HANDLING UNCERTAINTY IN WATER RESOURCE OPTIMISATION

J.A. GRIFFITHS[1]

[1]SRK Consulting (UK) Ltd, Churchill Way, Cardiff, Wales, UK; E-mail: jgriffiths@srk.co.uk

ABSTRACT

> *'There are known-knowns. These are things we know that we know.*
> *Then, there are known-unknowns. That is to say, things that we know, we don't know.*
> *But, there are also unknown-unknowns. These are things we don't know, we don't know…'*
>
> Donald Rumsfeld, 2002.

Due to the range and variation of water demands within any mining operation, the calculation, management, and optimisation of water-use can be a complex task. With multiple variables operating with often unpredictable or complex behavior, a formal process of water balancing and risk assessment is essential. This paper describes a number of water balance methods that can be used to represent the mine water management. The advantages and disadvantages of a simple spreadsheet approach are compared to more complex stochastic models, and with respect to input requirements, design time, process representation, outputs and predictive capacity. The ability of a stochastic-type model to assess the impact climatic variation is assessed using rainfall and evaporation summary statistics from humid-temperate, tropical-humid and semi-arid environments. Although employed within a course-scale comparison, it is concluded that the stochastic features within risk-analysis type software can provide an excellent tool for mine water managers to characterise the site water balance, identify potential risks and optimise water use. This approach may also be used to represent the potential impact of climate change on mining activities.

1. INTRODUCTION

Mining corporations need water to release the valuable mineral resources from their host lithology. Water is an efficient, low-cost and low energy way of transporting and mixing particles; it is used in crushing, screening, washing and floatation; and is an essential chemical ingredient in a range of metallurgical processes. In order to minimize and conserve water use, it is necessary to understand how much water is used at each step of the mineral extraction process, and how this need will change over time in response to external factors.

It is estimated that globally, the minerals industry uses approximately 80 percent groundwater, 15 percent surface water and 5 percent existing infrastructure water. At an estimated value of US$60 per cubic meter, the economic value of water used by the minerals industry is higher than that of both the industrial sector (US$30/m^3), and the agricultural industry (US$4/m^3), (Thyer, 2007). With increasing competition for water resources, the mining and minerals industries can be expected to come under increasing pressure to 'reduce, re-use and recycle' their supplies of fresh surface and ground-water.

At most mining operations, a mine water management plan is designed in order to integrate and manage the use of both surface and groundwater resources. This might include reference to surface water management plans, environmental management plans, and regional water-resource strategies, with the aim being to allow mine water managers to make the most economically efficient decisions with respect to both the profitability of mining operations and expected available water resources. By contrast the lack of a sound mine water management strategy can lead to the unsustainable use of water resources, and demand exceedence of available resources. The lack of a sound site-water management plan is a common cause of abstraction and discharge permit violations, which can become an expensive irritation to mine operators (Sawatsky et al., 1995).

This paper investigates the use of water-balance methodology to characterise, and ultimately optimise, the use of water within the mine site; as would be required within most mine water management plans. In particular the challenges of data, process and climate uncertainty are addressed, as these are frequently a cause of error in mine water demand estimates.

2. WATER BALANCE METHODOLOGY

At its most basic, water-balance creation for mining operations involves development of an inventory of inputs and outputs from the water-supply and ore-processing infrastructure. Recording of flows between system components allows identification of seasonal trends in water-use. Validation of the preliminary balance of water use within the site, is achieved by ensuring that total water into the site equals total water leaving the site. The approach can be applied to sub-components within the larger system, as well as to the whole system itself.

At an early stage in the development of a conceptual water-balance model it is useful to represent the system using a flow diagram. Figure 1 represents a simple mine water-balance consisting a process water dam (PWD), a storage water dam (Dam 2), a tailing site facility (TSF) and an external lake water supply. Rainfall and evaporation are not explicitly represented within the diagram, but will contribute to all ‘open’ storage within the system (PWD, TSF, Dam 2). Runoff into the dam, pits and TSF is also considered within the balance calculation.

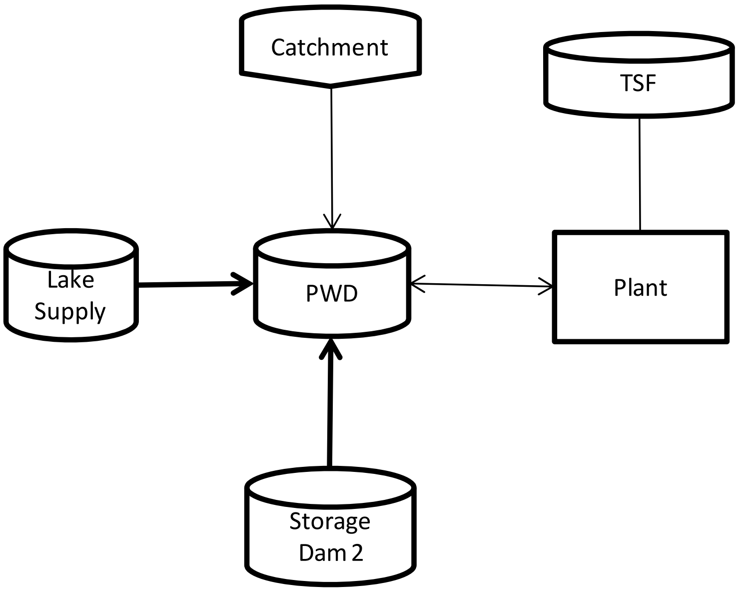


Figure 1**.** A basic schematic of mine water balance system.

Deterministic Models

The level of detail contained within Figure 1 can be quite effectively represented within a spreadsheet model, and designed to run at monthly time-steps. Given basic processing, rainfall, evaporation, and catchment data, remaining ‘unknowns’ within the system (e.g. dam or pit seepage rates, groundwater inflow rates, etc.), can be deduced from known information (on the assumption that: inputs - outputs = 0). These models are referred to as deterministic models as outcomes are precisely determined from known relationships between system components.

Model sophistication can be increased through representation of system control-gates such as valves, pumps, flow-splitters etc. Such system controls are often in place as safety mechanisms to prevent over-topping of storages components or to reduce the chance of demand exceedence above available supply, and are often dependent on water-level or flow-rate thresholds for triggering. This type of model may be more effectively run at daily intervals, but will accordingly require more detailed input data less sophisticated models.

Finally, an optimization target may be defined for the model. This involves setting a criteria to which the model must be balanced. Examples of such criteria may be to minimize total water use within the site; maximize recycling; or reduce total fresh water consumption.

Stochastic Models

Stochastic or probabilistic models allow the incorporation of variability and uncertainty in model parameters within the model. Such variability is produced through a number of different sources including measurement error; climatic variability; unforeseen changes in production schedules; logistical error; and flow rate uncertainties. Whilst most of these uncertainties can be represented using random number functions, they can present quite a challenge to implement realistically within a spreadsheet model, and may be more effectively represented using specialist software such as *GoldSim*, *@RISK*, or *Crystal Ball*.

Model Use

Water balance models are most often used to illustrate current water use and likely future demand. Ideally, they should also be able to predict how a system will react to changes, whether this be regulatory, climatic, managerial or infrastructural. The DWAF Best Practice Guidelines (DWAF, 2006), suggests that water balance development should aim to achieve the following:

- Allow auditing and assessment of the water reticulation system (for identification of wastage, seepage, leakage and pollution sources).

- Allow modelling and simulation of water management strategies to assist in water management decision-making processes.
- Assist in the design of storage requirements
- Provide information required to define and drive water management strategies.

Cote et.al., (2006), suggest that water balance models should vary in their complexity depending on their use, ranging from simple *conceptual* models, through *system* models and *engineering* models, to more complex *scientific* models (with data requirements increasing with complexity). Generally, mine water management will not require the complexity provided by scientific-level models unless particular components of the water supply system require more detailed investigation. Rather, it is system-level models that, whilst not detailed enough to allow use in an everyday engineering capacity, may be effectively used for strategic planning, performance assessment, system comparison, risk analysis and scenario modeling.

3. SOURCES OF UNCERTAINTY

Haimes (1998) divides uncertainty into two main categories: parameter or variable uncertainty - relating to the inherent and natural variation within the parameters or variables concerned; and knowledge uncertainty - relating to limitations in either access to information or a lack of understanding of modeled processes. Before using any model, the sources of uncertainty within that model must first be identified, and ideally quantified.

Input Data

The requirement for on-site hydrological data is often neglected at early stages of mine-site development. Basic hydrological data is necessary for realistic site characterisation, conceptual model development and initial numerical simulation. Once operations are underway, water flows and storage levels around the site need to be recorded at least monthly. Where data has been collected over a longer period it may be necessary to represent average annual variation and deviation from that variation between years. Figure 2 illustrates typical mine-site data relating to the transport and storage of water. Each data set describes both mean monthly quantity (volume flow or volume stored) and the extent of variation from that mean (standard deviation, and minimum and maximum limits).

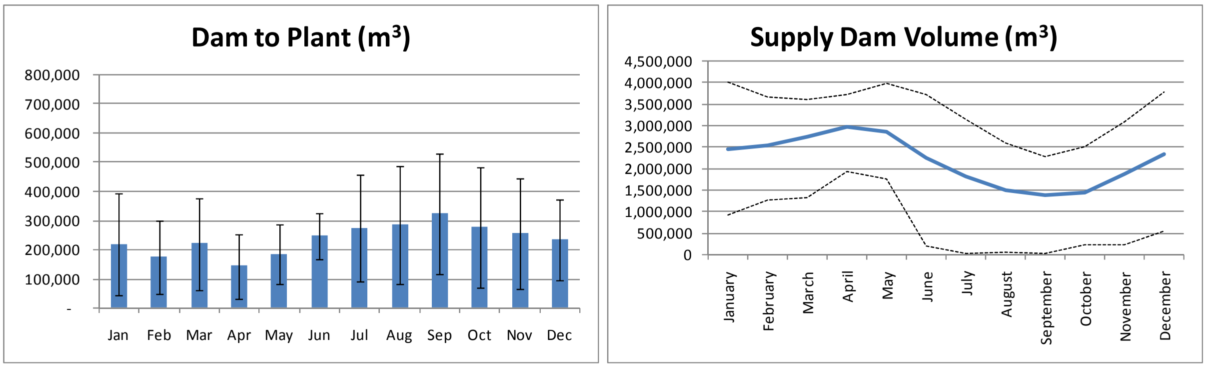


Figure 2. Example standard deviation and mean monthly water supply data from water dam to plant; and mean, minimum and maximum annual dam storage volume data (for years 2001 to 2007).

Measurement Error

In order to quantify flows between different components of the water balance, pipe valves, pump loggers, flumes and v-notch weirs should all be monitored, at least monthly. Recommended measurement accuracy for individual flows within the system is 1-5% of the total system flow. Water balance accuracy of individual flows and processes should be within 5-10%, and within 10-15% accuracy for the mine as a whole (DWAF, 2006).

In reality, gaps in monitoring data do occur due to equipment failure and or human error. Where it is not possible to deduce missing information from the water balance model, a best estimation should be made, based on experience, and with a liberal degree of uncertainty acknowledged. Accidental or intermittent seepage and spillages can also represent an un-measureable source of uncertainty. Seepage flows (from water tanks, into pits, from storage dams etc.) can be so dispersed that they are impossible to measure and so must remain as uncertainty to be resolved through the water balance.

Process and Management Uncertainty

McPhail (2005) suggests that it is often the TSF and other associated water management infrastructure (process water ponds; storm-water ponds; etc.), that have the greatest variability and uncertainty on a mine site, due to the inherent variability in rainfall, runoff, evaporation and seepage rates.

Commonly, 80% of water in circulation at a mine site is associated with the TSF, and the largest losses of water also occur within this facility, illustrating the criticality of representing both variation in climate parameters.

Uncertainty may also be found within the water take-up of the processing operation which is dependent on a number of often external factors such as grade of material being processed, logistical or financial issues, and unexpected changes to system operations. This type of uncertainty is less easy to quantify but may be represented within operational scenarios using ‘best-guess’ margins of error, as defined by experience and the scale of the operation under study.

Climate Change

At very least, the mine water-balance should be able to represent average, wet and dry years in order to allow a basic assessment of the amount of variability that is likely to be seen in available water resources, and to allow design of water management systems with enough flexibility to be able to cope with such conditions. In more complex models, calculation of 5^{th}, 50^{th} and 95^{th} percentile rainfall distributions can be used to illustrate dry, average and wet years respectively. Uncertainty created by inter-annual climate variability can be represented by standard deviation between years.

The use of water to support mining operations in often remote areas will be exacerbated by climate change. Increased variation in climatic variability will inevitably result in increased operational risks (i.e. the ability to meet licensed discharge and abstraction compliance), unless mitigation based on accurate representation of existing site water-balance has been made. Within this context, mine-water management is given increased importance. Indeed, whilst primary management strategies to improve mine water management and sustainable use include the reduction of process losses, increased water recycling, and reduction of evaporation losses, characterisation of a site’s ‘risk profile’ with respect to impact from climate change should also be made a priority.

4. DEALING WITH UNCERTAINTY

Decision support tools can be used to help develop planning strategies for dealing with the possible effects of climatic variability, and or other uncertainties. Such tools however, must be tailored to particular system characteristics, location and planning requirements. Decision support systems typically consist of models, data and software that allow multiple projections of future conditions, and should be able to indicate the advantages of specific courses of action. Key stages in the design of such a system include:

1. Identification of quantifiable measures of system performance (e.g. water supply/availability).
2. Identification of sources of uncertainty and their impact on performance indicators (sensitivity analysis).
3. Running future projections using different management scenarios (Monte Carlo simulation).
4. Running future projections incorporating known uncertainties.
5. Identification of preferred scenario with respect to system performance indicators.

Mining companies typically have a number of measures of system performance with respect to water management including the provision of sufficient water supply to processing plants; provision of potable and domestic water supply; maintenance of flows within surrounding water courses; and regulation of discharge amounts to the environment. In the following case study, the criteria of minimizing external water demand is discussed with respect to uncertainty introduced in the form of different climatic zone characteristics.

5. CASE STUDY

A generic mine-water balance model was constructed in order to assess the impact of regional climate zones (Humid-Temperate, Tropical-Humid and Semi-Arid) on model predictions. A hypothetical mine-site based on that illustrated in Figure 1 consists of a process water supply dam (PWD), tailings site facility (TSF), water supply dam (Dam 2), and an external lake water supply. Process plant water demand is described as a function of ore feed-rate and moisture content, and the required tailings density.

Rainfall is represented by mean monthly rainfall (mm) and standard deviation of monthly rainfall between years ($n>20$). Evapotranspiration rate (mm/day) is also represented by monthly averages. In order to represent natural variation that will occur in rainfall and evaporation between years, a second order Markov chain is used where the probability of a wet day occurring is based on the previous day’s rainfall. The depth of rainfall occurring on wet days in any month is predicted from the log normal distribution (defined by mean and standard deviation statistic) for that month. Daily evaporation is also fitted to a normal distribution for each month, but negatively correlated with precipitation (lower evaporation when it’s raining). Figure 3 illustrates the mean, and 5^{th} to 95^{th} percentile value range for annual variation in daily rainfall and evaporation (input data used to characterise different climate zones).

The Monte Carlo simulation technique was used with the model, whereby the model was run 100 times. For each run, values of rainfall and evaporation were randomly picked from the representative monthly distributions shown in Figure 3. Within each model run, rainfall and evaporation are used as input and output parameters to the PWD, TSF and Dam 2. Water for the process plant is taken directly from the PWD. Dam 2 is used to top-up the PWD to an operating volume

(180,000 m^3). If Dam 2 has insufficient water, water is taken from the lake water supply. The starting condition for Dam 2 is empty. Waste water from the plant is also recycled via the TSF.

Figure 3. Mean and 5th to 95th percentile value ranges for annual variation in daily precipitation and evaporation data for different climate zones.

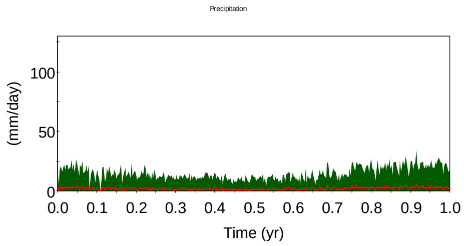
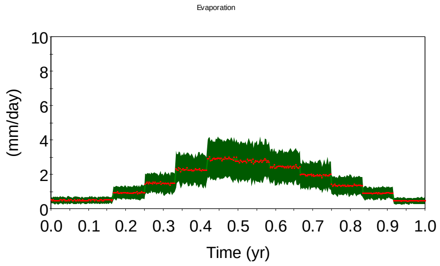
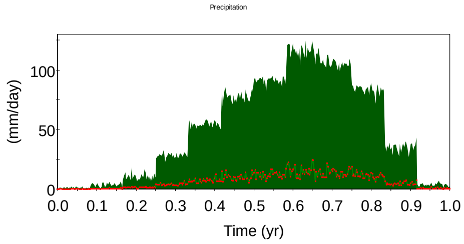
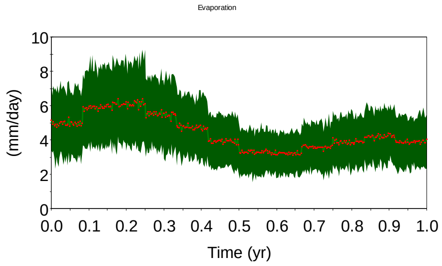
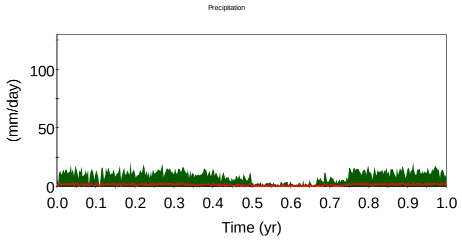
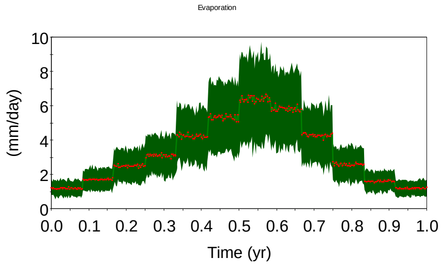
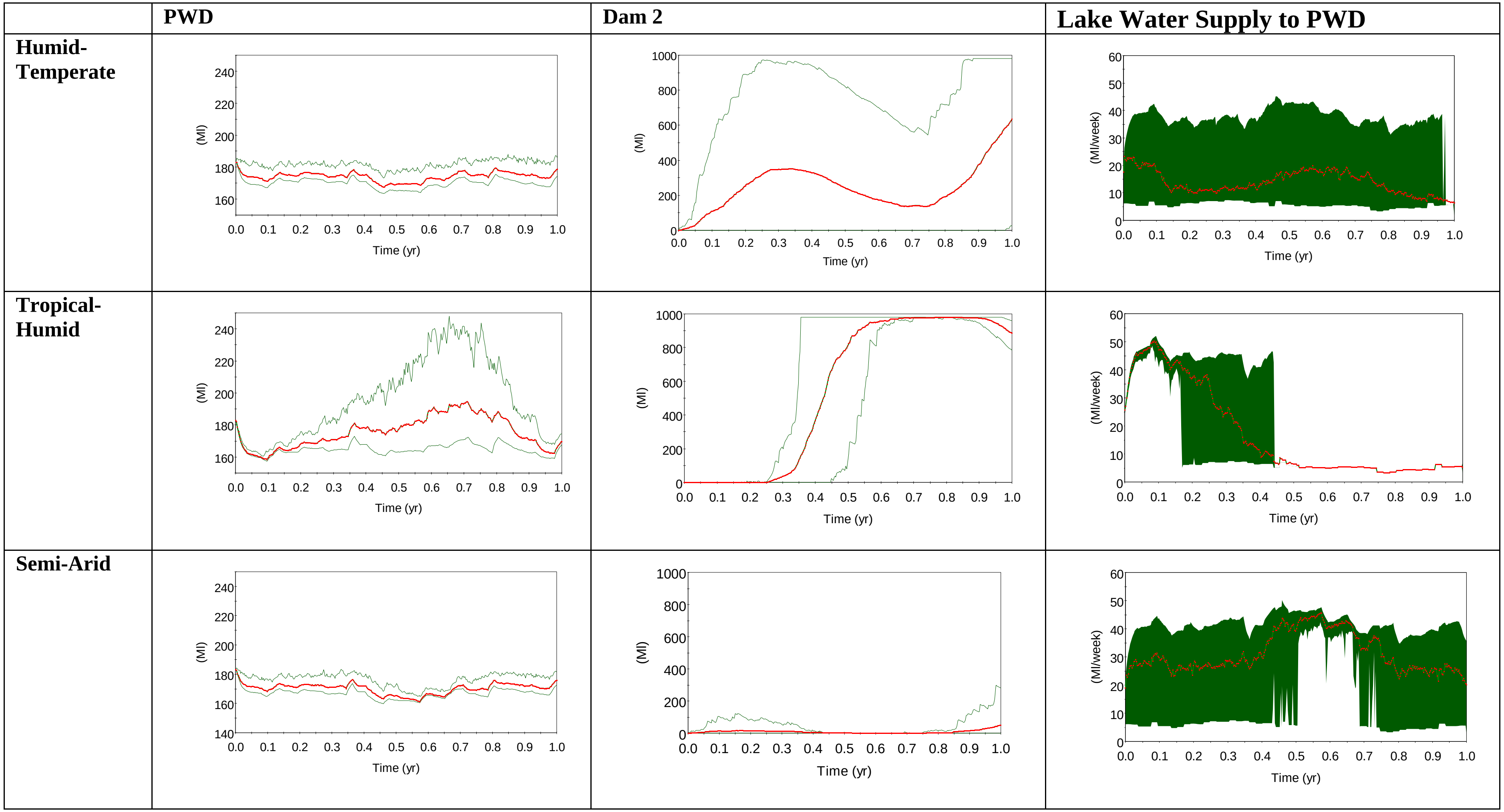
	Precipitation (mm/day)	**Mean Evaporation (mm/day)**
Humid - Temperate		
Tropical - Humid		
Semi - Arid		

Figure 4 illustrates the variation in mean, and 5th to 95th percentiles (for 100 simulations), for the calculated volume of water held within the PWD and Dam 2 throughout a year, and the amount of water required by the PWD from the Lake, to make up the shortfall from Dam 2. It can be seen that under humid-temperate climate, additional mine water demand from the lake water supply ranges between approximately 5,000 and 40,000 m^3/week throughout the year. Variation in the mean lake water demand indicates the likely increase in demand at the start of the year (due to low initial volume in Dam 2) and late summer (due to low rainfall). The high degree of uncertainty (large 5th to 95th percentile range) in lake water supply requirement, reflects the high variability of rainfall of the temperate climate.

Figure 4. Variation in mean and 5th to 95th percentiles of storages and flow between system components.



By contrast, if the model is run using precipitation and evaporation statistics representing the tropical-humid zone, minimal rainfall at the start of the year means that water demand will always be high (it can be seen that there is high certainty {or low uncertainty} of this). A period of transition occurs as the rainy season starts and both the PWD and Dam 2 start to fill. At this stage the need for external water supply decreases, though uncertainty increases (again due to inherent uncertainty within the rainfall data). In the last quarter of the year, rainfall is high and frequent and results in overtopping of Dam 2. However, because of the limited capacity of the dam (1,000,000 m^3), the need for a small amount of lake water supply will still exist.

The semi-arid climate zone is characterised by a low bimodal rainfall pattern with the wettest periods at the start and end of the year. This pattern is reflected in the variation of Dam 2 volume. This results in generally high uncertainty as to the requirement for external water supply (due to high inter-annual rainfall variability). The exception to this is the third quarter of the year when there is a high certainty of low rainfall, thus illustrating that there is a demand of 35,000 to 45,000 m^3/week for the lake water supply.

6. DISCUSSION

Two extremely pertinent questions that should be asked on completion of any water balance model, as posited by McPhail (2005), are ‘how accurate is the model?’ and ‘is it sufficient to base a water management strategy on?’. However, water balances should be assessed on their representativeness as well as their accuracy. In addition, the real strength of the water balance is not simply how well it represents existing conditions, but rather how well can it represent the system under changing conditions. For example, depletion in available water or an increase in water demand. A good water balance model then, should allow water managers to trial a number of different possible solutions with the model before implementing them in reality.

To some extent the case study scenarios are unrealistic, in that the same PWD, TSF and dam dimensions were employed within both a semi-arid and tropical humid environment. This is emphasised by the fact that in the tropical environment, Dam 2 would be regularly significantly over-topped in the third quarter of the year, whereas in the semi-arid climate it would never even reach half full. However, the exercise is useful in demonstrating the usefulness of such an approach to help visualise the system dynamics and identify where improvements can be made (e.g. increasing the capacity of Dam 2 to reduce the need for external supply).

On reflection, the basic approach to water balance creation, as suggested by Etchells and Malano (2007), whereby the design process is divided into three main stages is a good one. These involved the following steps:

1. Resource estimation.

   Used to characterise hydrological and storage capacity behavior, including estimation of external factors of rainfall, runoff, evaporation and seepage. These factors tend to be extremely dynamic and have a high degree of uncertainty that must be represented. Storage components such as lake and reservoirs also behave dynamically with respect to their structure and the number of input and output points that they are dependent on.

2. Representation of the distribution framework.

   This can be in the form of a set of rules and that reflect management procedures that govern the system and the regulatory framework within which water management takes place. Whilst more or less predefined, uncertainty may exist where the sets of rules are deviated from.

3. Demand estimation.

   Reflecting the behavior and pattern of water-user demand. User demand can be extremely complex, varying in extent depending on production seasonality, climatic variation and socio-economic influences. Depending on the storage system structure, there may also be a lag between actual user demand and the resulting demand on the system.

   The decision of which type of water balance model to use (deterministic or stochastic; steady-state or dynamic), will depend on the specific requirements of the task. Table 1 outlines the relative advantages and disadvantages of each approach with respect to representativeness, data dependency and model performance.

Table 1**.** Comparison of modeling approach advantages and disadvantages

Modelling Approach	**Purpose**	**Data Dependency**	**Uncertainty**	**Performance**
Mean Monthly Water Balance (Deterministic)	Represent average monthly water usage expected throughout life of mine.	Small	Low uncertainty Uncertainty not represented by model.	Steady-state
Mean Monthly Water Balance (Stochastic)	Represent average monthly water usage expected throughout life of mine.	Medium	Large uncertainty Uncertainty represented by model.	Steady-state
Continuous Monthly Water Balance (Deterministic)	Represent monthly water usage for given period (in addition to average monthly water usage).	Medium	Low uncertainty Uncertainty not represented by model.	Dynamic
Continuous Monthly Water Balance (Stochastic)	Represent monthly water usage for given period (in addition to average monthly water usage.	High	Large uncertainty Uncertainty not represented by model.	Dynamic

7. CONCLUSION

This paper has described a number of practical steps that can be taken to rationalise uncertainty within water balance modelling. Data collection and characterisation in particular, can be hugely improved by better client briefing in order to ensure that water management protocols are recorded and that an accurate record of water management is developed. Similarly, protocols for water monitoring should be drafted in order to ensure consistent monitoring procedures are conducted at a temporal frequency dictated by the model needs.

Recent collaboration between the author and the Meteorological office in the UK indicate that site specific rainfall and evaporation data for even the most remote area can now be provided along with necessary statistical descriptions needed to represent the inherent uncertainty (for both present and future conditions) within stochastic water balance models. It is suggested that significant changes in average and extreme rainfall, even within the UK, could be seen within five to ten years (sooner in some parts of the world). With the uncertainty of climate change surrounding future water resource management models, the use of stochastic simulation software for risk analysis and scenario modeling (as well as standard resource assessment) has obvious advantages over deterministic models.

It is also recommended that stochastic water resource models should be used with long-term climate prediction information earlier within the mine planning process. In this way, mine planners can take account of the potential extent and cost of water resources likely to be available throughout the life of mine, and adjust their mine plans accordingly if required.

Finally, to paraphrase Donald Rumsfeld, we could that in trying to deal with uncertainty, we are dealing with *unknown-knowns*, these are the things we sometimes *don't know we know*, at least until we make further investigation.

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