Modelling approach to predict peak inflows at the Argyle block cave mine, Western Australia

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Abstract

Argyle Diamond Mine is situated in the East Kimberley region of Western Australia. Block-cave mining is ongoing below the mined-out South Bowl pit. Average annual rainfall is about 800 mm. A constant flow of groundwater between 60-100 L/s enters the cave zone laterally from various permeable layers in the surrounding country rock. In addition, ephemeral runoff from the overlying pit rapidly infiltrates into the surface of the cave. In 2014, two major rainfall events occurred: 175 mm falling in 48hrs on 15th-16th January; and 213 mm falling in 72hrs on 6th-8th February. The January 2014 rainfall event caused a short term peak mine inflow of 500 L/s, whilst the February 2014 event caused a peak inflow of 1200 L/s.

A rainfall-runoff-frequency model was created to assess runoff volumes reaching the base of the pit. This was coupled with a numerical flow model developed to assess the passage of water from the pit floor to the mine extraction level. The model incorporated rock mass hydro-geomechanical changes based upon the predicted future Life of Mine cave zone propagation. The coupled model was calibrated to the two major 2014 runoff events. The model was then used to simulate a series of potential future rainfall-runoff events and future underground inflows. The analysis was used to develop a Trigger Action and Reponse Plan (TARP) for the future flood management.

Calibration demonstrated that peak inflows to the mine workings were found to be highly sensitive to the propagation of the caved zone to the pit surface over mine life and prior water content of the cave zone. Current pump capacity and operational alarms were found to be insufficient to deal with extreme inflow events. The model results were used to develop new criteria for activation of seasonal pumps within the mine.

Key words: Mine water, Block cave mining, Groundwater model, Flood management, Water balance

Introduction

Argyle Diamonds Limited (Argyle) is wholly owned by Rio Tinto Ltd and operates the Argyle diamond mine in the East Kimberley region of Western Australia. The region has tropical-monsoon climate, receiving approximately 90% of its rainfall during high intensity, highly variably cyclonic events in the wet season from November to April. Mining began in 1985 as an open pit operation but has recently transitioned to underground block cave mining. The block cave operation lies beneath the South Bowl open pit and started production in 2013.

The block cave operation intercepts groundwater within saturated zones surrounding the ore body, and also receives vertical inflows from infiltrating surface water captured by the overlying open pit. As underground mining has progressed, so the block cave operation has caused much greater hydraulic connection between the base of the open pit and the underground workings. Further enhancement of the cave zone permeability is likely to occur as future mining progresses. This presents a significant hazard for mine operations during the wet season when large volumes of surface water may be generated within the surface area of the pit.

A dynamic water infiltration model was required to assess inflows from the pit floor to the underground. The model needed to provide a range of possible outcomes and associated risks which could be used to address long-term issues related to underground pumping capacity and strategy.

Methods

A multi-phased approach was adopted to contribute to the development of a new TARP for future flood water management. In Phase 1, a surface water balance model developed in the GoldSim modelling platform was used to predict volumes of water reaching the base of the South Bowl pit. In Phase 2, a groundwater model of the cave zone was developed in order to predict future inflows to the underground mine, based on outputs from the surface water balance model. Finally in Phase 3 an operational mine water balance model was developed to assess the installed underground pumping capacity and available storage in response to inflows predicted by the groundwater model.

Phase 1: Development of a water balance model for the South Bowl pit

The principle objective of this phase was to estimate the volume of water reaching the pit which may infiltrate to the cave zone. Historically, prior to the commencement of the block cave operation, any water reaching the base of the pit has ponded to form a seasonal pit lake. However, in the last 2 years the material at the base of the South Bowl has become fractured and fragmented (Figure 2.1) as the cave zone has extended upward to the pit floor. The subsequent increase in permeability of the material has meant that a lake no longer forms and most water rapidly infiltrates.

The GoldSim modelling platform was used to create the rainfall-runoff water balance model for the South Bowl pit catchment. GoldSim is a generic dynamic simulator for deterministic and probabilistic modelling of functional relations between several elements or variables. A conceptual model of the pit water balance was developed to identify the main water balance elements as shown below in Figure 1.

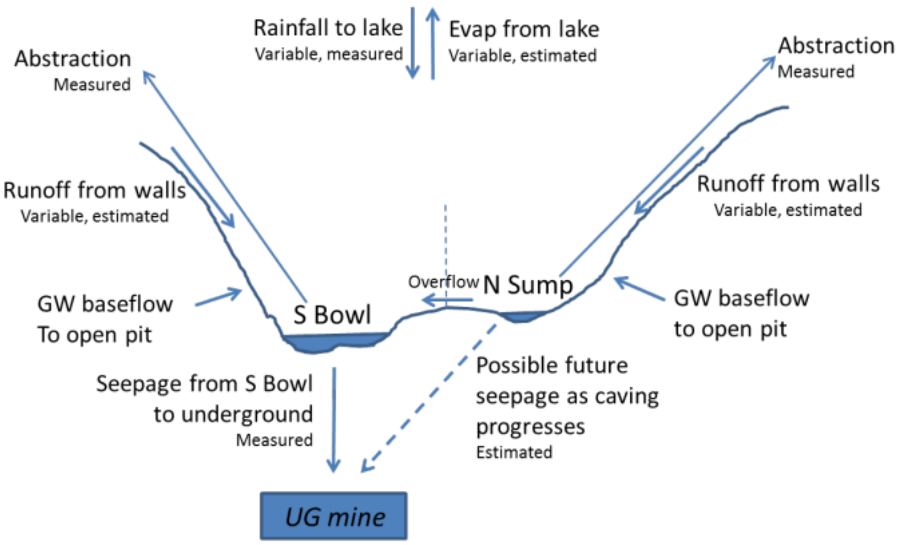

Figure 1 *Schematic of rainfall-runoff water balance components.*

The majority of water balance elements were known with a reasonable degree of certainty. A total of four years of daily rainfall and pan evaporation records were available from a nearby mine rain gauge and a Bureau of Meteorology site at Argyle aerodrome. The catchment area of both the North and South bowl and a stage volume relationship for both two pit lakes were calculated using spatial analysis software. The baseflow to the North Bowl and South Bowl was estimated from end of mine life pit dewatering rates and the daily record of pumping rates from the pit sumps post-closure.

Estimation of a runoff coefficient involved greater uncertainty. Previous studies have reported widely variable runoff coefficients, ranging from 11% to 40% of rainfall. These values were used as a starting point for calibration. Light rainfall events are either absorbed by the surface materials to reduce the soil moisture deficit, or held near surface by capillary forces and subsequently evaporated. For the purposes of the water balance, the threshold value for runoff to occur was set to 3 mm/d of precipitation. In addition, a dispersion factor was added to account for significant delayed pit lake abstraction rates observed, for example, four days after a significant flooding event in 2011. Conceptually this simulates shallow interflow through near surface fractures within the over-break zone.

During an early flooding event in 2011, prior to extensive development of cave zone, seepage from the South Bowl was calculated to be 2 – 2.2 l/s per metre of water depth at the base of the pit. Permeability was adjusted during time-variant calibration to account for the continued development of the cave zone. Since early 2013 a pit lake has no longer formed, therefore permeability was increased sufficiently to account for this in the water balance model. From this point all water reporting to the South Bowl is assumed to infiltrate to the cave zone.

The model was primarily calibrated using pit water levels measured in the South bowl. Calibrated historical model results are shown in Figure 2. Calibration was mainly achieved through varying the most uncertain parameters, namely the runoff coefficient and the pit floor hydraulic conductivity. This resulted in a final calibrated runoff coefficient of 25 %, and a runoff threshold of 3 mm. Time-varying hydraulic conductivity values were applied to simulate pit floor seepage, and were increased three times over the calibration period such that no pit lake formed beyond early 2013.

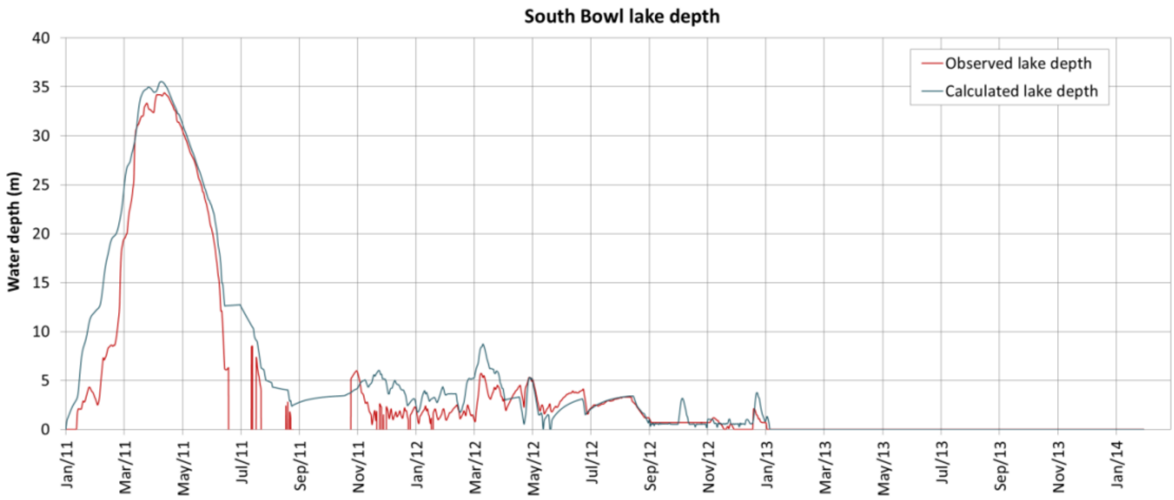

***Figure 2** Predicted versus observed pit lake depth*

Once calibrated, a series of predictive models (scenarios) were setup and run to provide time-varying inputs for input to the cave zone groundwater models. These comprised 4 scenarios:

Scenario 1, or Basecase, cycles an ‘average’ year of rainfall to create an average condition dataset. The year 2007/2008 was chosen as the yearly total rainfall of 770 mm was very close to the long term average of 784 mm/y. In addition, there were two short term rainfall events exceeding a total of 80 mm, and several isolated rainfall events would allow for inflow and recession curves to be generated for several periods. Average monthly evaporation rates and pit abstraction rates were also used.

A sensitivity analysis was run on the Basecase model to understand how changes to different parameters could affect model predictions. This work focused on the parameters known with the least certainty: runoff coefficient and runoff threshold. Rainfall was also adjusted, as whilst it was measured on site it is possible that the magnitude varied across the pit catchment.

It was found that the runoff threshold was the least sensitive parameter, and resulted in only a small change to the pit lake levels. Changing the rainfall depth and runoff coefficient by 20% resulted in a larger change to the calibrated peak lake level of +/- 5.2 m (or ~14.5%) and +/- 4.5 m (or ~12.5%) respectively, compared to the Basecase calibration. In early 2012 when the lake level is lower, the absolute levels are all within 1 m of base case, and from mid-2012 to January 2013 there are no significant differences seen. The results for these parameters are similar as they are inter-related in a similar fashion to catchment size and runoff percentage. As long as catchment size and rainfall are measured correctly, the errors associated with an inaccurate runoff percentage estimate are minimised.

Scenarios 2 and 3 involved respectively decreasing and increasing the 2007/2008 rainfall series by 20%, whilst maintaining basecase parameters. These series were then run from February 2014 onwards, when the historical rainfall series ends. Resultant peak flows reporting to the base of the South bowl were 766 l/s and 1167 l/s in Scenarios 2 and 3 respectively.

Scenario 4 involved simulating different rainfall events for different return periods as calculated by the Australian Bureau of Meteorology. IFDs (Intensity Frequency Duration) totals were available for 1 year, 2 year, 5 year, 10 year, 20 year, 50 year and 100 year return periods. The IFD data were created using the 2013 datasets as documented in Green et al. (2012). As the water balance model ran on daily timesteps, total rainfall depths for 24, 48, 72 and 96 hours were used.

Phase 2: Development of the cave zone seepage model

In order to improve the prediction of potential future inflows, a groundwater model of the cave zone was developed to assess the infiltration of recharge from the surface (the base of South Bowl) to the underground workings. The groundwater model is centred on two orthogonal sections, which coincide with those used in the geotechnical studies undertaken in FLAC 3D (Geonet 2013) to determine the geomechanical state of the rock mass throughout the mine development. The geotechnical modelling results facilitated the adjustment of the rock mass hydraulic parameters over time to generate a dynamic predictive time series of potential seepage from the surface to the workings.

The two key sections are shown in Figure 3a. The structural geology and the underground workings are shown in Figure 3b. The groundwater model incorporates:

- Detailed lithological representation of the subsurface.
- Inclusion of the underground workings.
- Significant geological structures, including the major faults that were incorporated within the geotechnical modelling.
- Hydraulic properties, which were initially determined from previous studies.
- Displacement contours, detailing changes in rock displacement throughout the development of the mine, as calculated in the 2013 geotechnical model.
- Calibration to rainfall and groundwater inflow data from early 2011 to mid-February 2014.

The groundwater model was developed using the SEEP/W finite element code, and consists of two orthogonal sections of known widths. As such the resultant inflows to the mine were scaled proportionately to the total area of the South Bowl. The groundwater model was initially calibrated to ensure that baseflow of approximately 100 L/s reported to the workings. The pit water balance model generated rates of water flow to the base of the South bowl for the historical period between 2011 and 2014, and was used the recharge input to the groundwater model. The model start date was set as January 2011.

A second calibration stage was then undertaken, focusing on the historical period between July 2013 and January 2014. This stage focused on matching modelled and observed inflows as the cave zone developed additional permeability and and an enhanced hydraulic connection with the base of South bowl. Deformation contours generated in the FLAC model were used to guide the distribution of enhanced permeability in the cave zone. Results from the first two calibration stages are presented in Figure 4. Also plotted are the actual recorded mine inflows, the GoldSim water balance recharge series and the simulated recharge to South Bowl in the groundwater model.

In general inflows show a reasonably close match to observed inflows, particularly in 2013 and 2014.

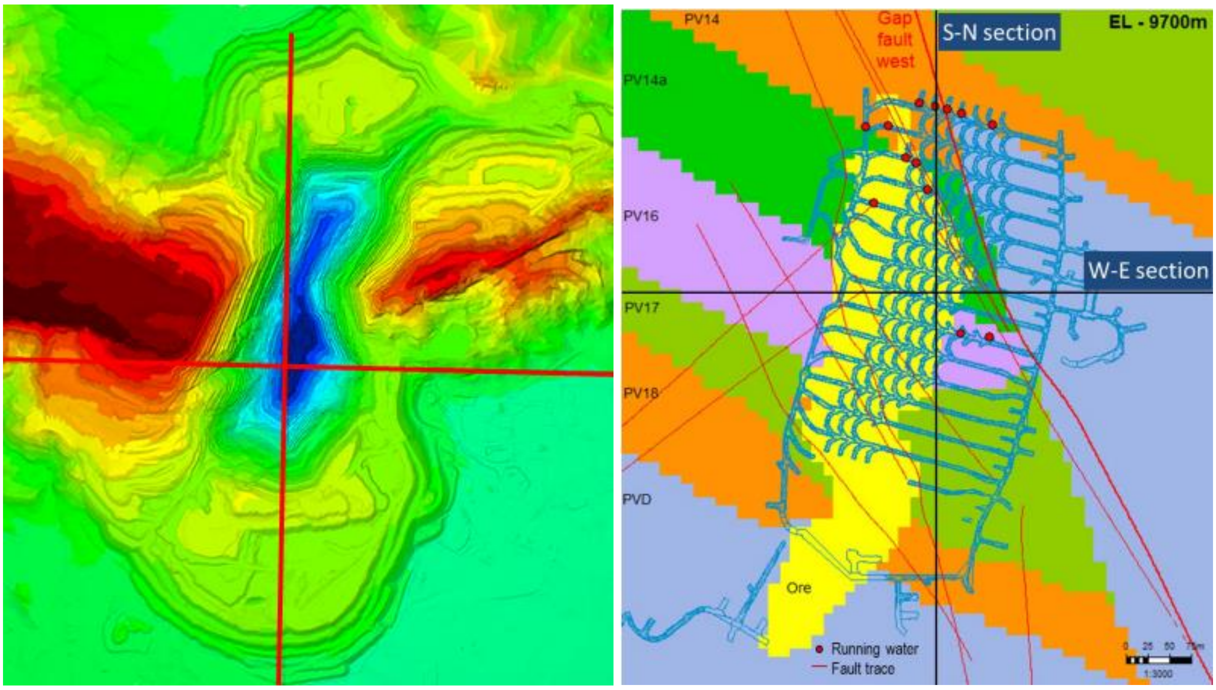

***Figure 3**. a) Location of the two sections in relation to the open pit, b) Location of the two sections in relation to the underground workings.*

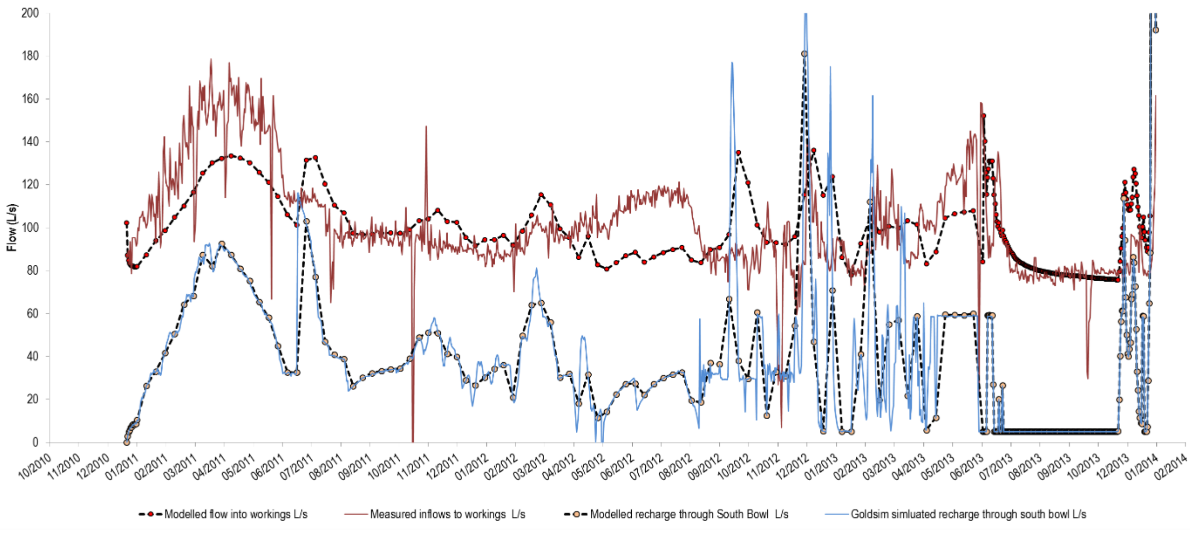

***Figure 4** Historical calibration to mine inflows*

The third and final stage of calibration focused on January and February 2014, where significant inflows of up to 1245 L/s were recorded entering the workings in response to two significant storm events. Calibration focused on fine tuning hydraulic parameters using a more recent displacement contour distribution representing geotechnical conditions in late 2013. The mine inflows modelled for both of the storm events in early 2014 are plotted in Figure 5. The first inflow peak in response to the January storm is overestimated by approximately 100 L/s whilst the second peak in response to the February storm event is underestimated by approximately 300 L/s. The discrepancies, particularly for the first peak, can be attributed to how the recharge is distributed throughout the day in the model rather than during a 2-3 hour period where Hortonian runoff would be expected to accumulate rapidly in the base of the pit. Since only daily rainfall and mine inflow data are available, it is neither possible nor defensible to create a representative hourly resolution recharge input file which could generate the appropriate inflow peaks to the mine. Peak inflows are predicted at the correct times, and recovery between peak flows is handled well as demonstrated by the trough between the two peaks in Figure 5.

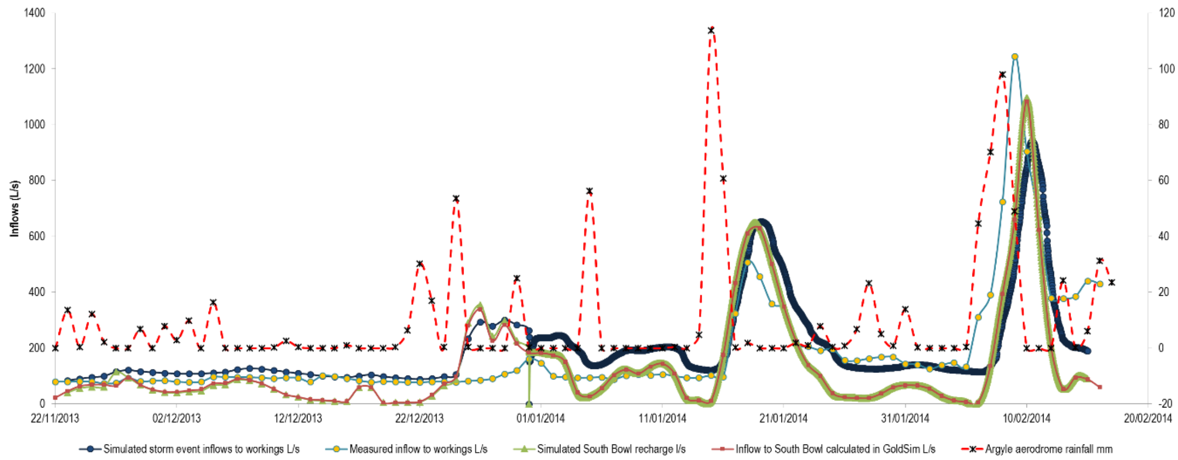

Figure 5 *Calibration to the January and February 2014 storm events*

Based upon the calibrated model, a series of predictive scenarios were run as described below.

Scenario 1: Baseline predictive model based upon the representative South Bowl recharge time series generated in the Scenario 1 GoldSim water balance model up to the end of 2020:

- 2014-2017: Final calibration displacement contours, representing geotechnical conditions at the end of 2013.
- 2017-2020: Predicted displacement contours for 2016 used. Both a pre-subsidence and post-subsidence pit floor were modelled with this displacement contour set. Magnitude of the subsidence of the pit floor was set at 100m, which corresponds to that predicted in the geotechnical studies.

Peak inflow rates to the mine were found in general to increase in response to greater rock deformation. The effect of any increase in storage was small during significant storm events. Inflows rates slightly increased with subsidence of the pit floor, which also led to a decrease in response time of inflows to precipitation by 1 to 2 hours.

Scenarios 2 and 3: Sensitivity analyses: +/- 20% rainfall. Recharge time series were produced by the GoldSim water balance model with modified rainfall. These runs served as a verification that simulated inflows varied accordingly with an increase or decrease in rainfall.

Scenario 4: Simulation of 24, 48, 72 and 96 hour storm events (time series also produced by GoldSim water balance model). The simulation of infiltration through the cave zone in response to representative return period storms provides the necessary data to develop a tool which can be used to estimate the likely inflows to the mine under various future storm conditions. The scenario was run with both the deformation contours used in the final calibrated model and those representing fully mobilised conditions after 2016. Subsidence of the pit floor was also considered. The maximum modelled peak inflows from all scenarios are summarised in Figure 6. Invariably 72 hour storms produce the highest peak inflows to the mine. 48 hour storms produce greater peak inflows to the mine if ground conditions are fully mobilised, although prior to 2016 the 96 hour storms tend to produce higher peak inflows as the ground is less permeable, which tends to promote concentration of inflows from longer duration storm events.

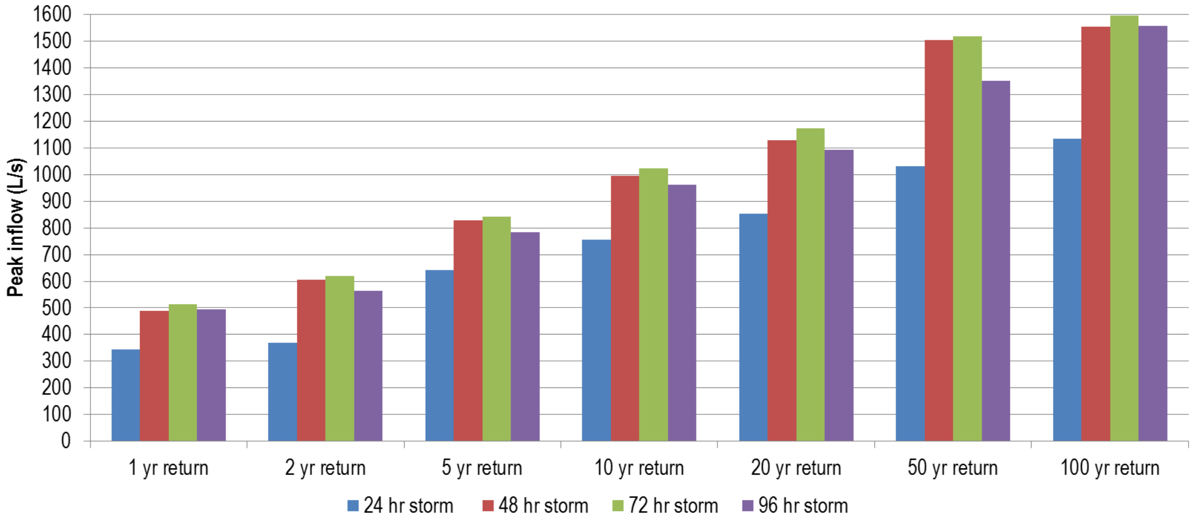

Figure 6 *Summary plot of maximum predicted inflows by storm event*

Scenario 5: This scenario was designed to evaluate the impact on mine inflows of pre-wetting of the rock mass by antecedent rainfall events. Sensitivity runs consisted of (i) a 2 year, 24 hour storm event preceded by a 1 year, 24 hour storm, and (ii) a 10 year, 24 hour storm event preceded by a 5 year, 24 hour storm. The recovery time between the storm events was progressively reduced to simulate the recharge from the second storm event occurring through partially saturated ground, and how this may impact the predicted peak inflows to the mine. Pre-wetting by antecedent rainfall was found to significantly increase simulated peak inflows to the mine if both storms events occurred within a period of 4 to 6 days.

Phase 3: Development of an operational mine water balance

In order to account for underground water storage and both duty and seasonal pump pumping capacity, a water balance model of the mine was constructed using the inflow results from the groundwater model. The water balance model was designed as an operational tool to assess the effectiveness of alternative dewatering system configurations in response to various storm events with the aim of contributing to the development of a new mine TARP. The model incorporates:

- The duty dewatering pumping rate (DDP)
- The seasonal dewatering pumping rate (SDP)
- The threshold water volume for activation of the SDP

The input to the water balance was provided by the groundwater model hydrographs assuming maximum cave zone development represented by the fully mobilised 2016 displacement contours and subsidence of the pit floor. Scaling factors to account for the preferential flow paths can be modified to compare alternative pumping rates and underground water storage configurations

Results from simulations using the current SDP trigger volume showed that inflows could be managed for 24 hour, 48 hour, 72 hour and 96 hour storms with 5 to 10 year return period with current underground storage capacity. However, with the exception of 24 hour storms, events with a return period greater than 20 years would generate inflows that would overwhelm current installed dewatering systems and underground storage.

The water balance was re-run using a lower SDP trigger volume. It was found that this enabled the mine to cope with inflows from all storm events with the exception of 50 to 100 year events of a duration greater than 24hrs. It was therefore recommended that the trigger should be set to this lower threshold, and reduced further in the wet season if necessary to better cope with high inflows.

An additional alarm for high intensity rainfall was also recommended, triggered once rainfall intensity reaches 30mm/hr. This is a conservative approach, as the groundwater model and operational mine water balance showed that rainfall exceeding this value would have the potential to generate inflows to the mine exceeding the capacity of the DDPs.

Conclusions

A multi-phased modelling approach was used to generate input for an operational mine water balance model. A surface water balance model was developed to estimate total volumes of flow reporting to the base of the South Bowl pit, and an infiltration model was developed to model seepage of groundwater through the cave zone to the mine workings. Output from these two models was then used as input to the operational mine water balance model to undertake an assessment of the current underground dewatering capacity, providing critical input to the development of the new TARP. The model can be used to estimate potential inflows to the mine in response to a range of representative storm events, and provides Argyle Diamonds Limited with the means to refine their dewatering strategy to better respond to future rainfall events.

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