Spring Flow Estimation After Mine Flooding in a Dolomitic Compartment

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Abstract Dewatering of a dolomitic compartment, delineated by dykes, is conducted to mine the gold bearing reefs below and reduce mine water ingress. A spring associated with the compartment ceased to flow due to dewatering taking place. Previous studies indicated flow across the dyke boundaries, is mainly due to the presence of grykes that transverse these boundaries. The question of when spring flow will be restored and what volume can be expected, normally requires a detailed numerical model. By making use of the Saturated Volume Fluctuation (SVF) method, a first order estimate of the predicted spring flow and restoration time is calculated.

Key words Spring flow recovery, mine flooding, dolomitic compartment, Saturated Volume Fluctuation

Introduction

The Gemsbokfontein West compartment is situated in the Western Basin of the South African gold mining basins. Mining takes place well below the overlying dolomitic aquifer and dewatering of this aquifer is required to reduce water ingress to the mine workings. Currently dewatering is still taking place at 77 Ml/d from two shafts within the compartment which has led to the cessation of the spring.

The question of when spring flow will be restored and what volume can be expected, generally requires a detailed numerical model accounting for the various boundary conditions e.g. dykes which are considered no flow boundaries and geological faults which are considered high transmissive zones. Since estimates of inflows from adjacent compartments exist from previous studies together with the leakage from the water courses into which the discharged water is pumped, the Saturated Volume Fluctuation (SVF) method was used to provide a first estimate of when spring flow will resume and what typical flow values will be expected.

Study Area

The mining area is characterized by dolomitic compartments formed by dykes compartmentalising the dolomite (fig. 1). Since dewatering operations commenced, the Gemsbokfontein Eye/Spring stopped flowing and this spring is situated in the low-lying area next to a dyke. A distinct drop in water level is observed across the area over time due to the dewatering that is taking place within the compartment.

Water contained in the shallow upper aquifer is attributed to infiltrating rainfall, recharging through weathered material, consequently being delayed by the low permeability of underlying dolomitic material. Although the low permeability of underlying unweathered material delays the infiltration of rainfall, a proportion of the water contained in the upper aquifer still migrates through to eventually recharge the lower aquifer. A significant portion of the groundwater levels were found to lie within the shallow weathered aquifer. The largest volume of water stored in the main dolomitic aquifer occurs in the first 100 m below the water level. The effective base-depth of this aquifer ranges between 150 m and 200 m below the surface. The underlying dolomites have an approximated thickness of 900 m to 1100 m, however it is unlikely that large amounts of groundwater flow occur below this depth, except along intersecting structural conduits leading to underground mine workings (SRK Consulting 2013).

The conceptual model of the dolomite aquifer consists of a weathered zone with the presence of grykes (highly weathered dolomite) with an average thickness of 5m and a tight dolomite zone below with some fracturing.

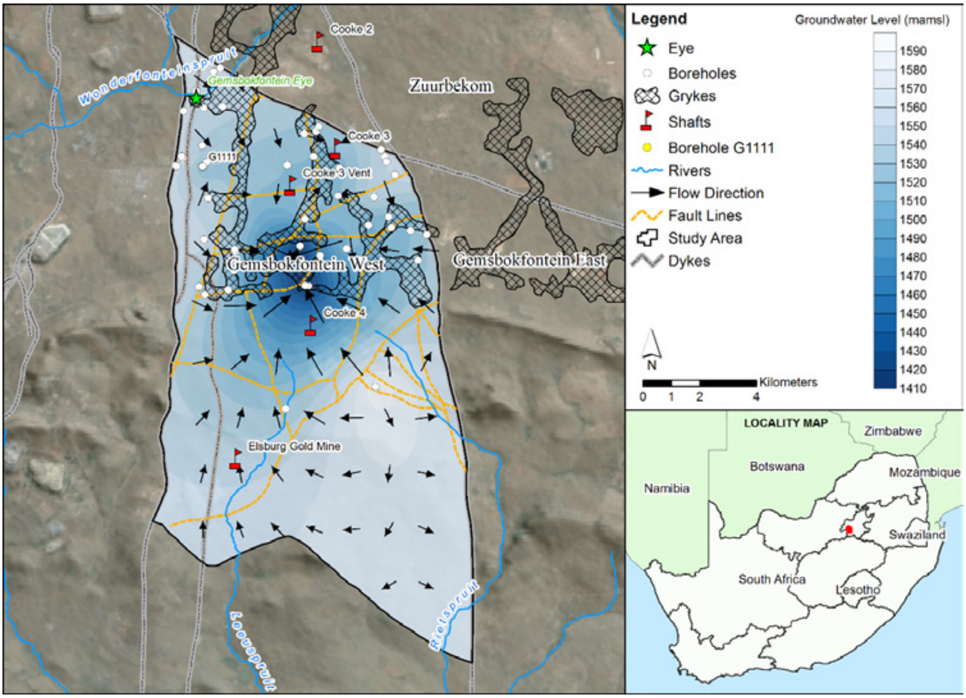

Figure 1 *Study area.*

MODFLOW Model

The MODFLOW model domain is larger than the dolomitic compartment in question and includes the following dolomitic compartments (fig. 1): Gemsbofontein West, Gemsbofontein East and Zuurbekom. A North-South cross-section of the model domain is presented in (fig. 2) to show the dipping of the dolomite layer and the relative thickness.

The MODFLOW model consists of the following three layers and their associated transmissivities: Transvaal (15 m^2/d), weathered dolomite (50 m^2/d) and deep lying dolomite (20

m^2/d). The occurrence of Grykes within the weathered dolomites were assigned a transmissivity of 500 m^2/d. Geological lineaments and fault zones were assigned a transmissivity of 100 m^2/d and dykes cutting through the study area were considered impermeable.

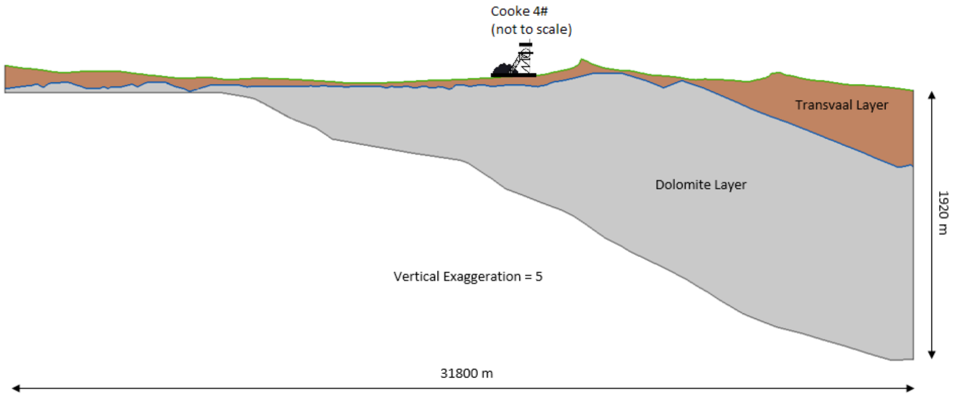

Figure 2 *Model domain cross-section.*

Methodology

The system in question is modelled making use of the SVF method (Van Tonder and Xu 2000) and then results are compared to that of an existing numerical model (set up using the MODFLOW code) for the same compartment.

The SVF method is based on a general groundwater balance, where the change in storage is expressed as a change in groundwater level and all inflows and outflows are translated to a change in head through the use of the aquifer area and specific yield (eq. 1).

$$h_t = h_{t-1} + \frac{R_t}{S_y} + \frac{Q_i - Q_{out}}{AS_y} \qquad (1)$$

where,

t	=	Current time step [T]	S_y	=	Specific Yield
h_t	=	Head in current time step [L]	A	=	Aquifer surface area [L^2]
h_{t-1}	=	Head in previous time step [L]	Q_{in}	=	Sum of all groundwater inflows [L^3]
R_t	=	Recharge in current time step [L]	Q_{out}	=	Sum of all groundwater outflows [L^3]

The fact that specific yield is used, assumes unconfined aquifer conditions. The head values are expressed in meters above mean sea level according to the sign convention used in Equation 1.

The SVF model considers an enclosed area where inflows and outflows are explicitly specified. Inflows from neighbouring compartments and stream losses will vary with a change in head and therefore it is required to make use of a conductance term to properly account for these head dependent inflows into the system. The conductance term (eq. 3) for the various inflows is formulated in terms of Darcy's law (eq. 2).

$$Q = kiA = k\frac{\Delta H}{L}A = C\Delta H \quad (2)$$

$$C = \frac{k}{L}A \quad (3)$$

where,

Q	=	*Flow (L^3/T)*	L	=	*Length of flow (L)*
k	=	*Hydraulic conductivity (L/T)*	ΔH	=	*Head loss (L)*
i	=	Hydraulic gradient (L/L)	C	=	Conductance (L^2/T)
A	=	Cross sectional area of flow (L^2)			

By substituting Equation 2 into Equation 1 the general form of the equation applied to the specified problem is presented in Equation 4.

$$h_t = h_{t-1} + \frac{R_t}{S_y} + \frac{\left[\sum_{i=1}^{n} C_i \Delta H_{it} + Q_i\right] - \left[\sum_{j=1}^{m} C_j \Delta H_{jt} + Q_{out}\right]}{A S_y} \quad (4)$$

where,

t	=	Current time step index	C_i	=	Conductance of inflow term i
n	=	Total number of inflow terms	C_j	=	*Conductance of outflow term j*
i	=	*Inflow term index*	ΔH_i	=	*Change in head of inflow term i*
m	=	*Total number of outflow terms*	ΔH_j	=	*Change in head of outflow term j*
j	=	*Outflow term index*	Q_{in}	=	Sum of all non-head dependent inflows
k	=	Specific Yield layer index	Q_{out}	=	Sum of all non-head dependent outflows

Model Calibration

Model calibration is achieved by making use of existing known inflows to estimate conductance values where applicable and calibrating the model response to observed measurements by changing recharge and specific yield to obtain the best fit. The known inflows and outflows to the system are summarised in Table 1. It should be noted that the stream losses are considered an inflow to the aquifer system.

Table 1 *Summary of known inflows and outflows.*

Inflows	Ml/d	Outflows	Ml/d
Zuurbekom Compartment	9	Cooke 4 Pumping	68
Gemsbok East Compartment	6	Cooke 3 Pumping	9
Leeuspruit Stream Loss	7.5	Gemsbokfontein Eye	0
Rietspruit Stream Loss	5		

The position of the observation borehole G1111 (fig. 1) was chosen to be in close proximity to the spring in question, but also outside the major cone of depression that exists around the shafts. The average drop in water level from historic to current water levels (2016) is estimated at 27m (fig. 2). Making use of the aforementioned drop in water level and current inflows to the system, conductance values for each of the inflows are estimated and the results are presented in Table 2.

Table 2 *Summary of known inflows and outflows.*

Source	Conductance (m^2/d)
Zuurbekom Compartment	315
Gemsbok East Compartment	210
Leeuspruit Stream Loss	260
Rietspruit Stream Loss	175

The model parameters that were used to obtain the best fit as shown in Figure 3 is presented in Table 3. The effective recharge percentage corresponds well to the 7.5% estimated by Enslin and Kriel (1968) and the 6.7% estimated by the Groundwater Resources Assessment Phase II Project (WRC 2005).

Table 3 *SVF fitting parameters.*

Parameter	Value
Study Area (km^2)	161
Specific Yield	0.0043
Effective Recharge (%)	7.1
Dolomite Storage (Ml/d)	23

The assumptions associated with the SVF model can be summarised as follows:

- All inflows are connected to the mine void via a network of faults within the study area.
- All dykes are considered impermeable and inflows from adjacent compartments are head dependent and therefore controlled via a conductance term.
- All leakage from rivers is also head dependent and controlled via a conductance term.

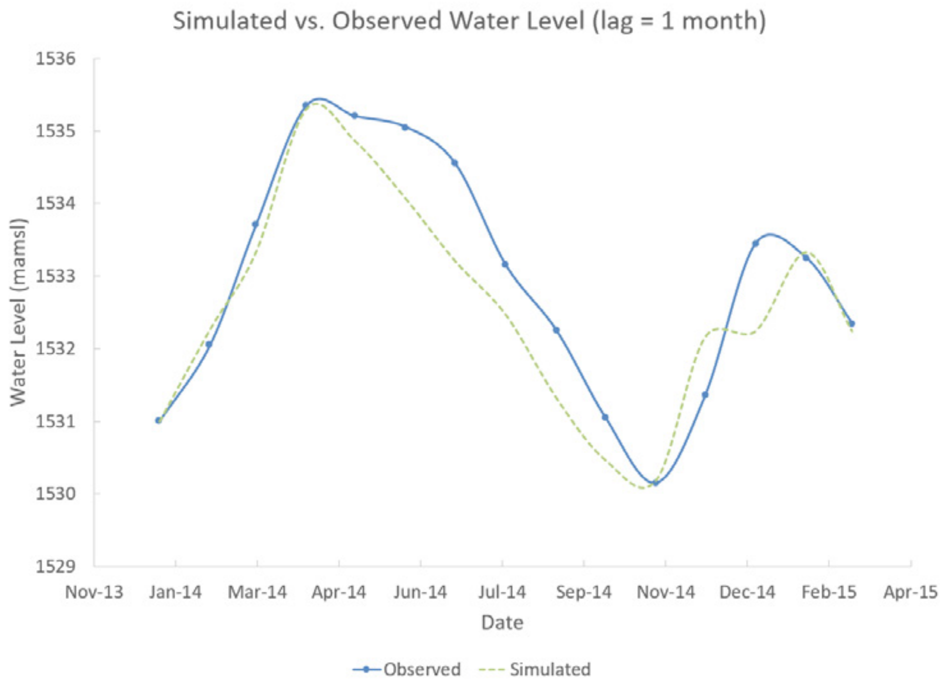

Figure 3 *Modelled versus observed groundwater levels.*

Results

The proposed SVF model was used for predictive modelling and a historic rainfall sequence was used to drive the simulation as shown in Figure 4. The model predict that spring flow will commence approximately 9 years after rewatering of the dolomites takes place when the total mine void has flooded. The average predicted spring flow, once fully restored, is estimated at ±12 Ml/d. Wolmerans (1984) reported a historic spring flow of 9.2 Ml/d. Usher and Scott (2001), Swart et al. (2003) and Dill et al. (2007) all reported historic spring flow of 8.6 Ml/d for the Gemsbokfontein spring prior to mining.

A comparison of the existing numerical model for the study area and the proposed SVF model is shown in Figure 5. Both models predict the start of spring flow within a year of each other. The SVF model seems to reach steady state after 15 years compared to the numerical model which only reach steady state after approximately 35 years. The steady state spring flow predictions are roughly within 1 Ml/d of each other. The difference in model behaviour is contributed to the fact that the numerical model explicitly accounts for transmissivities of fault lines that cut through the compartment leading to a higher outflow component and a reduced spring flow in the case of the numerical model. This would also explain the longer time period that is required to reach steady state.

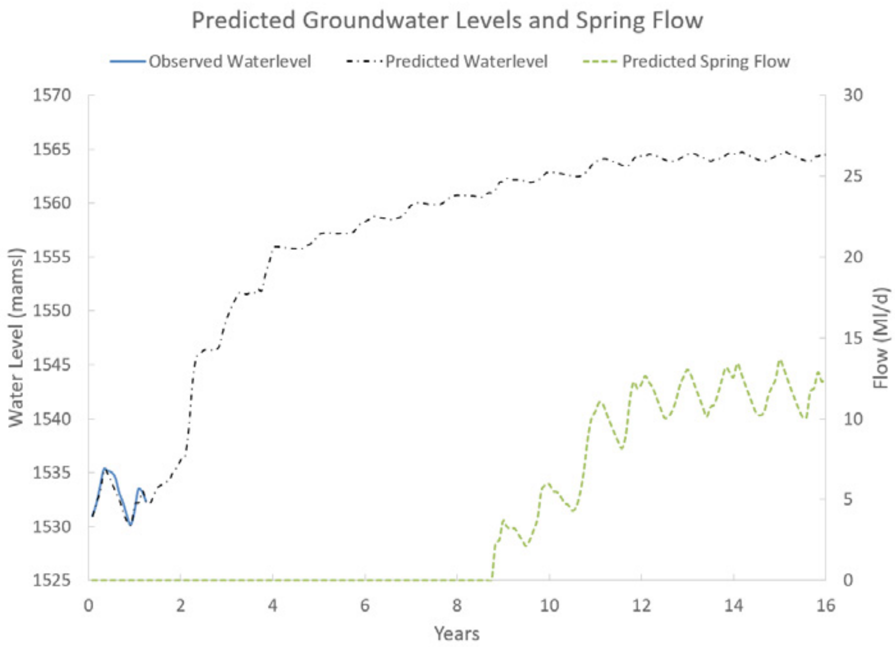

Figure 4 *Predicted groundwater levels and spring flow.*

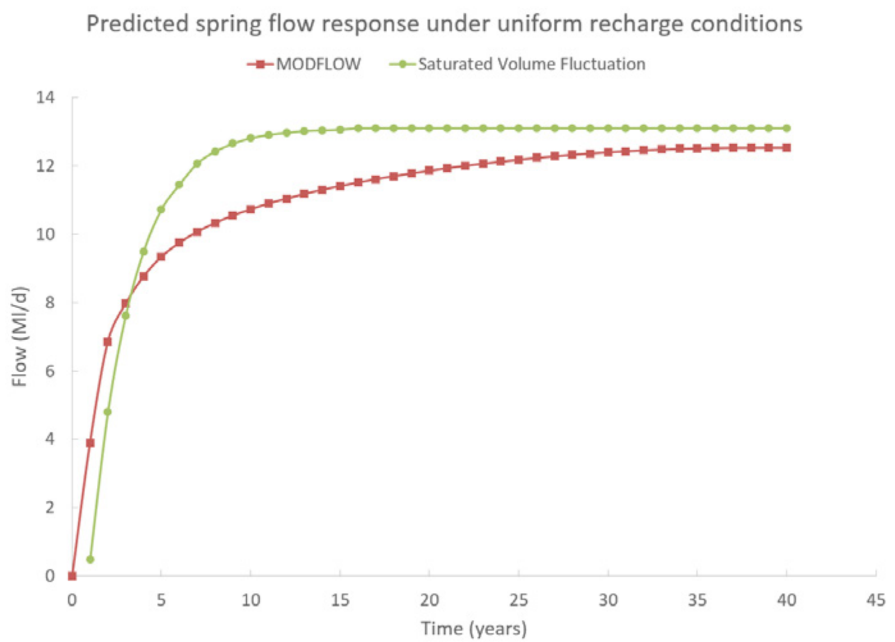

Figure 5 *Predicted spring flow comparison with MODFLOW scenario.*

Conclusions

Applying the SVF solution to spring flow predictions within a dolomitic compartment is a quick and effective way to obtain first order estimates of when spring flow will commence and typical volumes that can be expected, before embarking on a detailed numerical model capable of more detailed scenarios e.g. quality prognosis. The predictions from an existing numerical model of the study area and that of the proposed SVF model compare well considering the simplicity of the SVF model and the associated limitations and assumptions. However, the time to reach steady state differs as highly transmissive faults are not accounted for in the SVF model.

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