FEFLOW-model for mine dewatering and mine water management close to groundwater systems of varying salinity, Pilbara, Western Australia

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Abstract:
Some mine operational activities, such as pit dewatering and water injection to different aquifers may change groundwater dynamics in surrounding areas. Quantifying such changes may be a challenge if the aquifer system is very complicated. Fortescue Metals Group (FMG) has two iron ore mining sites, Cloudbreak and Christmas Creek, in the Pilbara area, Western Australia. These mines are the located between a mountain range and a marsh landscape. The groundwater in the region is hyper-saline beneath the marsh, but fresh to brackish in the mining areas. Both hydrogeological analyses and previous regional scale numerical models have predicted that the interface between the fresh and saline groundwater would move toward the mining area under proposed mine-dewatering conditions. The three major hydraulic processes to consider in the model are density driven flow, mine dewatering and groundwater injection of saline and brackish water. DHI was contracted to develop a high spatial resolution model (HSRM) for the mining area in order to investigate and model the complex groundwater dynamics. This model enables FMG to predict the movement of the saline/brackish groundwater interface as well as the quantity and salinity of dewatered groundwater in each mining pit under different mining plans. Moreover, the model can be used to assess the impact of various water management plans involving dewatering and water re-injection on the environment around the mine site. The work contributed to estimating available fresh/brackish groundwater resources and to reducing environmental impact through providing useful information to assist the design of mining plans that are environmentally friendly. This will ensure that Pilbara's iron ore deposits, which contribute significantly to the economy of Western Australia, can be exploited without sacrificing the region's environmental values.

Key words: Groundwater, Mining, Dewatering, Groundwater Management, Salinity, FEFLOW

Introduction

Environmental impact caused by mining activities, such as pit dewatering and water injection to different aquifers, must be assessed and minimized in order to obtain government's approval for mining. Groundwater modelling provides key information for assessing environmental impacts of various water management plans that are designed to meet mine operation requirements.

The Pilbara region of Western Australia doesn't make you think about water – unless you get thirsty looking at this arid landscape. However, the water that's hidden beneath the red plains poses a great challenge for local mining companies. On one hand mine operations require pit dewatering (pumping) and subsequent disposal (usually water injection) of surplus water after mine water use. On the other hand groundwater level drawdown/mounding cannot be over some limits in order to protect groundwater dependent ecosystems. FMG's Chichester mines are located only 5 to 10 km away from the Fortescue Marsh, underneath which is a hyper saline groundwater body. The ingress of the hyper saline water into mine pits due to mine dewatering is another challenge for mine water management.

Both hydrogeological analyses and previous regional scale numerical models have predicted that the interface between the fresh and saline groundwater would move toward the mining area under proposed mine-dewatering conditions (e.g. FMG 2010). The three major hydraulic processes to consider in modelling the aquifer system are density driven flow, mine dewatering and injection of saline water and surplus brackish water. In order to understand the dynamics of the interface between the fresh, brackish and saline groundwater, and furthermore to optimize operations, DHI was

contracted to develop a high spatial resolution model (HSRM) for the mining area (see *Figure 1*). DHI has done this complex challenge with the worldwide distributed in-house product FEFLOW.

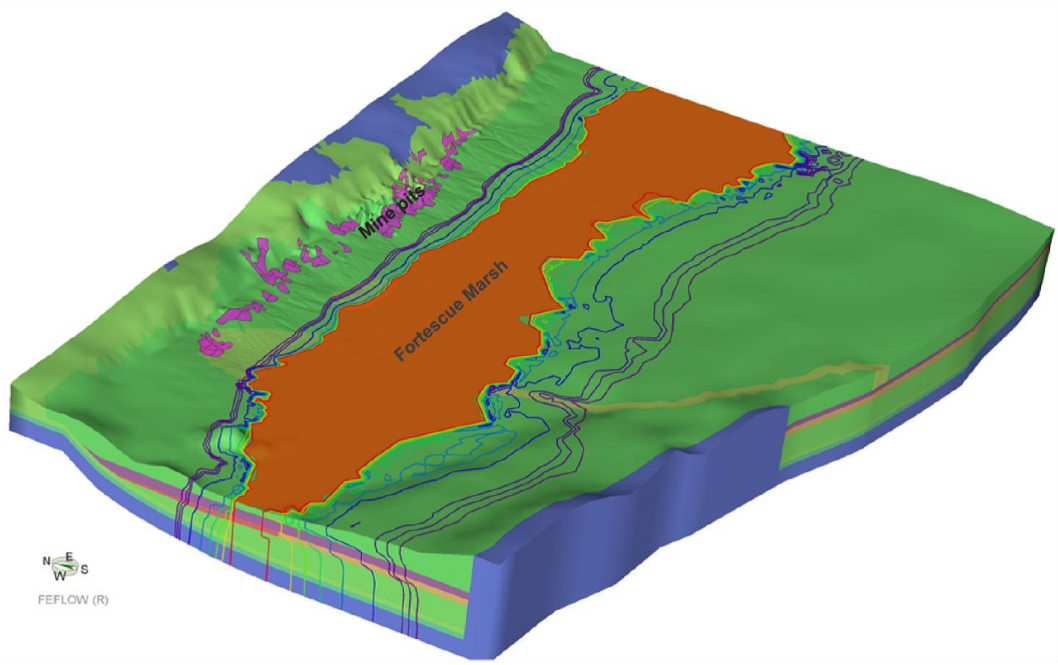

Figure 1: *3D - View of the model area with geology and modelled salinity concentration*

Model concept

The basic concept of the groundwater model includes essentially the following:

The model area is A = 2,745 km² and includes the existing and projected pits for mining activities, the southern located Fortescue Marsh and the northern located Chichester Range respectively.

The geologic setup of the domain of interest is transferred to geologic units with comparable hydrogeological properties, building up the most relevant hydrostratigraphical units of the hydrogeological model. The vertical model consists of the 9 basic hydrogeological layers shown in *Figure 2*.

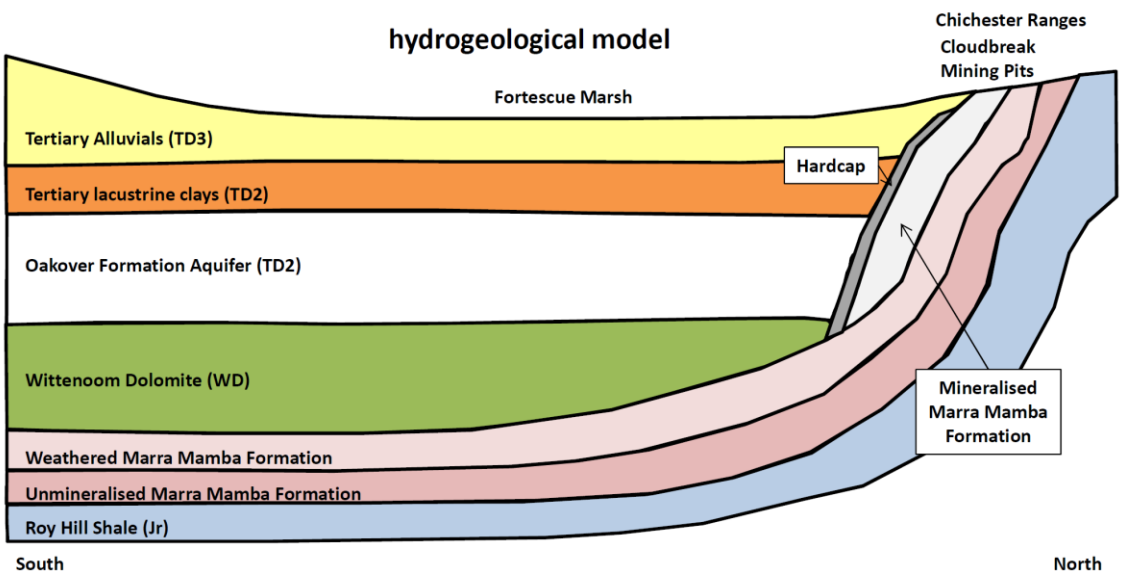

Figure 2: *Hydrogeological model consisting of 9 hydrogeological units*

Along the eastern and the western borders of the model, it is to be expected that the main gravity-driven groundwater flow is directed from the north and south towards the Fortescue Marsh. In contrast, the density-driven groundwater flow is mainly directed from the Fortescue Marsh, where extreme high salinities occur towards the south and the north, respectively. Hence, the eastern and the western borders of the model are defined as a no-flow boundary condition. The northern model boundary runs along the watershed in the Chichester mountain range and is defined as no-flow boundary condition. The southern model boundary is defined as fixed head and concentration boundary representing given groundwater and salinity conditions. The area covered by the Fortescue Marsh is defined over the total depth with constant mass concentration boundaries of c = 150,000 mg/l. Hydraulic parameters have been assigned to the model. They hydraulic conductivities range from 10^{-8} m/s to 10^{-4} m/s. Specific yields range from 0.2% to 5%.

A method for assigning groundwater recharge has been developed and considers the annual rainfall and the zonal differentiation of recharge coefficients due to strong variations in evaporation. The recharge coefficients range from 0.4% to 6 % of annual rainfall. The Fortescue Marsh has been assigned with negative recharge because of evaporation exceeds the rainfall.

A 3D groundwater model has been designed. The horizontal discretization of the model has been based on a supermesh including all relevant geometric and geological features (extent of marsh, mining pits) as well as the location of existing resp. projected pumping and injection wells. Each well is exactly represented by a single mesh node. The 2D finite – element mesh consists of 49,578 nodes and 98,924 elements. The lengths of the triangles vary between 500 m and 1000 m, and 15 m and 100 m in zones of mesh refinement near the mining pits, respectively. In order to build a 3D model of the aquifer system, the generated 2D finite – element mesh was extended in the z – direction corresponding to the hydrostratigraphic or hydrogeological units (see *Figure 2*). For numerical reasons of better simulating density driven flows, the primary 9 unit hydrogeological model was extended by additional numerical layers. As a result, the final 3D model contains 20 numerical layers. In total, the 3D model consists of over one million nodes and/or two millions finite elements.

Solute or mass transport and density-driven flow have been included in the numerical model. The linear dispersion law has been applied. The key parameters are assigned as follows: maximum concentration c_{max} 150,000 mg/l, density ratio λ = 0.116, longitudinal dispersivity D_L = 100 m and transversal dispersivity D_T = 10 m.

Additionally, in order to add problem specific functionality to FEFLOW, three plugins have been developed and used in the model. *SetMassBC2* sets a mass transport boundary condition for infiltration wells in case of infiltration and removes the boundary condition in case of no infiltration or pumping. The plugin can deal with either time-constant or time-varying concentrations or both within the same model. *VaryingBC* is designed to set and remove different types of boundary conditions and related constraint conditions for time periods at certain nodes. The plugin allows defining of boundary conditions and constraints based on time intervals. No additional constraints for the boundary conditions considered are needed. *MineDewatering* allows setting maximum hydraulic head for injection bores and (time-varying) minimum hydraulic heads for pumping wells. In contrast to using constraints, the boundary conditions are completely turned off when the limit is exceeded, the limits are not checked iteratively and the pumping or injection rates are continuously reduced over a threshold that can be freely defined.

Model calibration

The HSRS groundwater model was calibrated through both steady state and transient simulations for flow and mass transport.

The steady state calibration focused on achieving a reasonable flow and salinity distribution in the model domain under the so-called pre-mining conditions. The steady state model represents therefore the long-term groundwater flow state as it has been evolved of an initially fresh aquifer system by applying a constant concentration boundary condition. The actual historical evolution of the current salinity distribution is unknown; however, the process applied enables the derivation of a reasonable spatial distribution of salinity.

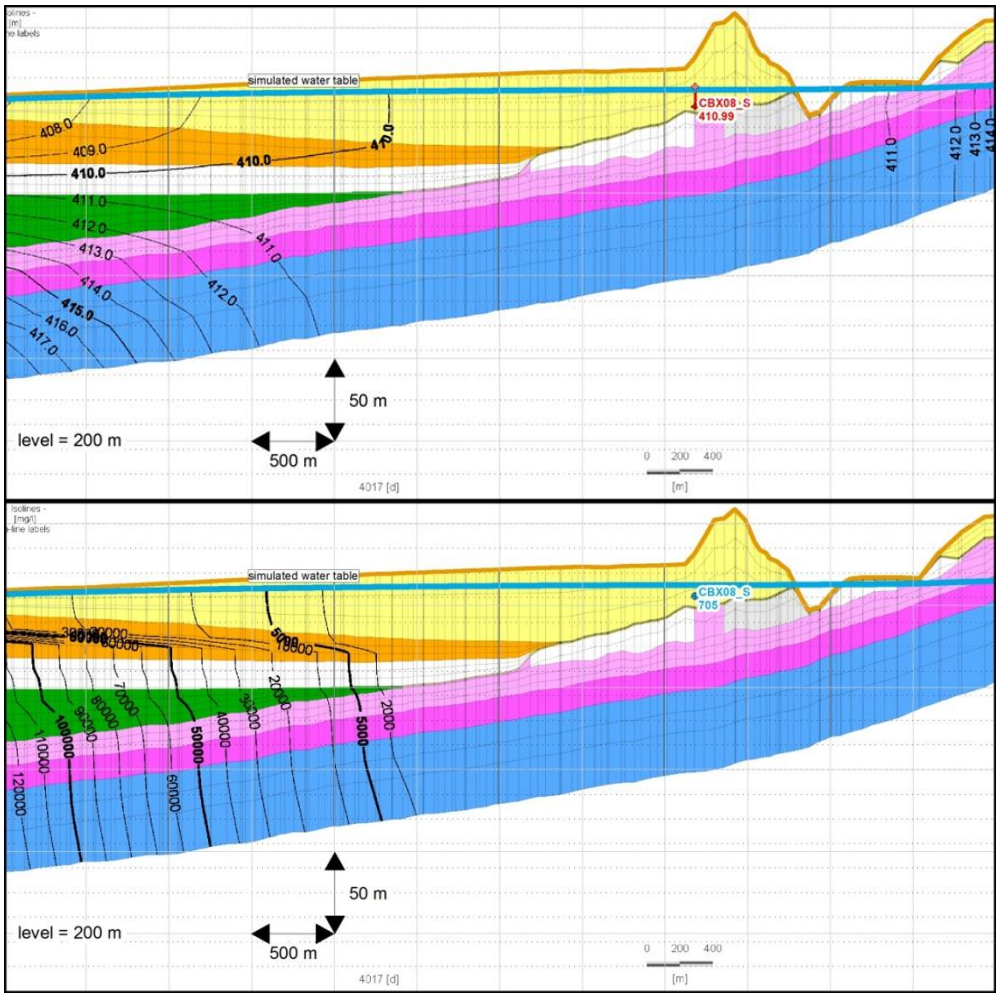

Figure 3: *pre mining distribution of groundwater heads (top) and salinity (bottom) along a section from the Fortescue marsh (left) to the Chichester range (right).*

The results illustrate a flow pattern consisting of two main groundwater flow regimes: The density driven flow beneath and in the vicinity of the Fortescue Marsh respectively and the topographic driven flow from the Chichester Ranges corresponding to the general topographic gradient and the geological setup. The highest salinities occur near the Fortescue Marsh and decrease towards the Chichester Range. The vertical distribution shows also, that the salinity transition zone is wider in the lower aquifers and much smaller in the upper aquifer. The low permeable tertiary lacustrine clays (TD2) act hereby as significant separating zone between the upper and the lower aquifer. The heavy and hyper saline water sinks down beneath the Fortescue Marsh, but the resulting density driven flow is limited by the low permeable Roy Hill layer. Consequently, heavy and saline groundwater is forced to flow laterally towards the Chichester Range, spreading the transition zone. Contrary, light and fresh groundwater flows according to the topographic gradient from the Chichester Range towards the Fortescue Marsh, forcing the salinity front back towards the Fortescue Marsh.

The transient calibration runs include the real dewatering and injection stressors during the period Jan. 2008 to Sept. 2011. This calibration period includes a period of significant anthropogenic influence by the Cloudbreak water management operation. A key component of the Cloudbreak water management is to return the excess part of extracted groundwater directly to the groundwater system. Brackish and saline waters are segregated and returned to compatible aquifers, so that brackish water resource is preserved for future use. Therefore DHI has been provided with well locations of brackish pumping wells, brackish and saline injection wells and sump pumps and time series of pumping rates and brackish and saline injection rates respectively. The data consist of 53,332 single salinity measurements and 116,227 single groundwater level measurements the period from 10.01.2007 to 16.10.2011.

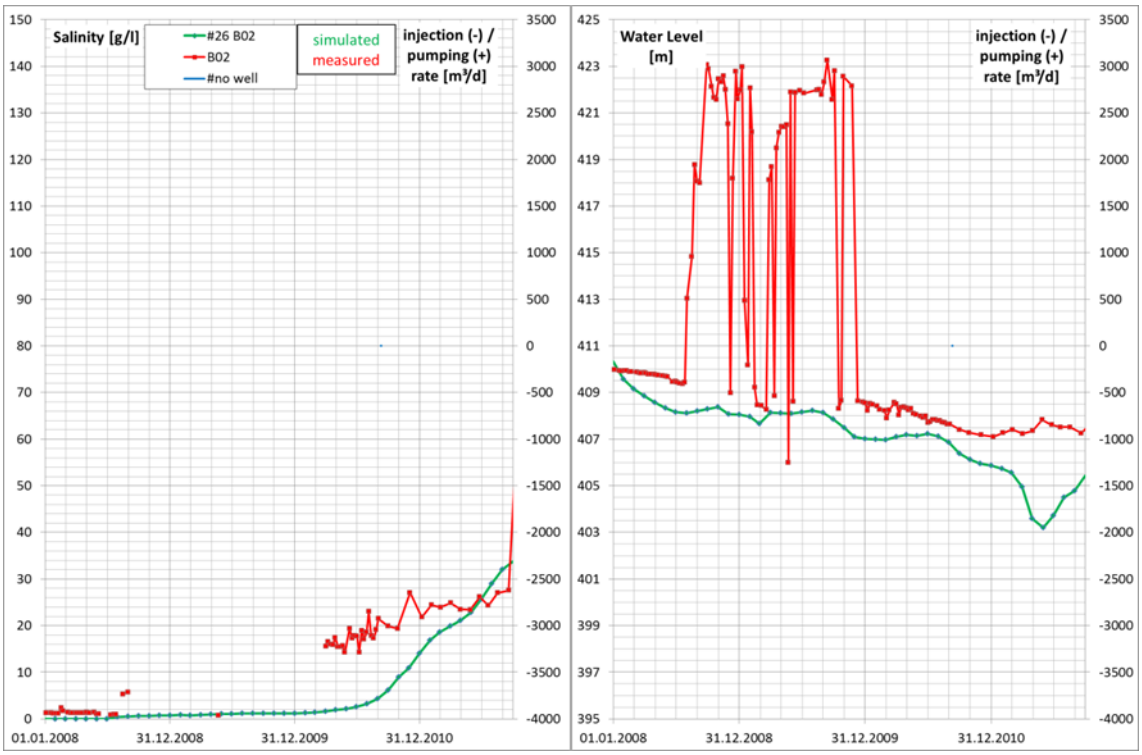

Figure 4: *transient calibration:*
measured and simulated salinities (left) and groundwater levels (right)

Generally, the achieved simulation results show a good agreement to the measured data. Accordingly the model does reproduce the dynamics of the measured salinity and water levels at most of the observation points and their spatial distributions as well. At the most observation points, especially at those located in the three active mining pits, a general groundwater depression of some meters can be observed. This is due to the strong groundwater abstraction. Because of the total amount of water abstraction exceeds the total injection volume, a general groundwater subsidence can be observed (see *Figure 4*, right). Accordingly, salinity increases slightly because of the saline front is moving towards the mine areas. Contrary, relatively constant water levels and salinities are observed at the observation points, which are located outside of the actual mining pits.

Mine dewatering scenario runs

The basis for the mine dewatering scenario prediction has been the Cloudbreak Life of Mine (LOM) Plan and the water management strategy (e.g. FMG 2011). Having used these as guidelines the following key elements have been represented in the model:

- Complete dewatering of pits whose bottom will be below water table in accordance with the mine sequence outlined in the LOM plan.
- Implementing dewatering by using seepage boundary condition at the base of ore body.
- Injection volume should roughly equal dewatering volume subtracted by mine water use
- Separating dewatering volume into 3 groups: (1) less than 6,000 mg/l; (2) between 6,000 and 9,000 mg/l and (3) larger than 9,000 mg/l based on predicted concentrations.
- Injection of remaining excess brackish water to brackish MMF aquifer through the brackish injection wells
- Injection of saline groundwater into saline Oakover aquifer through the saline injection wells
- Injection rates need to be adjusted to minimise GW drawdown. Principally, annual injection (assuming constant over the whole year) volume = dewatering volume - mine water use (10

GL/a) when dewatering volume is over 10 GL/a. Injection volume is zero when dewatering volume is less than 10 GL/a. The difference between (de-watering volume - injection volume) and mine water use should be reasonably small (assuming <2 GL/a) for each year. Since injection affects drawdown distribution (i.e. large dewatering requires large injection to reduce drawdown), hence iterative simulations were required.

- The initial conditions have to been taken from a distinct time step of the transient calibration.

The mine dewatering scenario simulation has three key stages, as follows:

- In the first stage the model is run with no anthropogenic activities, which provides data on water level for the average climatic sequence. This information is important for estimation of the impact of mine operation, which is quantified by groundwater level differences between these baseline scenarios and the scenarios under mining operations.
- In the second stage, an initial mining simulation is conducted with only abstraction and no injection. The annual abstraction volume is calculated for each year of the prediction period and then used to determine subsequent well injection rates and locations.
- In the third stage the calculated injection rates are then applied in a combined de-watering and injection scenario. This second dewatering simulation usually results in higher dewatering volumes due to re-circulation of the injected water back to the mine pits and requires several iterations to optimise required injection volumes and impacts. The distribution of groundwater drawdown and mounding from the final simulation is used to assess potential environmental impacts of mine dewatering and water injection.

The scenario simulations have been carried out by 49 simulation runs in order to achieve reliable results, which fulfil the specifications completely. Additionally, the simulation runs have served not only to optimize the dewatering - injection - balance, but also to recognize the influence of different mesh resolutions as well as alternative time stepping controls. The simulation results have been documented as charts of dewatering - injection – balances as well as water level and salinity differences of simulated conditions to certain reference conditions. *Figure 5* shows the dewatering – injection – balance for a scenario with dewatering and injection for each year under mining operation.

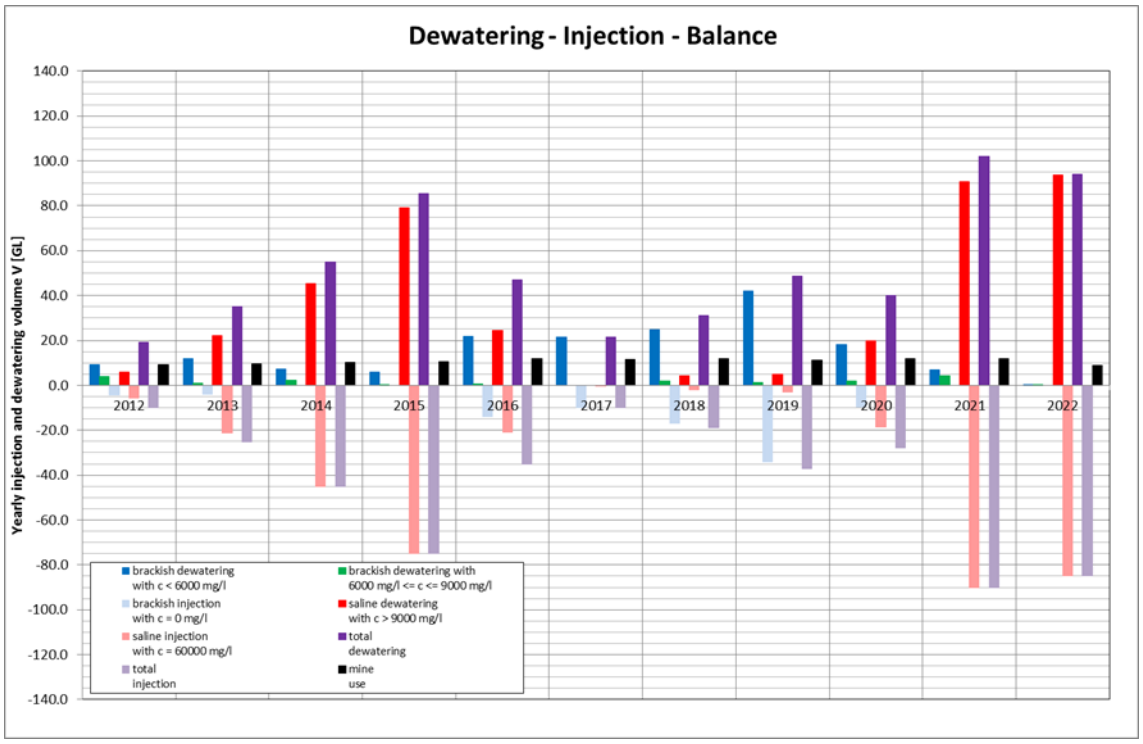

Figure 5: *Dewatering – injection – balance of scenario with dewatering and reinjection*

Depending on the count and location of the actually mined pits more or less dewatering is necessary. Maximum dewatering rates can reach up to 100 GL/a. Depending on the location of the pits, more or less brackish or saline water comes up. The black column shows the water available for mine use which is close to the necessary 10 GL/a. The exceeding water must be has to be injected whereby first all saline extracted water should be directly reinjected.

Conclusion and outlook

A realistic prediction of the groundwater salinity changes at a regional scale requires a model with high spatial resolution, which is usually limited due to the need to keep model running time at an acceptable level. So the main challenge was to ensure that a good model prediction accuracy could be achieved with fine enough spatial resolution whilst at the same time model run times are reasonable short. The model simulation time is a critical element for project delivery, which is often overlooked by modellers and project managers alike and can cause significant frustration to project managers later in the project delivery cycle.

In summary, the HSRS groundwater model is able to simulate reasonably well groundwater level and salinity dynamics in the aquifer system within practicably acceptable computer running time (several hours up to a couple of days). The chosen model approach and the model setup are suitable to simulate steady, long-term and short-term variations of groundwater levels and salinity. Strong anthropogenic influences and groundwater affecting measures can be represented and future states can be predicted reliably. The model is able to simulate the complex groundwater flow regime at the mining site. Model predictions were used to estimate available fresh/brackish groundwater resource and to assess potential environmental impacts caused by mining activities (dewatering and water injection).

Finally, a local scale model was constructed based on the above regional model and used to optimize the detail dewatering establishment for one pit. The numerical mesh of this model has been locally highly refined to represent horizontal wells (see *Figure 6*).

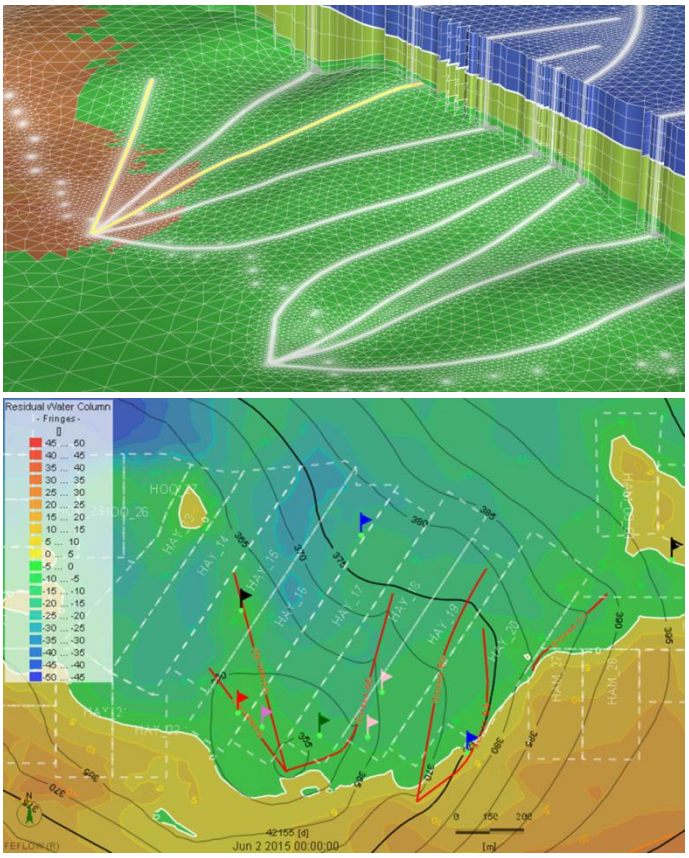

Figure 6: *3D-view of strongly refined mesh (top) and optimized horizontal wells and residual water depth over pit bottom (bottom).*

Acknowledgement

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