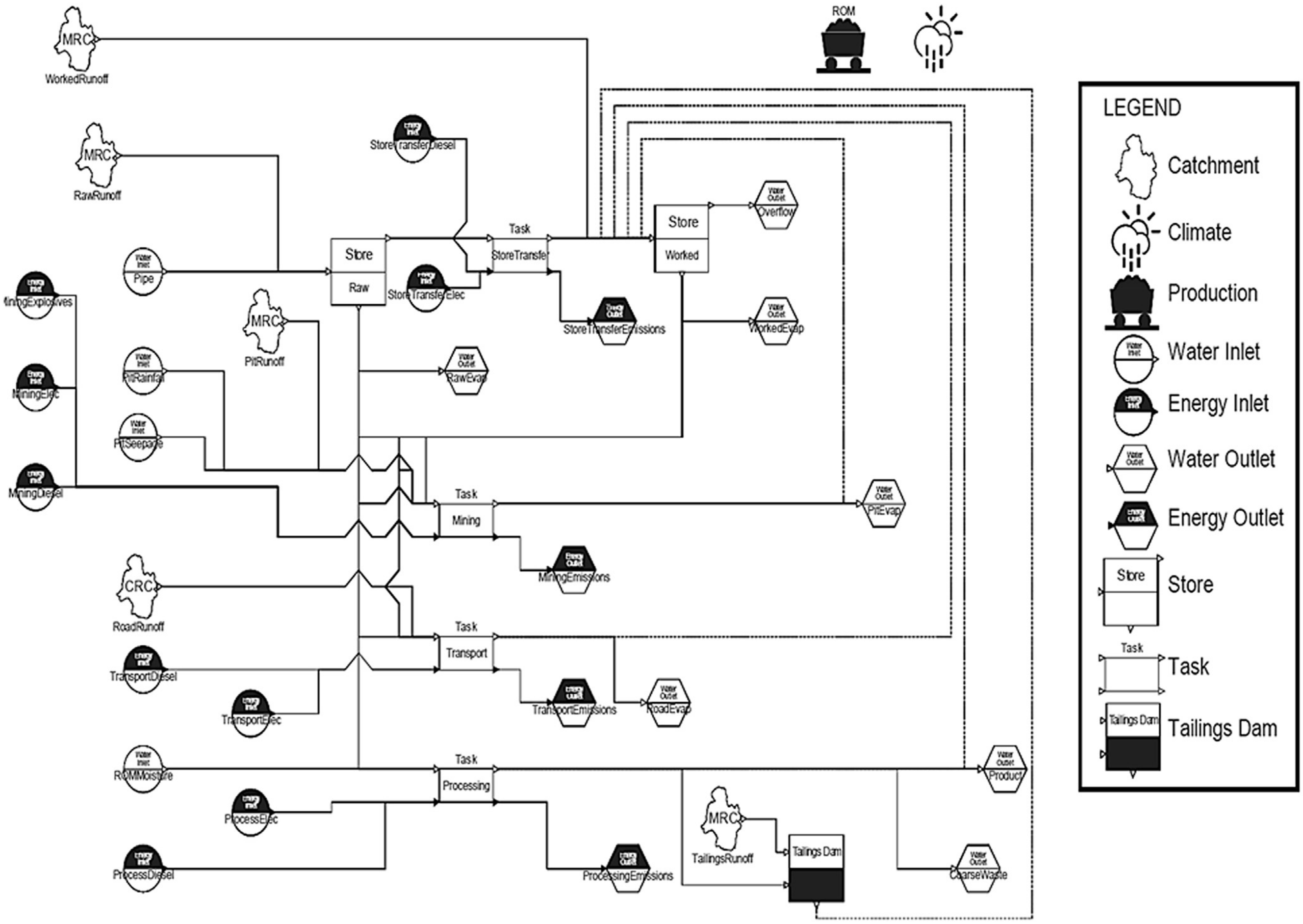

Fig. 4. Schematic of mining operations in HSM.

current literature as presented in Woodley and Keir (2014). The generated outputs of water and energy use highlighted the nexus between the two resources. The results of this model have been further validated by comparing them with other modelling outputs (Woodley et al., 2014). In this study, rheology data was fed into the HSM as an additional data input. The other data inputs into the HSM include:

- Parameters of the site water system such as volume, catchment areas, and surface areas of water storage;
- Geographical coordinates of site infrastructure related to the site water system;
- Climate data in the form of daily rainfall and pan evaporation time series;
- Estimates of the demands of water and energy from various components of the mine site operations; and
- Estimates of the make-up of energy sources required to meet the energy demands of the various operations on site.

In general, most of these data are not measured, and are estimated based on the experience of mine site staff. As it stands, there is no explicit consideration of input data uncertainty (and how this propagates through to model results) at this stage. Certainly this can be realised through uncertainty analysis of the model by a Monte Carlo simulation approach and various deleterious inputs. The author view, however, is that this provides little value for such an analysis as presented here.

In terms of the conversion of input data to output, the HSM uses a simple water and energy balance model to estimate the water pumping energy requirements between objects in the model; it assumes each water stream that connect objects within the model can be represented as a single virtual pipe of a prescribed diameter and hydraulic roughness (when in reality, there may be multiple connections). It is further assumed that for each inlet and outlet on a task object there is a single virtual pump of prescribed efficiency which may represent an array of physical pumps.

The HSM can be used to explore the relationship between water and energy either at the site or regional level, however, for this study, the authors focus only on the tailing management system. There were two main tasks considered in this study: processing tasks/activities and the tailings dam. As presented in Table 9, there are four water flows taken from HSM analysis: 1) store worked water to process; 2) store raw water to process; 3) excess water to store worked water; and 4) tailings transport to TSF.

5. Results and discussion

The results are now discussed in three sections: rheology, pumping energy estimation, and the water and energy nexus. The analyses are focused on the processing task where the tailings are generated and transported to the TSF.

5.1. Rheological characteristic analysis

Different concentrations of coal tailings have been tested to determine the rheological characteristics for each concentration. Typical rheological properties of coal tailings are shown in Figs. 6–7. The nature of the flow curves indicates that the viscosity has an initial plateau at low shear stresses (termed the zero-shear viscosity, η_0), followed by a highly shear thinning regime above a critical stress that is considered here to be an apparent yield stress. The figure includes fits of the yielding regime to the Herschel-Bulkley model in eq. (1). However, the research did not determine a big difference in the viscosity values of each point in the 65% and 70% mass solids as an indication of the yield stress value.

The shear data in Fig. 5a–c and Fig. 6, was obtained with the vane-shear rheometer and demonstrated that concentrated coal mine tailings are non-Newtonian fluids with yield pseudoplastic behaviour. This behaviour is shown the yield stress value being greater than zero ($\tau_0 > 0$) and the Herschel-Bulkley flow behaviour index being less than one ($n < 1$) (Sun et al., 2013; Rao, 2014) as shown in Table 7. In addition, the increasing slurry mass solids concentration was also accompanied by an increasing shear stress. For example, the shear stress value of the tailings slurries at 60% mass solids is higher than for that of 50% mass solids. The increasing shear stress has a close correlation with the increasing shear rate as well as increasing yield stress.

The rheology analysis also shows that only three options for tailings slurry can be transported by pipe (pumpable): 30%, 50%, and 60% mass solids. The others two options (65% and 70% mass solids) have very high yield stress as seen in Table 6 which means both are difficult to pump. Higher mass solids options which are not pumpable need to be managed with other disposal strategies such as a filter press but these have not been considered in this study.

The yield stress increases exponentially with the solids mass concentration as shown in Fig. 7. The yield stress also increased significantly when the solids mass concentration was between 50 and 60%. The detailed rheological characteristics of coal tailings are presented in Table 6. These results demonstrate that the coal tailings yield stress is an important parameter associated with the transport and disposal of tailings. Increasing the value of yield stress generates a higher volume of tailings transported to the TSF and a lower tailings footprint. The yield stress also contributes to the pipeline operations where the high yield stress value reduces the problem associated with pipeline operations as the tailings can be pumped in laminar flow (Nguyen and Boger, 1998). The laminar flow creates less solids deposition problems during transporting. However, high yield stress value is automatically triggered for increasing pumping energy (see Sections 5.2 and 5.3) as well as capital and operating costs.

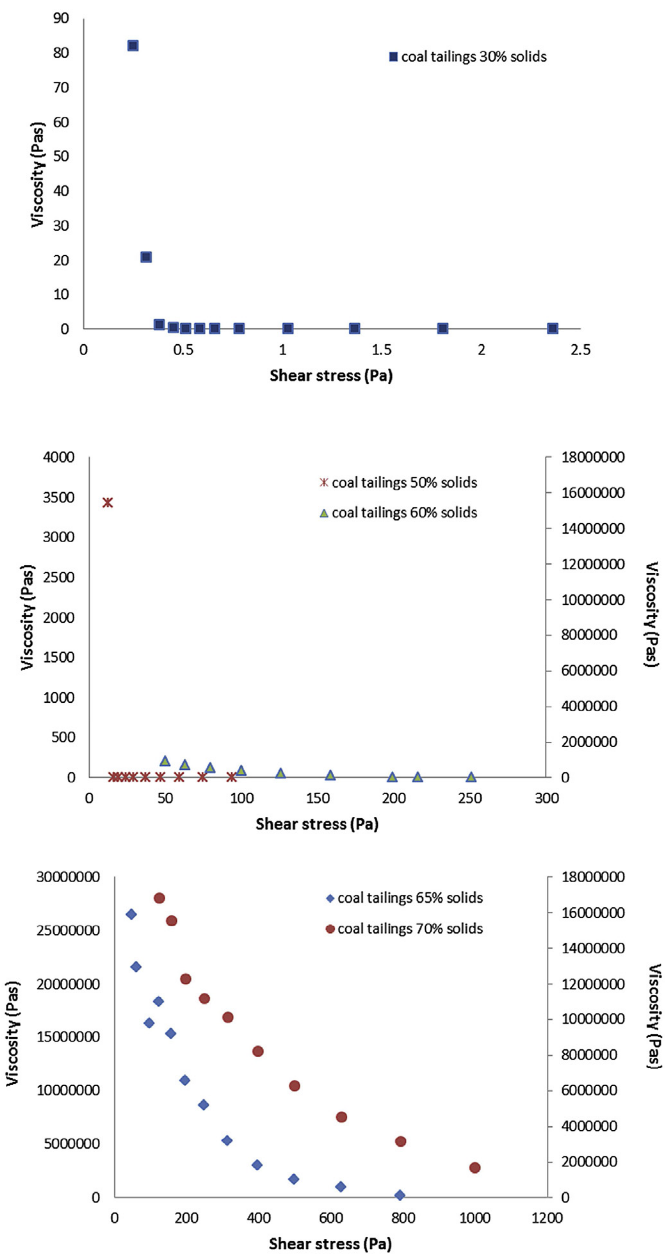

Fig. 5. a. Viscosity as a function of 30%-mass solids and shear stress. **b**. Viscosity as a function of 50% and 60%-mass solids and shear stress. **c**. Viscosity as a function of 65% and 70%-mass solids and shear stress.

5.2. Estimation of linear pumping energy

The energy estimation which includes pressure drop and pumping power consumption can be calculated from the basic flow property data such as those found in Figs. 5–7 and Table 6. The results for the pumping energy estimation are presented in Table 7 and Fig. 8 by using the rheological characteristics data and equations as shown in Section 4.2.3.

The three tailings slurry options presented in Table 7 show that the highest energy requirement occurred when the tailings mass solids changed from 30% to 50% as seen in Fig. 8. Increasing the mass solids from 50% to 60% led to an increase in energy used by

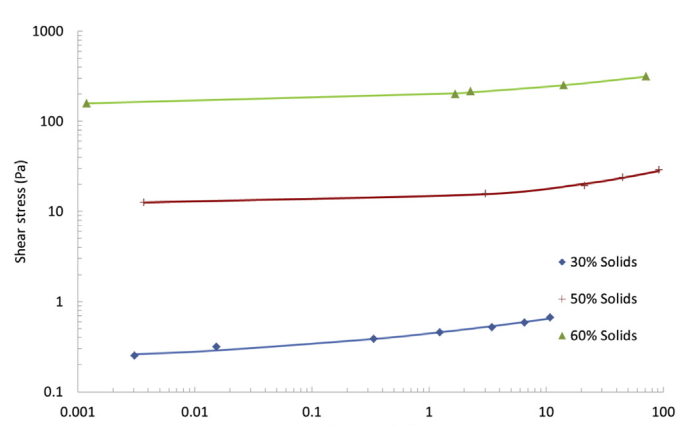

Fig. 6. Shear stress as a function of mass solids and shear rate.

Table 6
Rheological characteristics of the tailings.

Mass solids (%)	Rheological equation	R^2	Yield stress (τ_0)	Flow behaviour indexes (n)
30	$\tau = 0.21 + 0.233 \text{ x } (\dot{\gamma})^{0.266}$	0.99	0.21	0.266
50	$\tau = 12.46 + 1.826 \text{ x } (\dot{\gamma})^{0.476}$	0.99	12.46	0.476
60	$\tau = 152.69 + 44.338 \text{ x } (\dot{\gamma})^{0.302}$	0.99	152.69	0.302
65	–	–	>1178[a]	–
70	–	–	>2700[a]	–

[a] The yield stress (Pa) is too large – not pumpable.

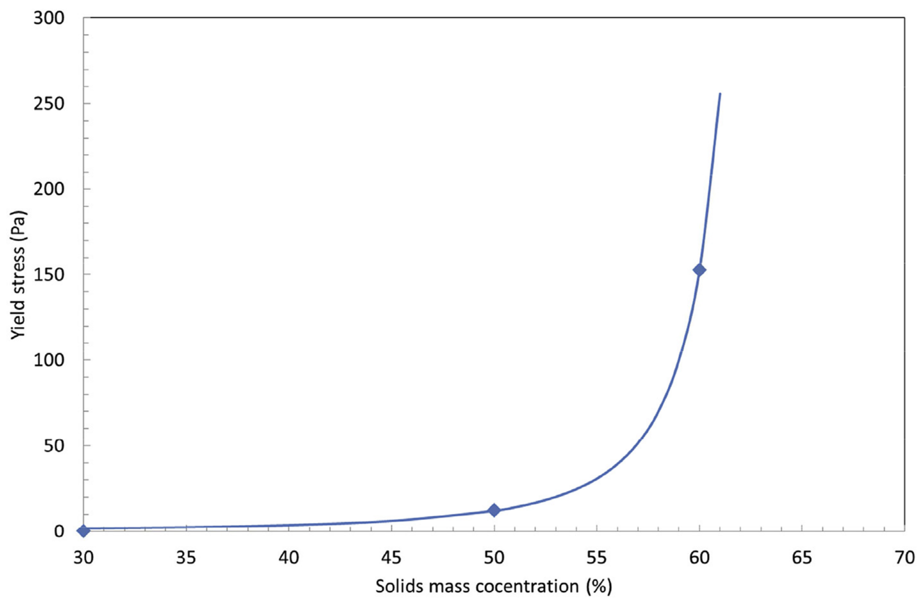

Fig. 7. Yield stress versus solids mass concentration (w/w).

Table 7
Linear pumping energy – estimation.

Mass solids (%)	Flow (m^3/s)	Coefficients			ΔP (Pa)	Energy (watt/m)
		a	b	c		
30	0.009	0.653	0.235	0.073	4.129	0.039
50	0.016	0.512	0.330	0.157	151.633	2.370
60	0.019	0.623	0.289	0.087	1996.401	37.445

35 W (14% higher). An increase in the amount of energy used is closely correlated with a dramatic increase in yield stress value (see Table 6) for all three mass solids slurry concentrations.

5.3. *Discussion on the water and energy nexus in coal tailings management*

Water and energy are two key inputs in mining operations. The increasing demand for water and energy use has a direct impact on mining companies' sustainability performance and production costs. Therefore, it is important to consider the correlation between these two major inputs during process planning, particularly regarding mine tailings management given its high demand for both inputs.

As described in Section 4.2.3, the HSM can be used as a tool to identify the relationship between water and energy use. The procedure for calculating water distribution energy requirements is as follows: (i) the length of each 'pipe' is calculated using the geographic coordinates associated with each object which is then multiplied by a tortuosity coefficient, representing the bends, curves etc. within each pipe; (ii) the difference in elevation between the beginning and end of each pipe is calculated; (iii) the head loss (energy loss due to friction) in each pipe is calculated using the current flow rate and the hydraulic roughness of the pipe; and (iv) the energy requirement for each virtual pump is then calculated based on the current flow rate, the virtual pump efficiency, and the differential head (the sum of the elevation difference and the head loss within the pipe) between the beginning and end of each pipe. A detailed analysis on how the HSM works including formula, and concept can be found in Woodley et al. (2014).

The rheology results were used as one of the main inputs to the HSM in generating the water and energy correlation as presented in Tables 8 and 9 and Figs. 9 and 10. In Fig. 4, a schematic diagram shows mining operations where water used in the processing task has three sources: the excess water from raw material moisture content, worked water storage, and raw water storage. More than 70% of processing plant (CHPP) water consumption is supplied from

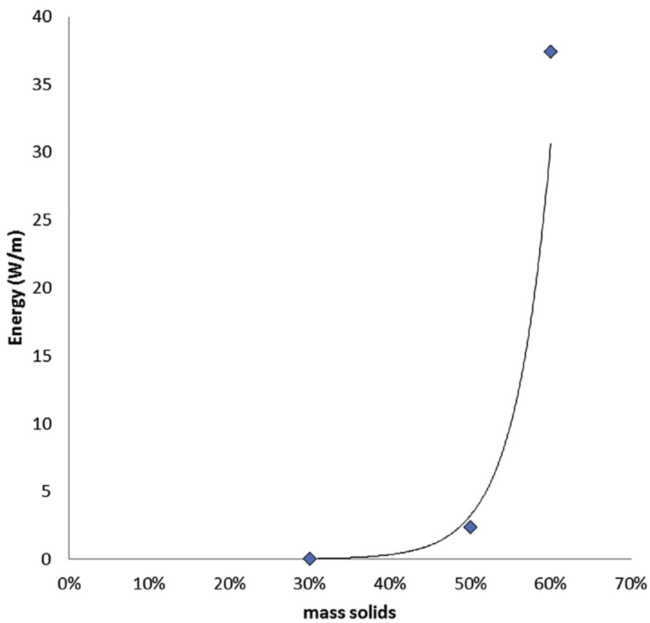

Fig. 8. Linear energy pumping estimation of coal tailings.

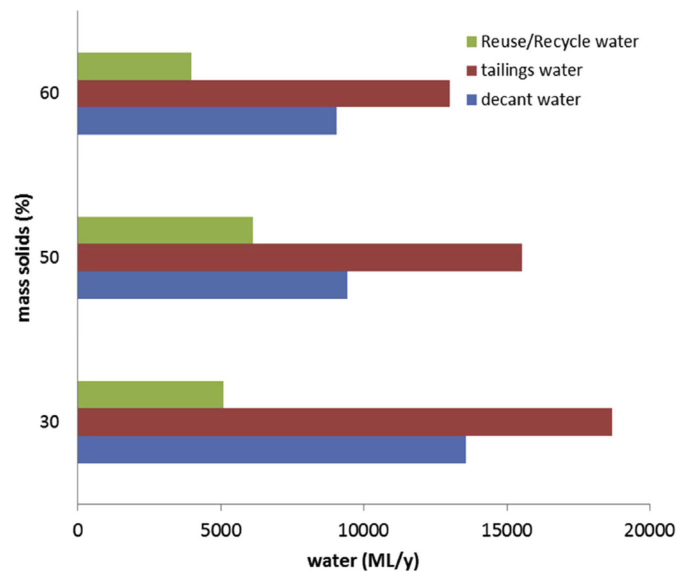

Fig. 10. Water balance in TSF.

Table 8
Processing water balance (ML/y).

Processing task/% solids		Inlet				Outlet				
		ROM	Worked water store	Raw water store	Total	Excess water	Product	Coarse water	Tailings water	Total
Opt-1	30%	8882	51,654	8892	69,428	38,933	11,547	296	18,652	69,482
Opt-2	50%	10,355	62,472	8114	80,941	51,602	13,461	345	15,532	80,941
Opt-3	60%	10,835	65,610	8250	84,696	57,247	14,086	361	13,002	84,696

Table 9
Energy required for processing task (TJ/y).

Flow	Energy (TJ/y)		
	Opt-1 (30% solids)	Opt-2 (50% solids)	Opt-3 (60% solids)
Store worked water to process	40.303	48.745	51.194
Store raw water to process	4.610	4.207	4.277
Excess water to store worked water	12.459	16.514	18.320
Tailings transport to TSF	0.639	34.759	563.749

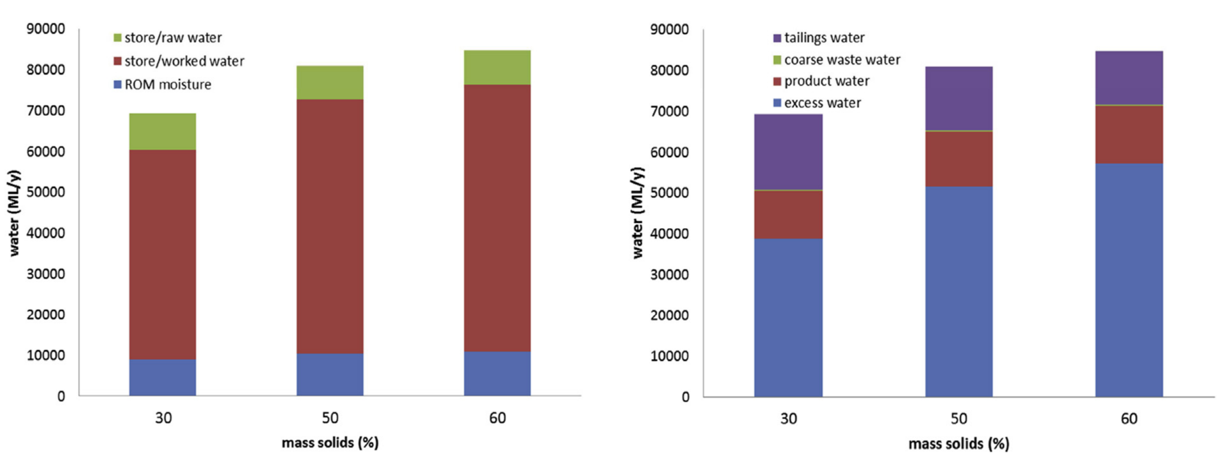

Fig. 9. Water inlet and outlet in processing task.

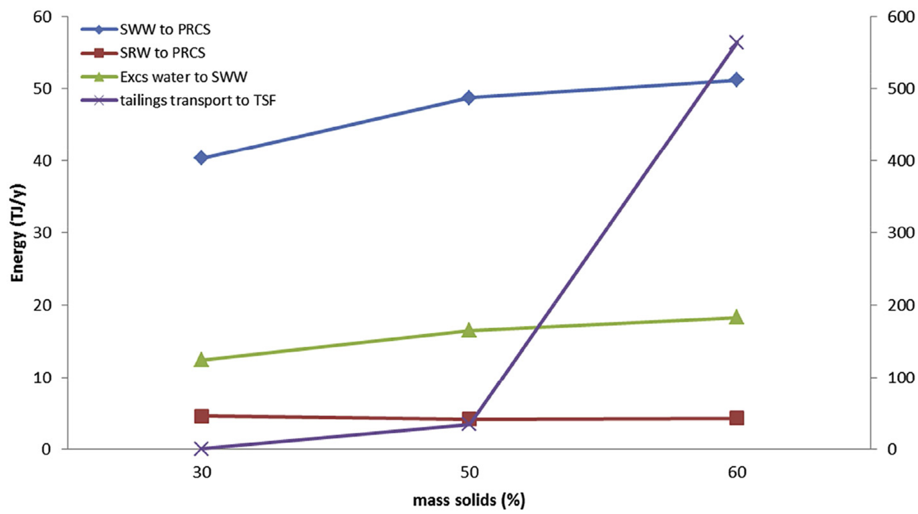

Fig. 11. Energy consumption for processing task.

Table 10
Tailings transportation option summary.

Options	Water (ML/y)	Decant water (ML/y)	Energy (TJ/y)	Water/Energy ratio (ML/TJ)	Reuse water ratio (%)
Tailings disposal-Option 1 (30% solids)	18,652	13,552	0.639	29,189	38
Tailings disposal-Option 2 (50% solids)	15,532	9409	34.759	447	65
Tailings disposal-Option 3 (60% solids)	13,002	9040	563.749	23	44

the worked water store as shown in Table 8. The worked water store receives the water from a runoff inlet, the raw water store, excess water, and the tailings decant water as described in Fig. 4.

As presented in Table 8, the lowest total water volume consumed by CHPP is for tailings management Option 1 (tailings slurry) with 69,428 ML water/year and the total volume difference with Option 2 and 3 is approximately 11,513 ML/year (16%) and 15,268 ML/year (22%) respectively. In addition, the volume of excess water pumped to worked water storage increases by more than 50% in Option 2 (50% mass solids) and Option 3 (60% mass solids).

As expected, the consumption of water needed for transporting tailings to the TSF decreased with increased tailings mass solids. As seen in Fig. 9, around 18,652 ML water/year is required for transporting tailings with 30% mass solids (Option 1) and the water demand declines around 30% when using Option 3 at 60% mass solids.

Overall, the decrease in water used in transferring tailings to the TSF lowers the volume of decanting water generated from the TSF as presented in Fig. 10. Tailings disposal Option 3 generates decant water 33% lower than slurry tailings disposal option. This means that tailings water transporting to the TSF can be reduced by around 30% with the application of Option 3. Decreasing the water load to the TSF should also increase the capacity and extend the lifespan of the facility.

The water distribution to and from the processing task in the case study used two methods: a gravity fed and pumping system. The pumping system is used to transport store worked water (SWW) to the CHPP, store raw water (SRW) to the CHPP, excess water to the SWW, and tailings from the CHPP to the TSF. The total energy required to transport water and tailings is presented in Table 9.

The energy required in pumping water from the store worked water to the CHPP is in the range of 40–51 TJ/year with the average difference in energy usage of each option being approximately 17%. The highest difference in energy usage occurs when coal tailings are pumped to the TSF as shown in Table 9. The energy pumping used in Option 2 to transport tailings into the TSF is 53 times higher than Option 1 and 881 times higher if tailings disposal Option 3 is selected.

Therefore, the energy consumption for tailings transport from the CHPP to the TSF is strongly dependent on the mass percent solids as shown in Fig. 11. The energy usage increases dramatically when the mass percent solids change from 50% to 60%. This result also corresponds well with the theoretical estimation from a rheology perspective (see Section 5.2).

The results from all three tailings disposal options are summarized in Table 10. The base case option (tailings slurry) transports water from the CHPP to the TSF at approximately 18,652 ML/y with 0.6 TJ energy use per year. Option 1 also generated a ratio between water consumption for tailings distribution and the volume of decant water at 38%. Increasing mass solids to 50% in Option 2 resulted in the lowering of water use to 15,532 ML/y whilst consuming 34.7 TJ/y of energy. In addition, Option 2 also reduces the water that is managed in the TSF by 30% and this can be seen from the high water reuse ratio. The reuse water ratio resulting from choosing Option 2 is 65% and the highest ratio compared with other options. Option 3 with 60% mass solids achieved a water savings of 3119 ML/y compared to the base case option with approximately 563 TJ/y energy required which is the highest of all three tailings management options examined.

6. Conclusions

This paper discusses the synergy and trade-offs between water and energy use in coal mine tailings management. Three of five mass percent solids options, which are pumpable tailings, were analysed further by using HSM to determine the optimum method for transporting tailings to the TSF. The results of this analysis highlight the importance of tailings disposal strategies in mine water management and the significance of the correlation between water and energy use. From the results presented, it can be concluded, firstly, the optimum option in terms of water and energy conservation, and water management is Option 2 for the tailings with 50% mass solids for this particular coal mine site. Secondly, coal mine tailings with a mass percent solid above 65% cannot be transported by pipeline. Thirdly, the water and energy nexus is not only associated with the pumping system but also with the technology used in processing. The outcome of this study is to provide guidelines for water and energy usage to assist in the decision making of tailings management strategies for coal mining. A good strategy is essential for improving sustainability performance of mine tailings disposal throughout the life of a mine.

Further study is required to assess the contribution of various other technologies in tailings management in terms of their energy and water consumption. Additional assessment of pumping and processing technology systems will provide a more complete estimation of energy and water usage in a particular tailings disposal strategy. Environmental and economic perspectives should also be considered in the assessment. These two considerations would complement this study to generate a more comprehensive framework for decision makers in choosing the appropriate tailings disposal strategies for a particular mine site. Examining the trade-off between water and energy use in tailings management is a good start in improving both the efficiency and sustainability performance of mine tailings management.

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