Estimation of Mine Water Ingress Volumes for the Witwatersrand Goldfields

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Abstract

Mining of gold and later uranium commenced in the Witwatersrand in 1886 and continued for more than a century. The underground workings of the individual mines are interconnected into three mining basins. In recent years, mines closed and stopped pumping water, allowing mines to flood. To address the risks posed by flooding, the South African government intervened, commissioning a treatment plant for each of the three mining basins.

Initially, historical pumping records were used to estimate required plant capacities. This paper proposes an improved method for estimating ingress volumes using water level and pumped volume data from the plants.

Keywords: Witwatersrand, Water Ingress, Flooding

Introduction

During the second half of the 19th Century, a number of gold deposits were discovered in the Zuid Afrikaansche Republiek, the largest being the Witwatersrand Goldfield, where public diggings were formally proclaimed in 1886. The City of Johannesburg grew around the early gold mines of the West Rand, Central Rand and East Rand. Within a few decades, the underground workings of these three goldfields extended along strike for many kilometres, eventually forming three distinct mining basins (denoted as Western, Central and Eastern Basins respectively, Figure 1) with interconnected underground workings. As the orebodies became depleted and the costs to mine at the great depths needed to access ore increased, the individual mines in each basin began to close and water began to flow from mine to mine. Pumping water from these workings further increased the operating costs of the individual mines forcing them to cease underground operations and cease pumping.

Following the cessation of underground mining and mine flooding in the Western Basin, acidic water began to discharge from the mine workings to the surface in 2002, polluting the downstream environment (Hobbs & Cobbing, 2007). This alerted the local community, as well as miners and regulators, to the risks associated with uncontrolled flooding of the underground workings in the Witwatersrand. As most mining had taken place well before legislation requiring mines to make financial provision for their post-closure impact, the South African state needed to take action to manage the environmental impacts of mine flooding. An inter-ministerial committee was convened, who appointed a team of experts, from which recommendations to construct pump- and treat plants in the three basins, as well as to implement projects to control the ingress of water into the underground workings (Coetzee *et al.*, 2010) were adopted in 2011.

In recommending the construction of pump and treat plants, it was realised that no definitive record of the volumes which had been pumped during the operations of all the mines in the three goldfields could be identified. Scott, (1995) compiled pumped volumes for the 1950s for the Central and Eastern Basins, based on records from individual mines, when all of the larger mines were still operating in these areas. Estimates were made for the Western Basin, based on groundwater and hydrological models and a 3-D reconstruction of the void volume using available mine plans (The Amanzi Water Treatment Venture, 1999), as well as volumes which had flowed from the mine workings, following the surface discharge in 2002.

Following the discharge of water from the Western Basin, pumps and a treatment plant were installed by the mining company active in the area and have been maintained by mining companies via various directives and agreements with the relevant state agencies. New pump- and treat stations were commissioned in 2014 in the Central Basin and 2016 in the Eastern Basin. In parallel, a programme, supported by the Department of Mineral Resources and Energy has been identifying and constructing engineering measures to reduce the ingress of surface water into the underground workings (Barradas *et al.*, 1996; Coetzee *et al.*, 2021; Palmer *et al.*, 2006; van Biljon & Walker, 2001).

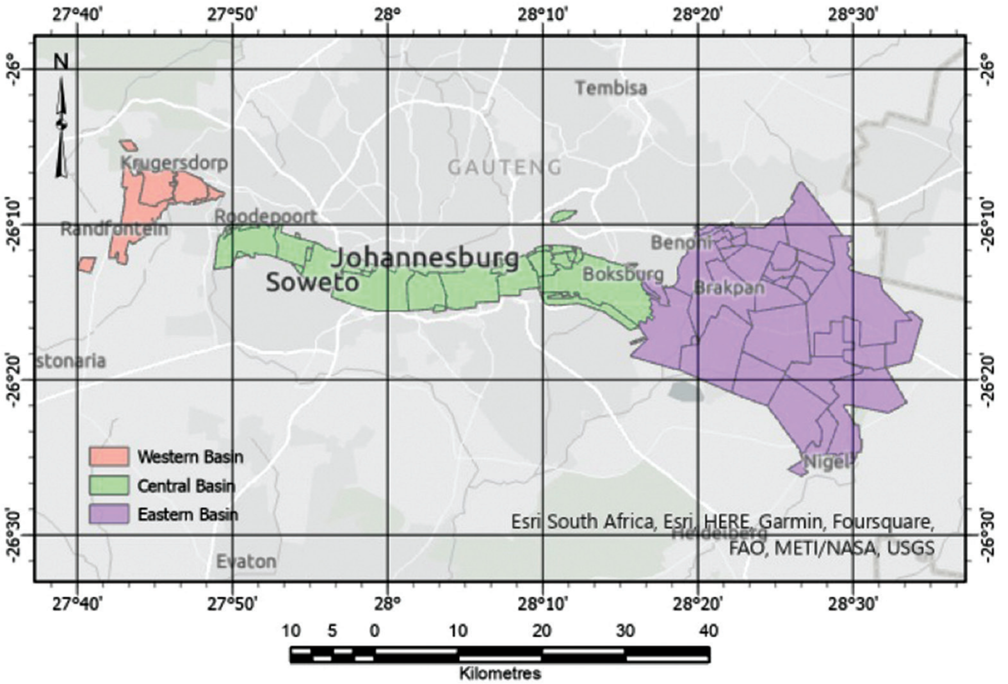

Figure 1 Location of the three Witwatersrand Basins.

Research questions

The following research questions were identified:

1. Can the daily pumping and water level data be used to determine ingress rates into the Western, Central and Eastern Basins of the Witwatersrand goldfields?
2. What is the effect of implemented ingress control measures on the ingress rates in the three basins?

Methods

Available data

Water levels and volumes pumped at three pumping stations are recorded and provided daily. These data have been compiled into time series to allow for further analysis.

Conceptual model relating volumes of ingress and pumping with water level

A simple conceptual model has been used to relate the volumes of water flowing into and pumped from the mine void and the water level. Two simple assumptions are made:

- The voidage, i.e. the volume of mine void into which water will flow (or be pumped) at any specific elevation in the mine (Younger, 2016) remains constant over the range of elevations for which the water volume estimate is made.; and
- The effect of ingress or pumping on the water level is instantaneous and is uniform across an entire mining basin. Monitoring data from multiple shafts support the validity of this assumption.

The conceptual model is illustrated on Figure 2, showing the key quantities used in the estimation of ingress volumes.

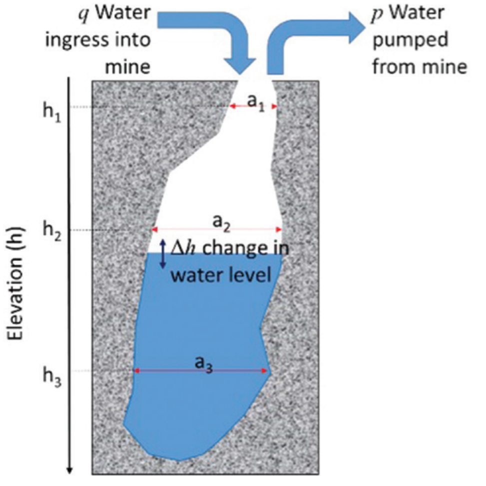

Figure 2 Conceptual model of ingress and pumping from the Witwatersrand mining basins.

Estimation of ingress volumes

For the *i*-th measurement of water level and volume pumped, the change in water level Δhi is given by the nett inflow of water into the mine void, qi-pi, divided by the area of the workings, ai, at the specific water elevation. The area of the workings – the voidage – is the volume of the workings in a depth interval, divided by the depth interval, with units m^3/m (units of area). This quantity can also be thought of as the area of the water surface in the mine void for any specific depth.

Three methods of estimation are proposed:

The $\Delta h_i = 0$ method

The simplest method of quantitatively determining q_i is to identify days where pumping does not change the water level from the previous days. In these cases:

$$\Delta h_i = 0 \qquad 1$$

$$\frac{q_i - p_i}{a} = 0 \qquad 2$$

Which is only possible if:

$$q_i = p_i \qquad 3$$

Unfortunately, this method depends on the existence of days where $\Delta h_i = 0$ and is limited by uncertainties in the data, particularly the depth measurements.

The $h_{t_1} = h_{t_2}$ method

This method is an extension of the previous method, but instead of identifying individual days where $\Delta h_i = 0$, it is applied by identifying two days, t_1 and t_2, which have the same water elevation:

$$\sum_{i=t_1}^{t_2} \Delta h_i = 0 \qquad 4$$

$$\sum_{i=t_1}^{t_2} \frac{q_i - p_i}{a} = 0 \qquad 5$$

Which implies that:

$$\sum_{i=t_1}^{t_2} q_i = \sum_{i=t_1}^{t_2} p_i \qquad 6$$

And that the average inflow over the time interval will be given by:

$$\overline{q_{t_1,t_2}} = \frac{1}{t_2 - t_1 + 1} \sum_{i=t_1}^{t_2} p_i \qquad 7$$

This method has the following advantages:

- By integrating pumping rates and water levels over extended periods, the effect of random uncertainties in these measurements is distributed and minimised; and
- The method makes no assumptions about the voidage, as the ingress rate is calculated from the volume of water pumped with no nett change in water elevation.

Similar to the $\Delta h_i = 0$ method, this method can only be applied under specific conditions, relying on a time interval with the same water level on the start and end dates.

Linear regression

The inflow volume can also be expressed as:

$$q_i = a_h \cdot \Delta h_i + p_i \qquad 8$$

Which defines a straight line relating net inflow volume and change in water level, assuming that the voidage is similar for a series of measurements.

Looking at multiple days pumping and water elevation changes, and assuming constant voidage, the average ingress rate, as well as an estimate for the voidage and uncertainties in these three quantities can be estimated by least squares fitting to any set or subset of data. The estimated voidage can then be used to calculate daily ingress volumes, inserting the daily pumped volume and water level change into equation 8.

This method is more versatile than the two previously described methods, requiring only variation in the water level and pumping rate to produce a reliable estimate, is sensitive to variations in the actual voidage over a range of elevations.

Results

Results from the Eastern Basin are presented on Figures 3 and 4 and Table 1 below. To remove the effect of seasonal rainfall and year-on-year variability in rainfall, a period of four hydrological years (1 October – 30 September) has been selected. During this period, an ingress control canal – the Van Ryn Canal - was constructed, with the aim of reducing inflow to the mine workings. The canal was completed in mid-October 2020, allowing the assessment of its effectiveness for the final hydrological year of the assessment (2020/21).

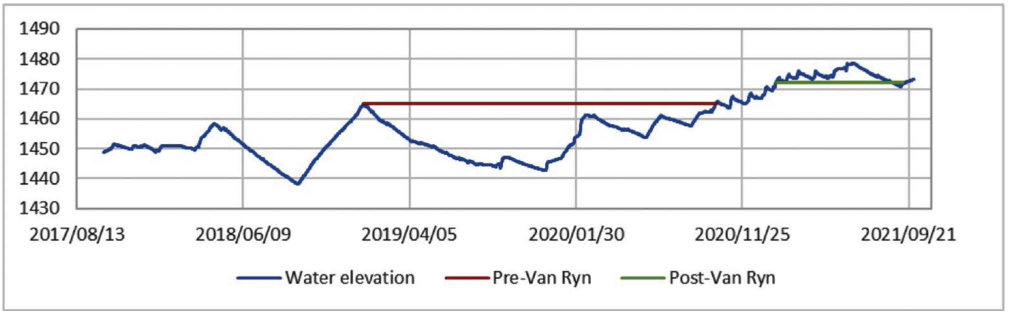

Figure 3 *Flow estimation in the Eastern Basin, using the* $h_{t_1} = h_{t_2}$ *method*

Table 1 *Results of flow estimation using the* $h_{t_1} = h_{t_2}$ *method for the Eastern Basin.*

	Date range	No. of days	Start level (m.a.m.s.l)	End level (m.a.m.s.l)	Volume pumped (ML)	Daily ingress rate (ML/d)
Pre-Van Ryn Canal	2019/01/12 – 2020/10/08	635	1 463.14	1 463.16	41 525.6	65.4
Post-Van Ryn Canal	2021/01/25 – 2021/09/11	229	1 469.88	1 469.93	11 740.5	51.3

Using the linear interpolation method for the entire period in question, a mean ingress volume of 62±4 ML/d is calculated for the four year period (Figure 4).

Ingress volumes of 55 ML/d and 29 ML/d are estimated for the Central and Western Basins, respectively, calculated as the weighted average of a number of estimates using the $h_{t_1} = h_{t_2}$ method.

Discussion: Validity of the assumptions made in the estimation methods

Estimations made using methods based on periods (single days or longer periods) with the same start and end water level are insensitive to the assumption of depth-independent voidage. However, they are only applicable for periods which satisfy the water level requirement. This limits their applicability, particularly in periods when the water level follows a constant dewatering or rewatering trend.

On the other hand, the linear regression method assumes a depth-invariant voidage, which is unlikely to be the case. This can be accommodated by utilising the method only over periods where the overall change in water level is relatively small. The near-total extraction of ore at shallow depths over the large extent of the mining basins in the Witwatersrand, as seen on historical mine plans (University of the Witwatersrand, 2012), is also likely to balance out local variability in voidage.

During the first half of 2022, a period of downtime on the pumps at the Eastern

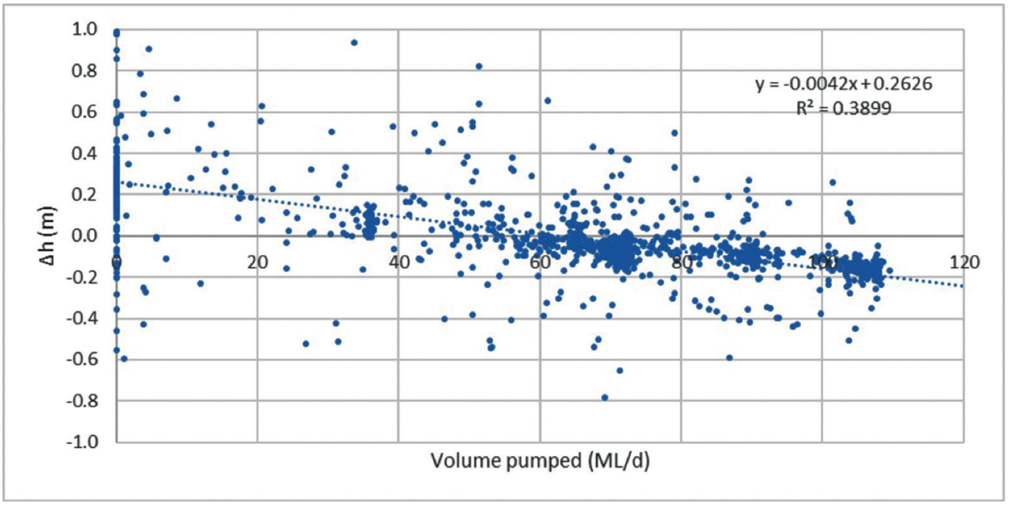

Figure 4 *Estimation of ingress rate by linear interpolation for the 2017–18 – 2020/21 hydrological years*

Basin plant has led to a constant rewatering trend. As the water level has risen, the daily rate of rise has decreased substantially. The constantly rising water level and constant, zero pumping volume prevents the use of any of these methods to estimate water ingress volume. Two plausible explanations are proposed:

- An increase in voidage at the current water level, which is likely due to the void water level rising into near-surface workings where more material was extracted and shallow workings in the Black Reef which overly the Witwatersrand strata; and/or
- The rising water level reducing the head difference between the groundwater above the workings and the workings themselves, resulting in reduced inflow.

When pumping is resumed, the resultant lowering of the water level will allow resolution of this dilemma.

Conclusions

Three methods are proposed which allow the estimation of water ingress volumes into the mine workings of the Witwatersrand, using water level and pumping volume data. Ingress rates have been determined for the Western, Central and Eastern Basins of the Witwatersrand. During the period of investigation, an ingress control canal was constructed in the Eastern Basin, which has been shown to result in a substantial decrease in the volume of water flowing into the underground workings.

Acknowledgements

Many thanks to the Department of Mineral Resources and Energy for support for this project and constructive insights. Thanks to the Department of Water and Sanitation and Trans Caledon Tunnel Authority for the provision of data from the mine water treatment plants.

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