Model Simulations of the Layered Development of Waste Rock Stockpiles, Progressive Moisture Changes and Potential Seepage Generation in a Low Rainfall Environment: Case Study of an Australian Mine Development

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Abstract

Models simulating saturated-unsaturated flow processes have been developed and run to understand the potential risks of seepage generation from waste rock stockpiles in a low-rainfall, iron ore mining province.

The stockpiles are modelled within a holistic, waste rock stockpile - hydrogeological context. The temporal (staged) development of the stockpiles was modelled to reflect ongoing wetting-drying, with sensitivity testing undertaken to address data gaps.

The study results indicate that the nature of the staged development of waste rock stockpiles, low rates of rainfall and significant depth to groundwater make it unlikely that seepage fluxes to the underlying groundwater system would occur.

Keywords: hydrogeology, waste rock, seepage impacts

Introduction

SIMEC Mining is currently considering developing a new, hematite iron ore (open cut) mine at Iron Sultan, located at the Camel Hills ("Site"), approximately 45 km west of the town of Whyalla in South Australia, Australia (Figure 1). Two-dimensional modelling of saturated-unsaturated flow processes was undertaken of the progressive, layered development of the waste rock stockpiles to better understand seepage generation processes, taking account the underlying hydrogeological conditions and potential changes to groundwater conditions due to mining.

Site Setting

The Site is located in the Gawler Ranges district and to the west of the Iron Baron Mining Area (IBMA) (Figure 1) and within an arid to semi-arid climate, with potential evaporation substantially higher than rainfall (average rainfall and "Class A" pan evaporation are 270 and 2,550/annum respectively). The Site is located on the western flank of the regionally extensive, north-south trending Middleback Ranges (~350 m Australian Height Datum, mAHD).

Figure 1 *Site Location (adapted from information provided by SIMEC Mining)*

Geology and Hydrogeology

The Site is situated in the Gawler Craton, a stable crystalline basement province containing Archaean to Mesoproterozoic rocks with thin overlying sediments of Neoproterozoic to Quaternary age overlying the basement rock (Rudd, 1094; Drexel et al., 1993; Parker and Flint, 2012). The basement rocks comprise Banded Iron Formation (BIF) and Granites/Schistose rocks. The regional hydrogeology is characterised by unconfined/confined, fractured rock hydrogeological units of the Middleback Ranges underlying unconfined aquifers in surficial Tertiary and Quaternary sediments located in lower areas of the landscape. The fractured rock units contain groundwater that are saline to brackish in water quality and have low yields. Groundwater of potable quality is mostly found in Quaternary limestone and Tertiary sand aquifers (Berens et al., 2011). Site-specific field investigations have been undertaken to understand site hydrogeological conditions at Camel Hills (Puhalovich, 2018).

Groundwater recharge occurs where basement rocks outcrop or sub-crop at or near the Ranges (Berens et al., 2011). Estimates of net groundwater recharge have been made using groundwater quality data and the CSIRO groundwater recharge-discharge calculation method (Leaney et al., 2011). Specific inputs included annual rainfall, annual rainfall chloride flux, groundwater chloride concentration, soil clay content, soil type, and vegetation type. Net groundwater recharge rates are estimated to range from 0.3 to 6.1 mm/year (or about 0.1 to 2.3 % of average annual rainfall).

Climate

The Site lies within an arid to semi-arid climate, with potential evaporation rates significantly greater than rainfall rates. Daily rainfall data are available from Bureau of Meteorology (BoM) Station 18117 (Whyalla – Moola, 1958 - present, located ~10 km from Site) and ("Class A") pan evaporation data are available from the nearest BoM climate Station 18120 (Whyalla – Aero, 1983 - present, located ~38 km from Site). There exists a substantial, negative rainfall : evaporation deficit at the Site. The intensity of storm events typically range from 10 to 40 mm/day, occurring in both summer and winter months, with only 15 days each year when daily rainfall exceeded daily average evaporation between 1983 and 2013.

Development of Waste Rock Dump (WRD) and Low-Grade Ore Stockpile (LGOS)

The WRD and LGOS is currently planned to be constructed immediately to the west of the pit (Figure 2). The WRD will comprise 4.3 Mm^3 of rock / sediments and will be built using "end dumping" methods over a 4 ½ year (Life-of-Mine) period. Mining will occur above the water table and so it is expected that excavated materials will be dry.

It is not possible to define specific material zones within the WRD and LGOS as the placed materials will not be segregated. The deposit's geology model has identified nine "geozones". The WRD's materials primarily comprise "Sediment Cover (sand, calcrete and clay/scree")" (54.5%), "Scree Cover" (24.0%) and "BIF" / "Shear Zone" / "Clay Lenses" (19.4%).

The geotechnical properties of the above materials are untested, so are defined here as being equivalent to a medium to coarse grained sand. The "sand" component within the Sediment Cover materials will only be encountered at the near surface and so the "clay" component will likely dominate the waste materials in this Geozone.

There are also no data available relating to the saturated and unsaturated hydraulic properties of the WRD materials. It is therefore assumed that, given the above, the saturated (maximum) hydraulic conductivities and porosities of the waste rock materials are likely to range between 1 and 4 m/d and 0.1 to 0.3, respectively.

Study Objectives

The study objectives were to better understand the potential infiltration, saturation and seepage flux characteristics, and the sensitivity of various materials parameters, for the proposed WRD and LGOS in the operational period.

Figure 2 *Site Layout*

Conceptual Model

Rainfall will infiltrate into the WRD and LGOS structures, primarily in areas where uncompacted waste rock slopes exist and in active placement areas. Incident rainfall on compacted benches and haul roads is unlikely to infiltrate; ponded waters are likely to evaporate given the low rainfall – high evaporation climate.

During the operational period, wetting and drying phases will occur depending on the prevailing climate conditions. Seepage fronts from the WRD-LGOS will periodically occur and migrate vertically down through the waste materials, thereby increasing moisture levels and in-situ hydraulic conductivities. Seepage may reach the water table and potentially affect groundwater quality. In this scenario, were it to occur, seepage affected groundwater quality would migrate to the north-west, given the results of hydrogeological investigations (Puhalovich, 2018).

Modelling Approach

The approach followed comprised calculating potential infiltration fluxes to the WRD, followed by development of a saturated-unsaturated (flow process) model of the WRD using Feflow software.

Infiltration fluxes to the WRD were estimated by calculating the difference between measured daily rainfall and estimated daily evaporation (using monthly Class A pan data). A Pan factor of 0.8 was applied to the Class A Pan evaporation estimates. This approach is conservative since compaction of the upper surface of the WRD would likely result in significant runoff during peak storm events. The initial infiltration flux scenario tested was as follows: Scenario 1: "High Case" (1973 annual rainfall year, nearest to 5% annual exceedance of 450 mm/annum).

The unsaturated hydraulic conductivities of these materials are a function of maximum hydraulic conductivity (which occurs when the waste materials are saturated) and degree of saturation. The relationships assumed to exist between unsaturated hydraulic conductivities, pressure heads and degree of saturation can be replicated using the 'van Genuchten' model, as defined below.

$$se = (s - sr) / (ss - sr) = \left\{ \frac{[1 + (-\alpha\Psi)n]-m,}{1,} \quad \begin{matrix} \Psi < 0 \\ \Psi \geq 0 \end{matrix} \right.$$

$$Kr = se0.5[1 - (1 - se1/m)m]2$$

$$m = 1 - 1/n$$

$$\alpha > 0, n > 1$$

s	Saturation	(fluid volume per void volume)
sr	Residual saturation	(fluid volume per void volume)
ss	Maximum saturation	(fluid volume per void volume)
se	Effective saturation	(unitless)
Ψ	Pressure head	(units of length)
α	Fitting parameter	(units of length-1)
m, n	Fitting parameters	(unitless)
Kr	Relative conductivity	(unitless)

Model Development

A two-dimensional Feflow section model was developed along the section shown in Figure

2, interpreted to be a current (pre-mining) groundwater flow line from the Camel Hills site to Salt Creek (assumed discharge location to the north-west). The model comprises 16,303 elements and 8,516 nodes with boundary conditions and the pre-development heads applied presented in Figure 3.

Assumed hydraulic properties in the model were based on the results of single well permeability tests undertaken at the Camel Hills deposit and related interpretations (Puhalovich, 2018). Effective porosity and specific storage were assumed, based on experience elsewhere, to be 0.01 to 0.05 and 0.0001 m/m, respectively. Model boundary conditions comprised Dirichlet ("constant-head") boundary conditions of 145 and 151 mAHD were set along the model's western and eastern boundaries, reflecting groundwater flow gradients. Constant-head boundary conditions were also applied on the embankment slopes when pressure at a point on the slope is > 0 kPa (i.e. seepage faces). A Neumann Boundary Condition (Darcy "fixed flux") was applied to the plateau of the WRD with the net infiltration (daily) fluxes calculated applied. The upper layer of the WRD, to which the net infiltration fluxes were applied, was increased by around 4.5 m each year.

Results of Model Simulations

The model simulated the progressive raising of lifts of the WRD by applying daily positive-negative fluxes to the uppermost surface of each layer (~4.5 m) of waste rock placed over the four and half years of operations. These fluxes are constrained such that pressures do not exceed the elevation of the upper surface of the waste rock and are not permitted to fall to below -200 kPa (given absence of fine silty/clayey materials within the waste rock).

Monitoring points 1 to 10 were set at the base of the WRD (Figure 3) to track whether groundwater pressures exceeded phreatic conditions (i.e. > 0 kPa), to indicate whether seepage fluxes are sufficiently high to result in saturated conditions beneath the WRD and seepage to the underlying water table. These points indicate increases in groundwater pressures and moisture contents. However, groundwater pressures do not exceed phreatic that would indicate vertical seepage and impacts to the underlying groundwater system, i.e. model predicted groundwater pressures (Figure 4) indicate that saturated conditions are not encountered. Model results indicate that model boundary inflows and outflows are low and remain unchanged, with groundwater outflows at Salt Creek ("model boundary outflow") constant at around 0.1 to 0.2 m³/d/m. Groundwater storage changes within the WRD are also presented in Figure 5. The figure shows significant infiltration fluxes in the first year of WRD operation, with ris-

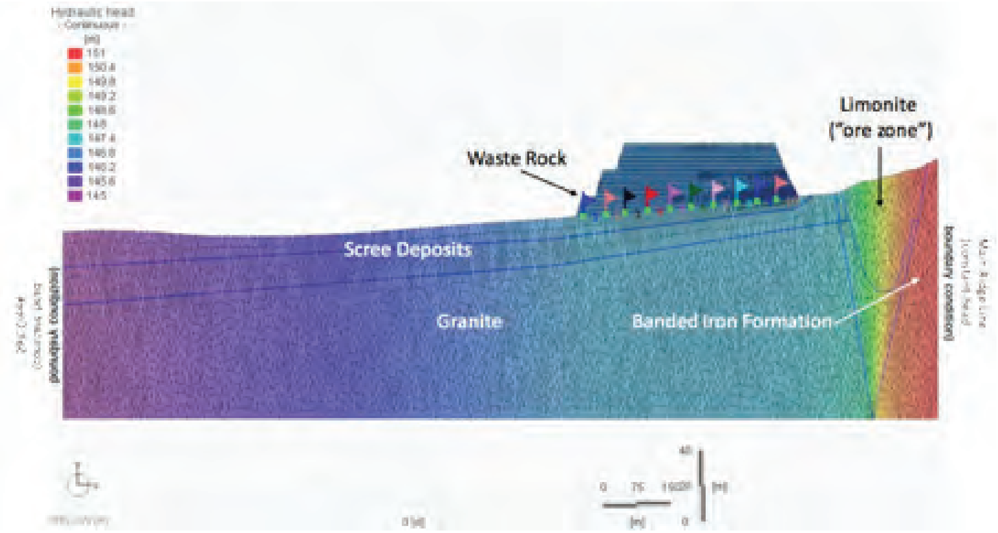

Figure 3 Model Design

ing groundwater storage. After the first year, however, groundwater storage is progressively lost due to net negative fluxes (due to evaporation) from years 1.0 to 4.5. The model results indicate that there no changes in groundwater storage beneath the WRD.

Sensitivity testing was undertaken to assess whether the properties (untested) of waste rock materials could significantly increase the likelihood of seepage fluxes. Table 1 presents the results of the sensitivity testing scenarios. It was found that the only scenario

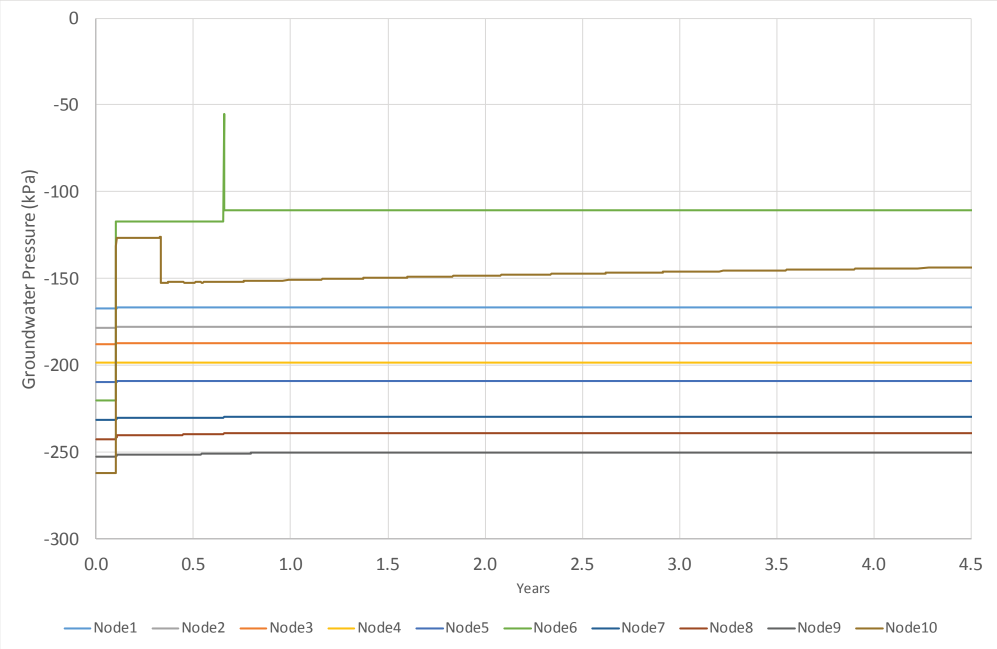

Figure 4 *Model Predicted Groundwater Pressures (base of WRD)*

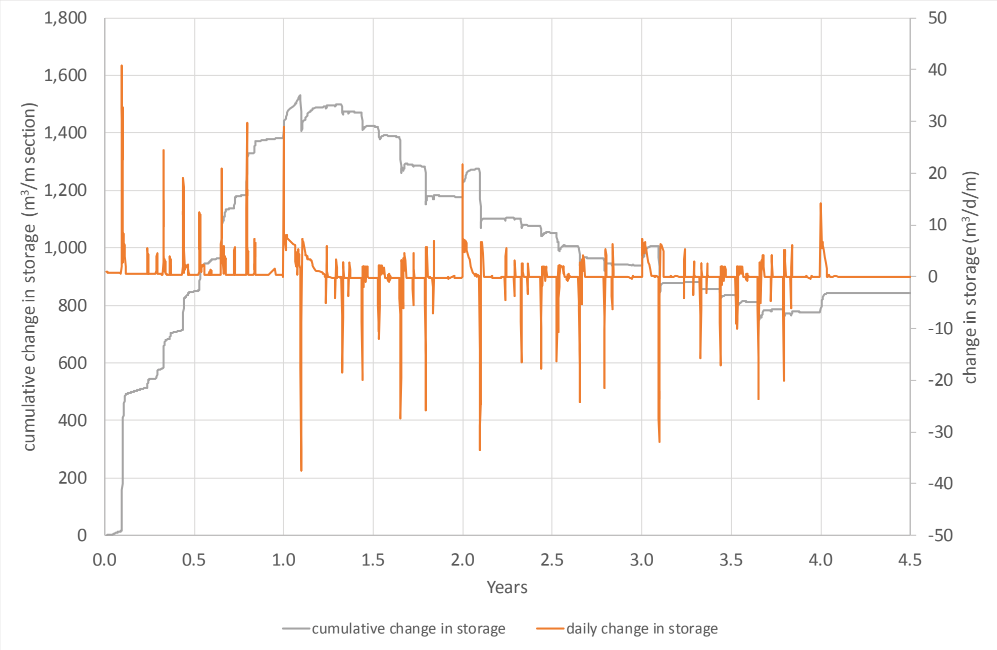

Figure 5 *Model Predicted Groundwater Pressures (base of WRD)*

***Table 1** Results of model sensitivity testing – groundwater pressures at base of WRD (kPa)*

Scenario	Min. Pressure	Average Pressure	Max. Pressure	Comment
Base Case	-261.76	-191.70	-55.58	
SENS1	-261.76	-190.52	-62.69	Anisotropy of waste rock materials increased from 0.1 to 1.0
SENS2	-97.79	-55.76	15.62	Saturation of three lowest layers in waste rock (4.5 m) changed from 0% to 100%
SENS3	-261.76	-180.18	-40.89	Reduce unsaturated porosity from 0.3 to 0.15
SENS4	-261.76	-105.05	-12.78	Reduce unsaturated porosity from 0.3 to 0.05
SENS5	-261.76	-204.41	-82.45	Increase unsaturated porosity from 0.3 to 0.4
SENS6	-262.18	-198.46	-56.42	Reduce saturated hydraulic conductivity (K) of waste rock from 4 to 2 m/day
SENS7	-261.76	-203.29	-149.91	Reduce saturated hydraulic conductivity of waste rock from 4 to 0.5 m/day
SENS8	-261.76	-191.70	-55.57	Modified Unsaturated Materials Properties (Pressure Head vs Rel. K): Abscissa min. increased from -10 to -1
SENS9	-261.76	-191.70	-55.57	Modified Unsaturated Materials Properties (Pressure Head vs Rel. K): Abscissa min. decreased from -10 to -200, max. increased from -0.0001 to -0.01
SENS10	-261.76	-191.82	-55.57	Modified Unsaturated Materials Properties (Saturation vs Rel. K): Abscissa min. increased from 0 to 0.001

that could result in seepage from the WRD (i.e. groundwater pressure at base of WRD > 0 kPa) would be a situation where initial waste rock layers were deposited in a saturated condition. Above water table mining makes this scenario unlikely.

Conclusions

The results of the study indicate that seepage fluxes from the waste rock dump and low-grade ore stockpile are unlikely to occur during the operational period. This is considered primarily due to the low rainfall, high evaporation environment and coarse nature of waste rock deposited.

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