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Full Length Research Paper

Application of system dynamic approach for water planning and decision making under water scarcity at Jwaneng diamond mine

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Business operations under water scarcity requires efficient water management to avoid disruptions to prolong lifespan of the water resources. One way to enhance effective water resource management is the use of approaches that study the system in holistically. One such approach is system dynamic approach. Thus, in this article, water use by mining sector in Botswana is assessed using system dynamic approach. Results indicate that water use per tonne at the mine is highly erractic. Consequently, this leads to ineffective water resource management. Simulation of the developed model reveal that if average water consumption of 0.8 m^3/t is achieved, the mine could have saved a total of 0.26 million m^3 for 3 years. Moreover, findings also reveal that water use is also highly erratic. Results from the simulating reveal that reducing water use per tonnage and increasing water reuse will lead to water saving and conservation at the mines.

Key words: System dynamic approach, demand, supply, use, reuse, feedbacks, system, mine.

INTRODUCTION

Business operations under water scarcity situations need prudent, careful planning to avoid costly disruption from depletion. Careful planning is only possible through management tools. Alegre et al (2007) notes that to enhance operation on a business-as-usual for long term under water scarcity, climate change impacts and variability, tools are essential. Consequently, mining activities in Botswana are faced with such situations where water scarcity is a problem. For instance, it is estimated that the wellfields currently supplying diamonds mines (Orapa, letlhakane and Jwaneng mines) have the life time of 20 years unless other groundwater options are explored (Zhou and Masindera, 1998). Moreover, drought is a recurrent climatic event in the country with a return period of 2 years (Masike, 2007). Generally, droughts are accompanied by acute water shortage such that economic activities can be seriously disrupted. Thus, it is imperative that careful planning on water resources is emphasis in production decision making in the country. Careful planning will ensure that business-as-usual is achieved during acute water scarcity. Moreover, it can also prolong the life time of the existing non-renewable water sources.

Incidentally, the mining sector is one of the major water users in the country. With increase in world demand for diamonds particularly from Asian countries such as China and India, more water will be required. In addition, increase in diamond production from recovery diamonds from tailings, may also lead to increase in water demand in the mining sector. These increases in water demand coupled with the impacts of climate change on water resourcers through decline in annual precipitation (Masike, 2008) could result in serious water scarcity in the country. Therefore, environmental tools will increasily be needed to facilitate in water utilisation efficiency under future acute water scarcity scenarios. Over the years environmental tools have proved to be indespesable and an integral part of environmental management and protection. Some of the tools that have increasingly been used are environmental audit and natural resource accounts. In Botswana, natural resources accounts have been adopted to enable decision making of resources allocation (Department of Environmental Affairs (DEA) and Center of Applied Research, 2006; Hambira, 2007; Lange, 1997).

In this article, water use audits are integrated to water resources account as an approach for water planning and decision making under scarcity and uncertainty

Table 1. Water consumption sectors at Jwaneng.

Consumption sectors	Consumption (m^3)
Mine	742249.8
Indusrtial	38685.35
Township	153566.9
Losses	76728.29
North west field abatraction	956230.6

scenarios. This exercise is used for Jwaneng diamond mine which is owned by Debswana a joint venture between Government of Botswana and De Beers. A system dynamic approach is used as a framework for integrating water use audits in water accounts. Coupling the two tools as a framework for water resources management in advantageous in that water as a system has various components and therefore it is appropriate to manage it in a hoslitic level. The other advantage of combining the two tools is that it enables monitoring from the water accounts direction and also can monitor production performance from the water use audits direction. Thus, this article highly emphasis a systems thinking approach in water resource management at the mines.

Water demand at the Jwaneng township

National water demands have been increasing over the years, due to economic growth, population growth and increases in household incomes. Increases in household incomes led to higher household water per capita consumption over the years (Masike, 2007; Umoh et al., 2007). One of the economic activities that has contributed significantly to increases in national water demand/ consumption both directly and indirectly is the mining sector, especially diamond mines. Directly, the growth in the mining sector led to increase in water demand for its operations. Indirectly, the growth in the mining sector resulted in growth of other economic sectors such as construction, wholesale and retails sector and infrastructural development. In addition, economic growth driven by the mining sector, led to increases in household incomes which resulted in increases in per capita water demands. Due to economic growth daily per capita water consumption increased from 90 L per day to 115 L between 1980 and 2007.

The most important mines that contributed both directly and indirectly to national water demand increases are the Jwaneng, Letlhakane and Orapa diamond mines. Jwaneng township water consumption has closely minimicked national water demand growth. The increase in water demand at the Jwaneng township is a result of increases in population growth, household income and the expansion of the Jwaneng Mine. In addition, may have reduced incentives to conserve water.

Monthly average abstraction increased from 0.4 to 0.7 million m^3 between 1982 and 2007. This represents a 75% increase in water demand. Both the domestic and mining sectors are accountable for this increase in water demand over the year. Water abstraction and demand pattern for the Jwaneng township is characterised by oscillation behaviour. Oscillation behaviour is a result of both positive and negative feedbacks but with a dominance of negative feedback through its dynamics (Masike, 2007; Kirkwood, 1998). The feedbacks which are responsible for the oscillation behaviour are a result of internal interaction between the system. In addition, external factors such as climatic conditions (temperature and rainfall) may also be playing a vital role in the feedbacks of the water system at Jwaneng Township. For instance, winter months have lower demand than summer months, indicating that temperature may be responsible for the oscillation behaviour.

Jwaneng township water demand can be categorised into two main groups: the township water use (domestic, industrial and institutional sectors) and the mine activities. Table 1. shows water consumption by different sectors at the Jwaneng township. The mine sector with an average consumption of 74 2249 m^3 per month is the largest water consumer. It consumes over 75% of the total abstracted groundwater from the Jwaneng Northern Wellfield. In fact, Jwaneng mine consuming at over 10 million m^3 per year, is the largest water user compared to other diamond mines in the country.

Water supply and feedbacks for Jwaneng mine and township

Mining sector in the country is total dependent on groundwater for its operations. This is not a surpise given the semi-aridity of the country. Jwaneng mine and township is supplied by the Jwaneng Northern Wellfield which is located approximately 45 km in the Kweneng District (DWA, 2006). The wellfield covers approximately 300 km^2 (Phatshimo, 2007) and the aquifers are of Sandstones of the Ecca formation (DWA, 2006). Groundwater abstraction from the Northern Wellfield started in 1981. A total of 62 boreholes have been drilled into the Sandstones aquifers. Of which 28 boreholes are production and the rest (34) are monitoring boreholes. Groundwater abstraction in the Jwaneng township entails acquiring water rights. Incidentally, water rights legally governs abstraction rate as abstraction rates are legally governed by water rights.

The current water right hold by the township is 15 million m^3 per year. Water rights are meant to protect other water users in the aquifer and also to ensure groundwater sustainability. Thus, the objective of the water rights is to achieve allocational equity in water resources in the aquifer. However, given that the water rights are static while recharge rates are highly dynamics, water rights cannot ensure groundwater sustainability. Other water users in the Jwaneng Northern Wellfield

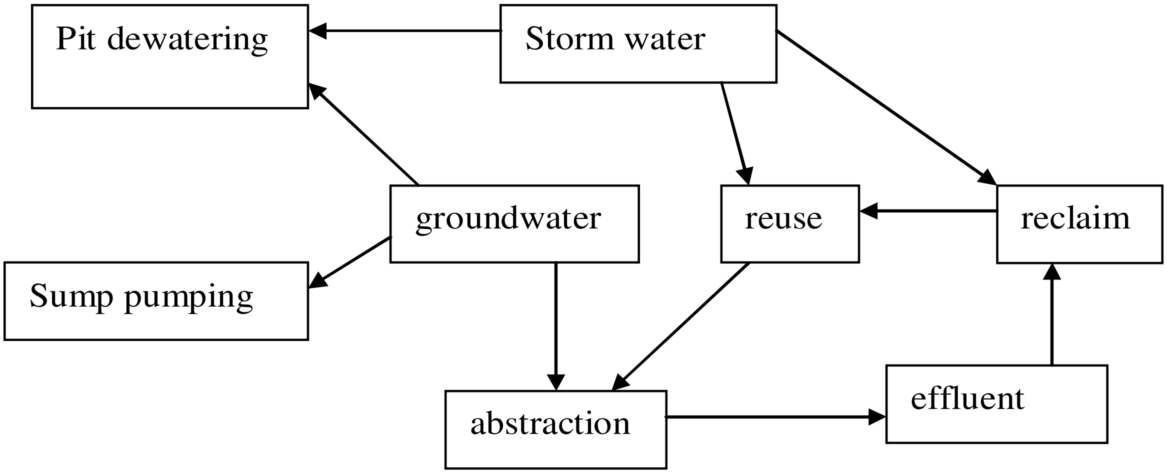

Figure 1. Components of water supply for Jwaneng mine.

(JNW) are farmers who use same aquifers to water their livestock and domestic demand from the settlements of Takatokwane and Motokwe. The current abstraction regime by the Jwaneng township is to abstract 1.20 million m^3 per month which is below the legally recommended rights of 1.25 million m^3 monthly.

Due to intensive abstraction rates to service both the township and the mine, the water levels at the monitoring boreholes in the JNW is highly dynamic (Department of Water Affairs, 2006). In addition, to the highly dynamics of the water levels, studies have indicated that pumping of the JNW far exceeds the recharge and natural inflows into the aquifer. It is reported that close to 60% of the production boreholes shows fluctuations in the water levels of close to 25 m.

Though, the JNW is the primary source of water supply to the diamond mine sector, there are other secondary sources. These secondary sources are stormwater and water reuse and recycling. Storm water can be divided into pit dewatering and water harvesting. Storm water is function of precipitation and therefore, highly variable over time. If integrated in the mining water system, these water resources could act as a limiting factor to the abstraction rate and therefore contribute to groundwater sustainability and thus prolong the life time of the aquifer. Water reuse and recycling is the secondary source of water supply for the mine. It is a secondary source in the sense that the primary source is water abstracted from groundwater and storm-water (rainwater). The relationship between groundwater abstraction and water reuse and recycling for wastewater can be depicted as in Figure 1. Figure 2 on the other hand depicts the influence of different components of water system at the mine. The signs in brackets indicate how one variable affect the other variable. For instance, groundwater abstraction positively affects quantity of wastewater. Intuitively, an increase in the quantity of wastewater will enhance its usage, hence a positive sign. Consequently, increase in utilisation of wastewate negatively affects groundwater abstraction rates. Therefore a balancing (negative) loop as indicated by the middle sign exist between groundwater and waste water for the mine. The effect of a balancing loop is to create an oscillation behaviour in groundwater abstraction rates. Therefore, water system in the mining indusrty has feedbacks and it is the feedbacks that make the dynamics of the system to be highly illusive and complex. Thus, water management at the mine can effectively be managed by system dynamic methodology.

Water use audits for mine

Water use audits is a scientific framework of tracking and categorising water use in a production process or utility (Alegre et al., 2006). It is a tool that is used to account and quantify water from source and its distribution amongst different uses in production processes. It is a system that accounts for all water abstracted or pumped from source to the production processes. It is a management tool that gives a concise and detailed information on the different uses at the facility. This is an important tool for water planning and decision making for the following reasons: First, water use audits can identify production processes that are inefficient, if they are set targets on water use at each stage. Therefore, based on the information, policies for improvements can be implemented. Secondly, audits can identify processes where reclaiming and reuse of wastewater can be maximised. Lastly, it is possible to estimate distributional losses with precision and thus, be able to manage it properly (Alegre et al., 2006). Thus, if used properly, water use audits can have a positive impact on abstraction rates of groundwater and thus, influencing water sustainability.

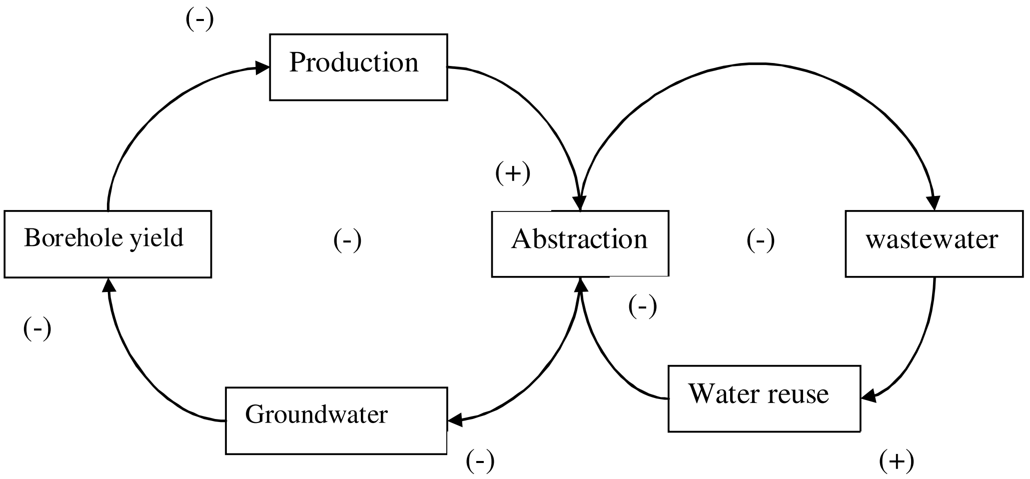

Figure 2. Feedback loop at Jwaneng mine.

In order to derive water use audits for any production process, two aspects are essential. Firstly, the life cycle or the production processes must be known. Secondly, water meters are essential elements to provide precise readings needed for auditing. In addition, accuracy of water meter reading are essential. Thus, servicing of the water meters is important. The starting point of water use audits construction is the system input (Alegre et al., 2006). A system input represents the amount of water pumped into the activity at a point in time. The system input can be derived mathematically as follows:

$$SI = WL + U$$

Where, SI= system input,
WL is the water loss,
U is the amount of water actually used.

Jwaneng mine is one of the facilities that has a comprehensive and accurate water metering system. All the meters readings are electronically operated. Meters are installed at the source of pumping and at the receiving point. Thus, the two meter system enable estimation of transmission water loss. In addition, meters have been installed at a receiving point for each production process. Consquently, these meters measure the amount of water use by each production process. Lastly, there is another meter installed to measure water going to the township. It is also imperative to have a complete knowledge of the life cycle of the diamond production. Diamond mining involves blasting, digging, loading, crushing and sort. In the life cycle of diamond mining, water is an essential factor input in the diamond production processes.

Water is primarily used to separate diamonds for the ore. The two processes where water is use extensively are the Main Treatment Plant (MTP) and the Recrush Plant Material (Recrush). Other processes that also use water are the BSP and Aquarium. At the MTP, diamond production commences with crushing, washing and screening slimes/grits, transfer the cleaned required sized ore for concentration separation at Dense Media separation (DMS). It is at the DMS where a lot of water is used in the diamond production process Table 2. The separation process begin when ore is mixed with FerroSillicone and water. Separation occurs through a process of overflowing and sinking. Water is recovered by the process of overflow and is pumped to the tanks. At these tanks, there are degritting cyclones where ore is separated and slimy water is mixed with flocculent to quicken the process of settling slime. Media overflow is classified as clean water and is collected for water reuse and recycling. The underflow is slurry (high content of soil material) and is pumped to the slime dams. At the slime dams, recovery of water continues through a process of gravity separation. However, recovery of water at the slime dams is low as the dams are built on earth. Therefore, seepage rate is high and water can only be captured after the earth has been saturated. The slurry is pumped near the walls of the slime dams and the fluid material is pushed to the center of the dams. Water recovery pumps are located at the center of the dams and water is pumped to the silt treatment plants. Incidentally, it takes over 2 months for saturation of the earth to occur and recovering of water. Hence cyclical oscillation after two months. A similar process on water use and recover occurs at the Recrush plant.

Based on past water use, the system input for the Jwaneng mine can be depicted as follows:

$$SI = 93\% + 7\%$$

where 93% is the authorised water use,
7% is the water losses from source,
93% of the system input is divided into diamond production processes.

Table 2. Proportion of water use in production processes.

Production process	Water use (%)
MTP	75.73
BSP	5.44
Recrush	16.31
Domestic mine	1.39

Table 3. Water consumption and return rate to the slime dams.

Consumptive/ retention factor	0.12
Water return to slime dam/ waste water	0.88
Reuse factor	0.15
Losses factor (through soil retension, evaporation and seepage)	0.8

An investigation into the water use for the Jwaneng mine particularly at the MTP and recrush plant reveal that though mining is water intensive, its consumptive rate is extremely low. Table 3. shows the consumptive, return to slime dams of slurry, reuse and losses factors at the Jwaneng mining. Only 12% of the water allocated to the mining production process is retained or consumed by the mining processed. Therefore, 88% of the water allocated to the mining processes is returned to the slime dams as slurry. Another revealation from the water use audits is that only 15% of the total amount of water returned to slime dams is reused in the mining processes. In essence, the percentage losses is 80% of the abstracted water from the JNW. Obviously, the losses are from evaporation, seepage, leakages and retention by the soil or earth materials. Thus, from the analysis, the following observations are made on current water demand and utilisation in the Jwaneng Mine. Firstly, water reuse and recycling is quite low. This is made difficulty by the process of separating water from the slurry. The current method that is used which allows saturation to occur before recovery takes place results in less water recovery. Moreover, as water is allowed to collect before it can be pumped to dams, most of it is lost through evaporation rates. In addition, water use per tonnage and reuse is highly variable over time (Figure 3 and 4). Currently, the mine target of water use per tonnage is 0.77 m^3/t. Obviously, observed water consumption is highly variable around thetarget of 0.77 m^3/t. Thus, these variability in water resuse and usage per tonnage have impacts on abstraction of groundwater resources.

System dynamic approach for water management

In order to integrate water use audits to water accounts, system dynamic model as a framework is used. System dynamic model was chosen for the following reasons: Firstly, the water system in the Jwaneng mine has feedbacks (Figure 2) which makes the system complex and illusive (Masike, 2007; Wilson, 1981). System dynamic model is the only competent to handle presence of feedbacks. Secondly, the Jwaneng water system has many components which makes it difficult to manage through mental model. Moreover, to manage such system is a holistic approach, system dynamic model is required. Thirdly, a system dynamic model is an approach that breakdown a system into various components and study them in isolation or separately. After an independent vigorous analysis of different component, the components are assembled and simulated in a holistic manner (Wolstenholme, 1990, 1992). Therefore, for water use audits and accounts this approach is the most appropriate as components of production and their consumption patterns can be studied separately. Lastly, a model such as system dynamic model will enable simulation of the system under different management scenarios such as increase in rate of reuse and recycling, increase efficiency, different loss percentage. The simulation results will enable management to determine how abstraction rates will be affected under different scenarios and also how business-as-usual operations can be achieved under different uncertainities such as droughts and climate change.

Simulation and discussions on findings from water accounts and audits

Simulating water use at the Jwaneng mine is extremely difficult due to the current highly erractic and random functional relationship between production measured in ore tonnage and water usage (Figure 4). Secondly, simulation of water system at the Jwaneng mine is made difficult by the erractic and random systems behaviour in usage of return water from the slime dams (Figure 3). Simulation on water usage at the mine was done based on observed average coefficients between production (tonnage of ore) and water quantity, and average coeffiecent between water returned to slime dams and water return to the plant Figure 5 depicts observed and simulated water production based on observed ore production in tonnes and water consumption per tonnage of ore at 0.8 m^3 per ton. As depicted, the observed water used is highly varible. Obviously variability in cubic meter of water per tonnage of ore implies that management are not fully able to control water efficiency at plant. Figure 6 on the other hand, depicts estimated difference between observed and simulated water consumption at the mine.

A negative consumption depicts water that could be saved when water consumption per ton of ore is below the average consumption of 0.8 m^3/t. While a positive difference show water consumption when actual consumption is above 0.8 m^3/t. Between 2004 and 2007, if the mine had averaged consumption of 0.8 m^3/t, the

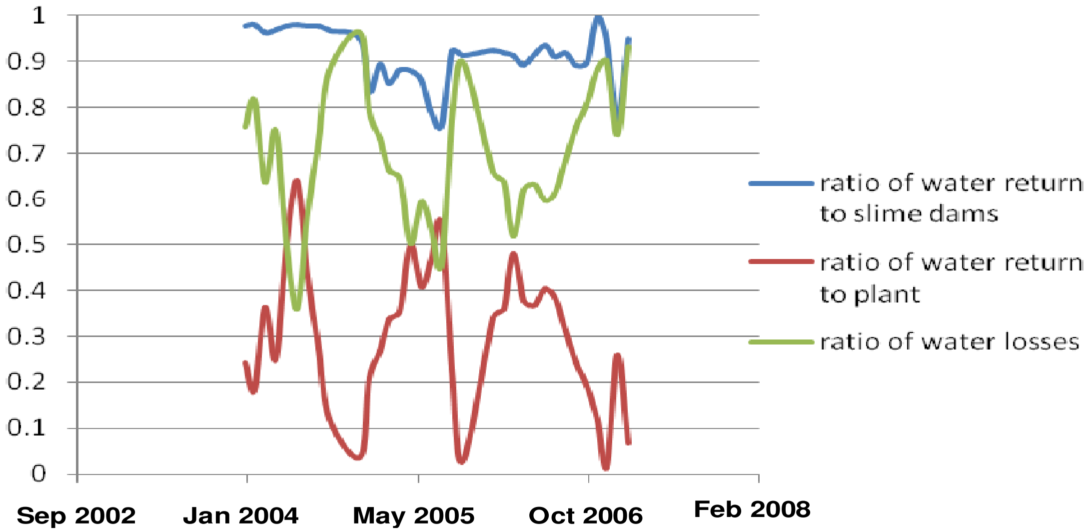

Figure 3. Ratios of water return to slime dams and return water from slime dams to plant.

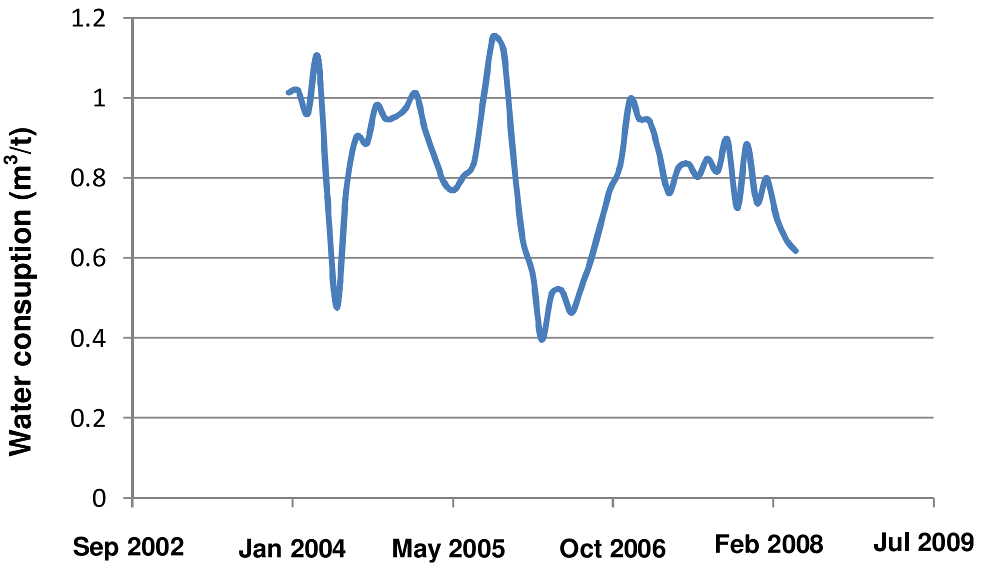

Figure 4. Water consumption ratio to tonnage of ore.

mine could have saved a total of 0.26 million m^3.

Figure 7 on the other hand, shows observed and simulated fresh water demand and therefore abstracted for the mine between 2004 and 2008. The simulated fresh water demand is based on the average water consumption of 0.8 m^3/t and the reuse ratio of 0.3 m^3 per m^3 of water usage at the mine. A combination of 0.8 m^3/ton consumption and the water reuse ratio of 0.3 per m^3 of water used at the mine result in a lower demand for fresh water.

If the target water use m^3/t of 0.77 is achieved by the mine, water consumption and asbtraction could be reduced significantly. Figure 8 depicts observed and simulated fresh water demand based on different water use per tonnage of ore and the target water use. While Figure 9 shows water usage at the mine based on different usage and reuse scenarios over time. Lastly, Figure 10 shows fresh water demand for the mine based on different usage and different reuse scenarios. Therefore, from the simulation based on different water use per tonnage and reuse of water from slime dams, there is a huge opportunity for the improvement on water usage and effeciecny at the Jwaneng mine.

Though management have set a target on consumption per tonnage of ore, observed data reveal that for the past three years, current water consumption at the Jwaneng mine at different mining processes is highly variable over time. Most importantly, analysis of water useage per

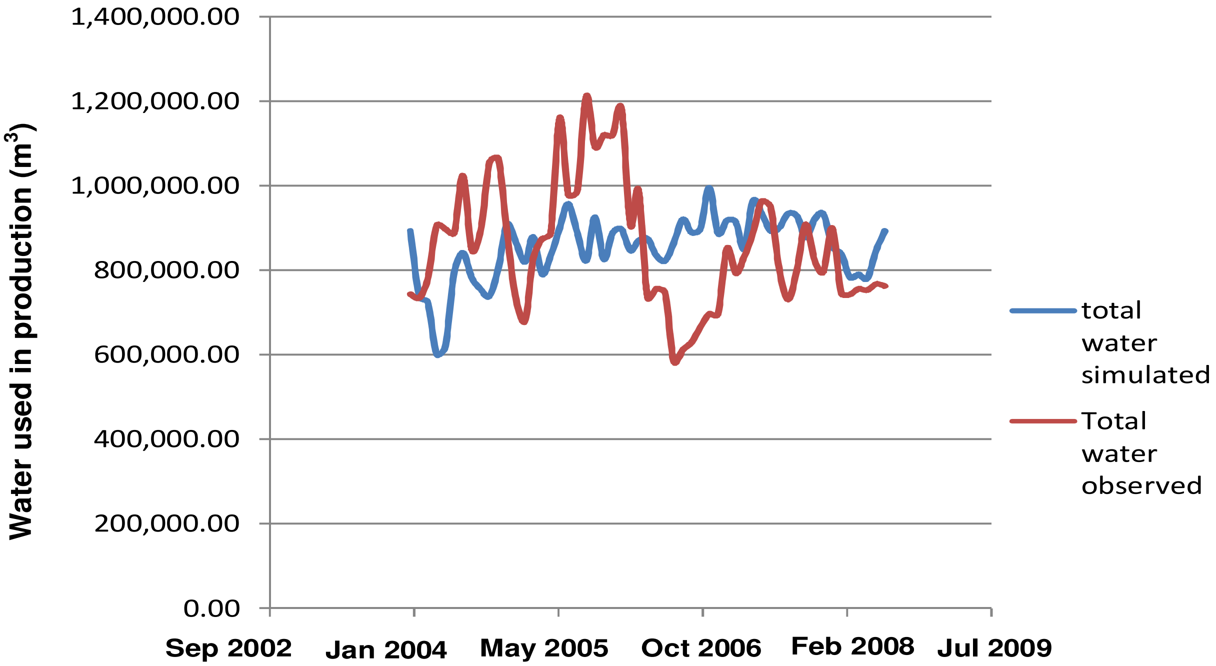

Figure 5. Observed and simulated water used based on 0.8 m^3 per tonnage of ore.

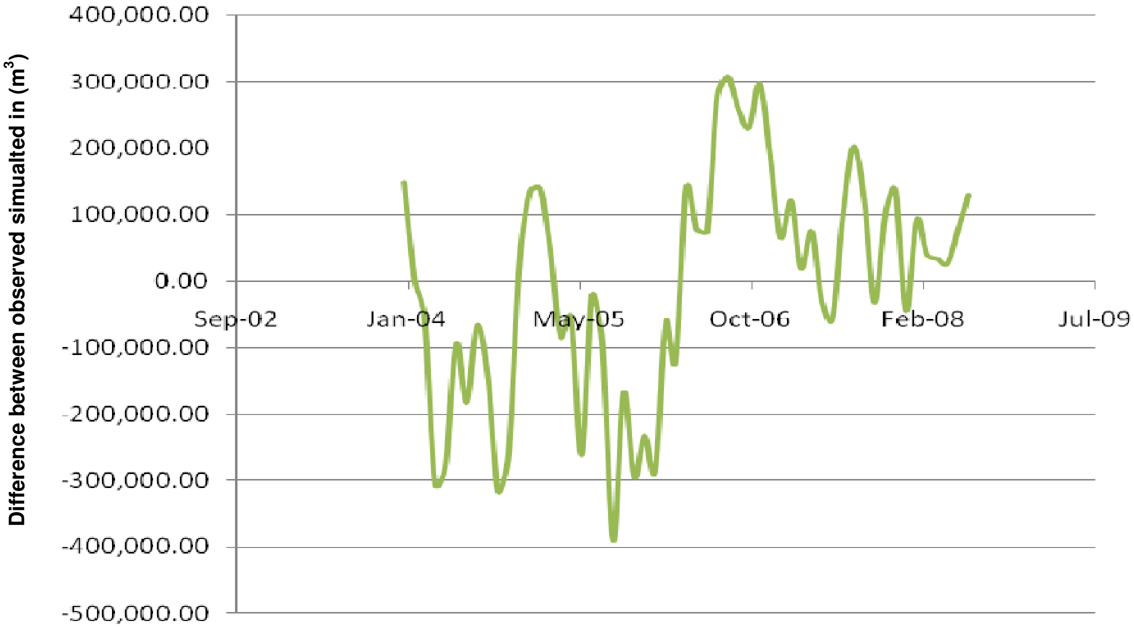

Figure 6. Difference between water consumed and simulated based on 0.8 m^3 per tonnage.

tonnage of ore indicate that there are instances where consumption per tonnage has been as low as 0.4 m^3/t. Therefore, there is room for improvement in water use efficiency at the mine. Secondly, water reuse is one of the areas efficiency can be increased. Analysis of data show that over time, reuse has also been highly variable fluctuating between 0.6 and 0 m^3 per m^3 of water used at the plant. From the simulation results, it is clear that two factors that influence water abstraction from the Northern Wellfield are water usage per tonnage and water reuse from the slime dams. Simulation results show that if water useage per tonnage of ore can be reduce significantly and

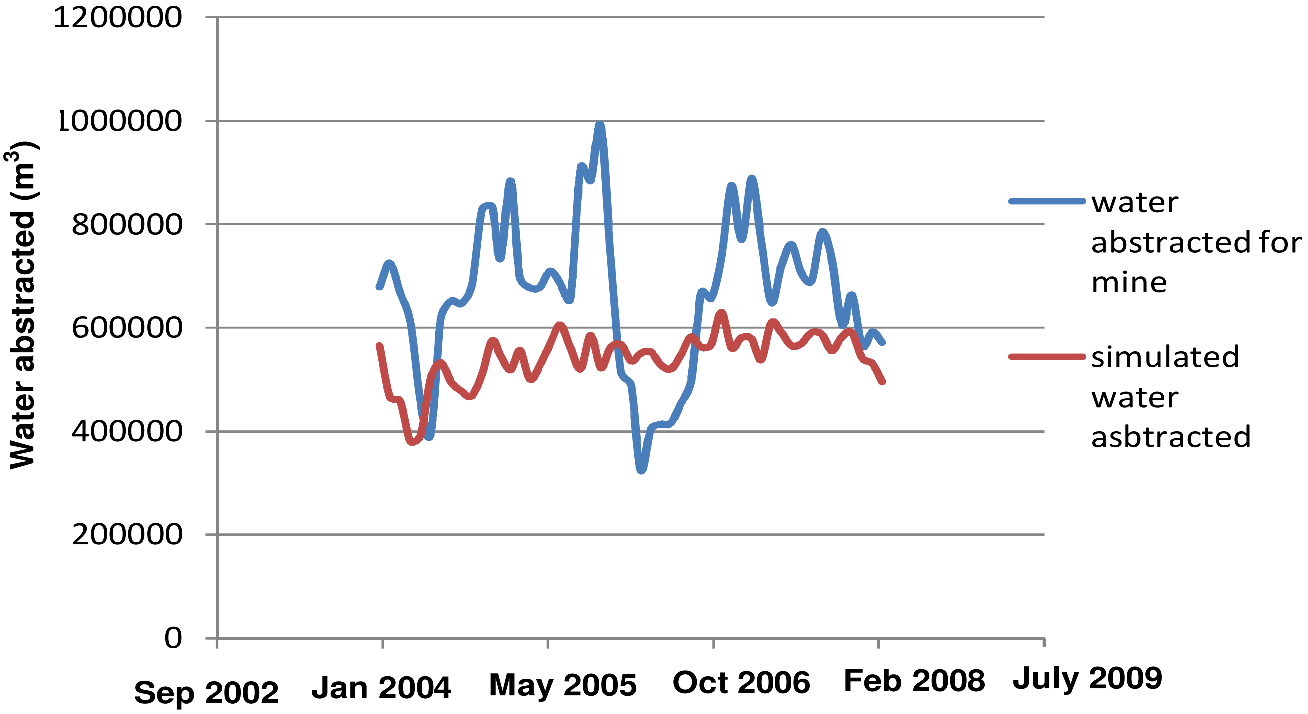

Figure 7. Observed and simulated water abstractino based on water usage of 0.8 m^3 per tonnage of ore.

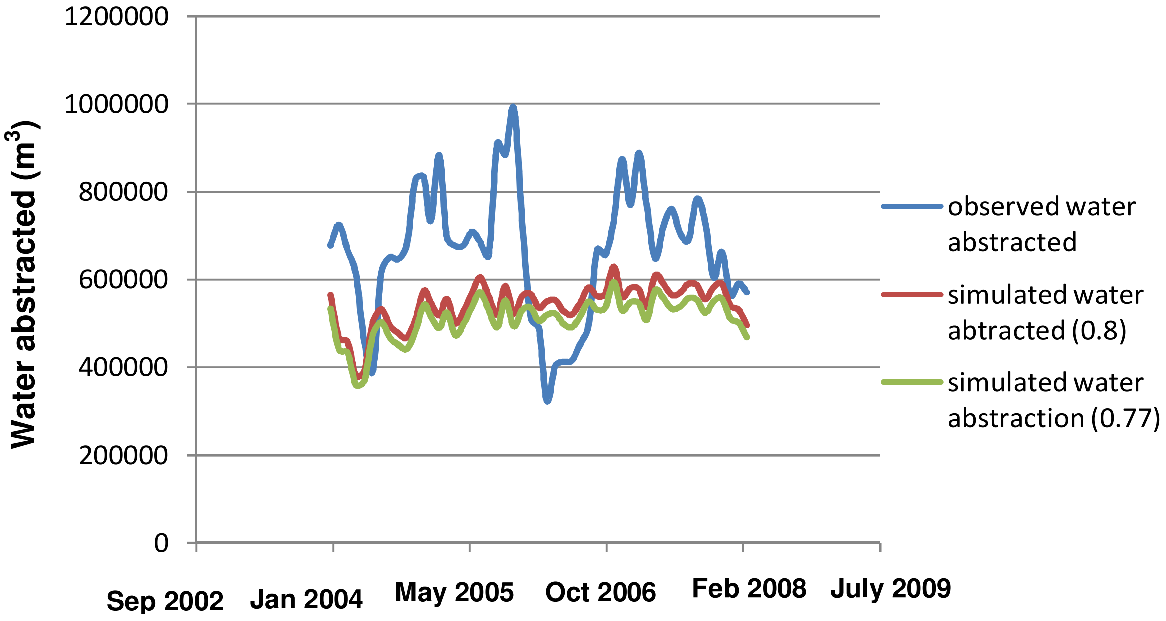

Figure 8. Observed and simulated water abstraction based on different water usage scenarios.

at the same time reuse of water increased significantly, then fresh water demand can be reduced significantly. Therefore, as implied Jwaneng mine can operate as business-as-usual even during the water scarce period particularly during drought years. However, the projected life time of the aquifers of 20 years can also be prolonged if these scenarios are achieved.

CONCLUSIONS

Operating under water scarcity regime needs carefully

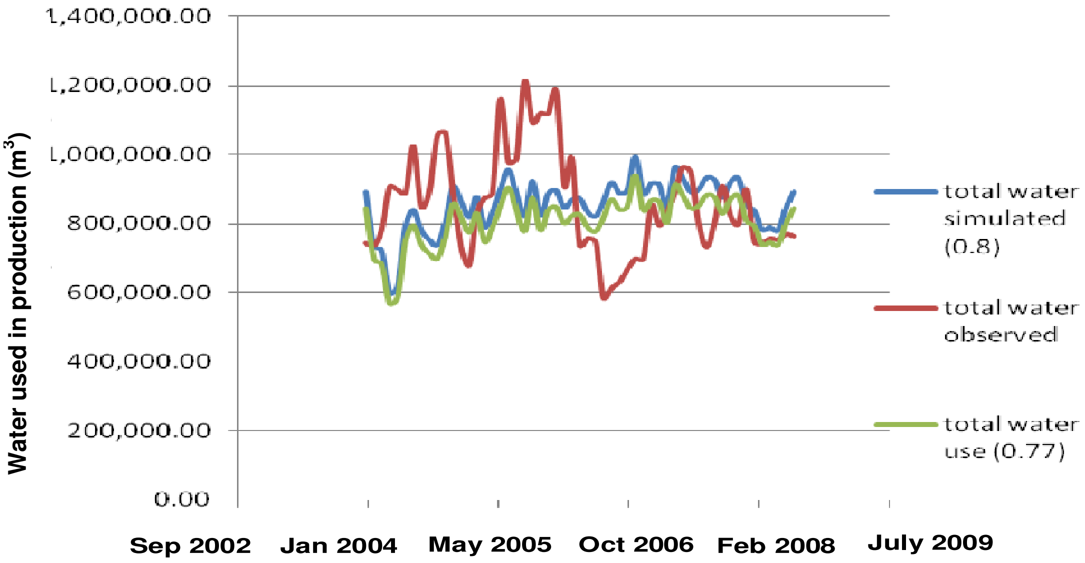

Figure 9. Observed and simlated water used in production based on different scenarios.

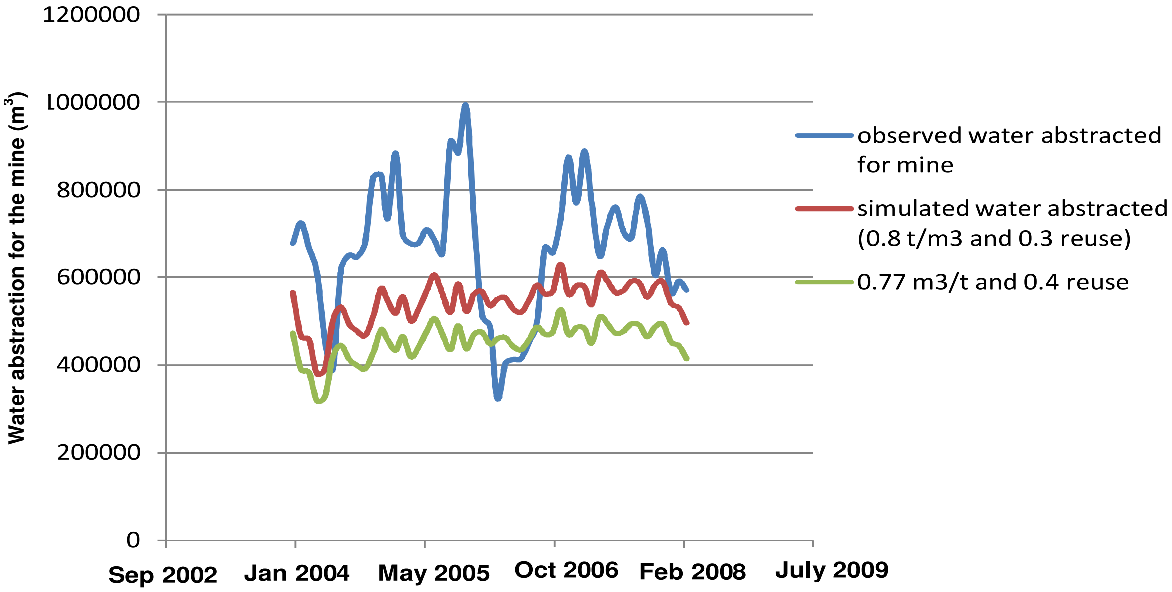

Figure 10. Observed and simulated water abstraction rates based on different usage and reuse scenarios.

planning and management of water resources. This is the situation confronting management at the Jwaneng mine. Though the mine has come up with target to enhance water efficiency at the plant, analysis of consumption data show that at the moment management is not able to control both water consumption and water reuse at the plant. Simulation results show that if the set target can be achieved and the reuse rate improved, then fresh water demand can be reduced significantly. Consequently, abstraction rates at the mines can be reduced considerable. It is also recommended that waste water from the township should be incorporated in the Jwaneng Plant water management scheme. This exercise could increase secondary sources of water available to the plant. Obviously, abstraction rates from the wellfield could be reduced significantly. It is important to note that climate change impacts on water resources could be signficant such that business-as-usual for the plant could become difficult in future. Thus, improvement in water useage is imperative for future operations of the mine. In order for the Jwaneng wellfield to be used sustainability and operate under business as usual given scarcity and uncertainty there is a need to optimise use of waste from both the mine and the domestic sector.

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