Assessment of Hydrogeological Hazards in Operational Mines using Objective-Focussed Modelling and Hazard Mapping Tools

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Abstract

The workflow and methods outlined in this paper provide a recommended approach to proactive groundwater-related hazard assessment. Key steps include the undertaking of an initial hazard mapping exercise, the development of a local hazard-focussed groundwater model, and a detailed hazard mapping exercise designed to identify and prioritise hazard types and locations. The outputs inform hazard control measures including effective management decision-making, future monitoring requirements, mine planning and hazard-specific Trigger Action Response Plans. This targeted workflow for hazard management improves outcomes compared with other, less proactive approaches.

Introduction

Sudden underground water inrushes are an example of potentially catastrophic events that can result from lack of hazard awareness and planning, and supporting information and data, during mine operations. The iterative cycle of Monitor -> Model -> Manage that forms the basis of mine site groundwater management is effective but does not deal well with unexpected and unpredicted events that can occur under a variety of circumstances through life of mine. Such events can result in loss of production and, in the worst cases, loss of life and/or loss of the mine (i.e., a catastrophic inflow).

An ongoing awareness of potential hydrogeological hazards combined with clearly defined and structured hazard assessment methodologies and tools enable mines to mitigate these risks.

Water Inrush Hazards

Inrush hazards in mining are associated with a variety of geological and hydrogeological contexts. To understand and mitigate such hazards, the mine design and mine development planning processes must consider the local and semi-regional hydrology and hydrogeology.

In underground potash mining, for example, the predominant threat is from permeable units in the hanging-wall (and to some extent the footwall also) combined with local 'problem zones', for example, geological structures, areas of atypical geology in the mining horizon, thickness of salt above or below the mineral horizon etc. Water hazards are also encountered at shafts (both during sinking and operations) in such settings. Prugger and Prugger (1991), in their overview of water problems in Saskatchewan potash mines, concluded that "*a continuous awareness of the water hazard and the careful consideration of the possibilities of water inflows must be foremost in the mind of all potash miners*". They cite loss of knowledge (when key staff at a mine move on or retire) as a primary issue and they promote an open exchange of information as a key mitigating process.

Water inrush can occur in many other mine settings beyond evaporite deposits. Causes of inrushes can be classified into those associated with the natural geological/ hydrogeological system (e.g., intercepting a water-bearing fault) and those associated with the mining process itself (e.g. the hydraulic opening of an area of old, interconnected workings). Typical scenarios involving unexpected inrush include: a new development encountering water; a raise bore pilot hole intercepting workings with no test work or hydraulic checks prior to breakthrough; mine workings intercepting unsealed boreholes that are open to surface.

Control of ground conditions, including inflow hazards, are typically evaluated and managed through a Ground Control Management Plan (GCMP). The GCMP includes safe design, implementation and verification of ground control measures designed to mitigate the risks associated with the particular mining operation. At some operations a specific Inflow and Inundation Management Plan or equivalent will be established (for example; Perenti, 2020).

Groundwater Hazard Workflow

Here we present workflow techniques and tools to assess risks associated with specific hydrogeological hazards within the context of clear, focussed objectives. This approach has been applied on several projects the authors have been involved with recently and involves the following steps (refer to Figure 1):

- The first step is typically to undertake an initial hazard mapping exercise, whereby we use spatial and statistical software to identify and prioritise hazard types and locations.
- Depending on the data already available this may be followed by focussed test work, installation of instrumentation and data collection.
- The next step comprises development of a local hazard-focussed groundwater model whereby targeted approaches and modelling techniques are applied to meet the objectives of a specific hazard risk assessment.
- Multiple datasets of contributing factors, along with outputs from the local hazard model, form inputs to a more detailed hazard mapping exercise designed to predict where hazard-related risk is greatest. Datasets are given weightings using an analytical hierarchy process and are spatially and statistically analysed using multi-criteria decision analysis.
- The outputs inform management decisions, future monitoring requirements, mine planning and hazard-specific TARPs (Trigger Action Response Plans).

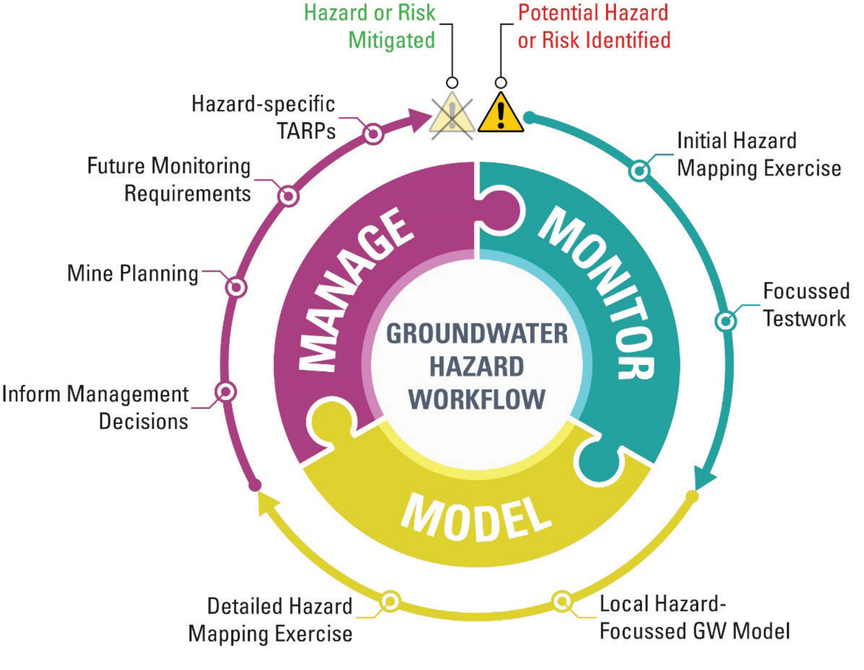

Figure 1 *Groundwater Hazard Workflow*

The workflow aligns with the Monitor > Model > Manage cycle but involves a single pass of these stages in order to understand and put in place targeted preventative/ mitigating measures.

Identification of Potential Hazard and Risk

The groundwater hazard workflow is triggered by the identification of the potential hazard. This trigger can occur at any of the stage of the routine site Monitor -> Model -> Manage iterative cycle. In an ideal world, the hazard would be identified during the routine site monitoring or modelling stages. However, in the worst case, and possibly most commonly, the inrush event is identified and addressed, through mitigation, during the management stage once the hazard trigger (such as a tunnel or shaft penetrating a permeable aquifer) has already been initiated. Once the potential hazard has been identified and assessed, then our workflow for hazard mitigation is as per the clockwise steps in the outer circle of **Figure 1**. This is similar to the routine Monitor -> Model -> Manage approach, but is completed on a shorter timescale and is non-iterative.

Initial Hazard Mapping Exercise (IHME)

The IHME involves a high-level assessment of the potential hazard and associated risks. The aim is to pre-empt the event and take steps to reduce that worst-case impact. A trigger event to initiating the IHME might comprise; unusual responses in a monitoring programme, an atypically high magnitude/ prolonged rainfall event or period, awareness of a potential change in geology/ ground conditions predicted during mine advancement, or observations of increased seepage at a mine face.

Alternatively, where sudden or catastrophic inflow is a constant risk to the mining operation the initial hazard mapping exercise may be a routine and regular exercise which is constantly being updated with new information from monitoring and other data sources. Here, more targeted spatial and statistic software may be employed to continually re-assess risks through methods such as composite hazard analysis.

Once groundwater hazard workflow is triggered the aim of the IHME is to focus on the potential hazard and collate all relevant information and data. A preliminary conceptual hydrogeological model (CHM) supports this process by focussing on two considerations; firstly, what are the key factors that both characterise the hazard and determine the possible range of events that could result; second, which of these factors and system characteristics are understood and which are not. Increased knowledge and level of certainly equates to reduced risk; the CHM helps identify which factors are constrained (through existing assessment; monitoring etc) and which are poorly constrained. It is the latter where focussed testwork is required.

Focussed Testwork

Many methods can be employed, through targeted testwork beyond the mine's routine monitoring infrastructure, to improve hydrogeological understanding and constrain risks associated with an identified inflow hazard. Geophysics plays a major role in underground potash environments (Funk et al, 2019). Water injection tests are considered a reliable method for determining seepage potential in specific host rock horizons and also for targeted features such as faults, particularly in coal mine settings (Cao et al, 2022). Often the focus is simply on collecting more observational data, such as seepage rates, and sampling /monitoring data such as water chemistry and responses in piezometers.

Local Hazard-Focussed Modelling

At this point in the workflow, there is often a requirement for a more refined CHM based on data from the preceding workflow steps, followed by numerical groundwater modelling of the hazard. If a regional model already exists for the site, it is tempting to assume its direct use for the hazard scenarios, however we have rarely found it to be the best option. Instead, the regional model, if available, should form one of the many inputs to the development of a local Hazard-focussed Groundwater Model (HGM).

Some of our key approaches and modelling techniques, specific to the objectives of a hazard risk assessment, are summarised below:

- *Model domain*. The key advantages of decreasing the HGM model domain are to allow for increased grid discretisation around the area of interest and shorter time steps for evaluation of short-term climatic variability and response to extreme events. These changes will typically decrease scenario run times and improve convergence. The regional model (if available) and analytical data are used to extract appropriate groundwater boundary conditions. Whilst it is relatively standard practice to significantly reduce the total planar area of the model domain by considering the zone of influence (e.g., drawdown), our methodology also includes potential vertical reduction of the model domain, as applicable. This requires a robust understanding of the CHM such that the specific hydrogeological unit(s) of relevance to the hazard are identified, and vertical recharge/discharge interactions be appropriately represented in the specified boundary conditions. An example of a local HGM Domain (horizontally and vertically) and associated boundary conditions is illustrated in **Figure 2**.
- *Discretisation*. Finer discretisation should be considered for the specific inrush hazard. The balance between model discretisation and model scenario run times and convergence is project-specific and occasionally more than one grid discretisation model setup is required to meet the objectives of various predictive scenarios. This potential flexibility should be included in the model design.
- *Parameterisation*. Due to the local scale of the HGM, the traditional 'representative elementary volume' (REV) approach to represent bulk hydraulic properties may not be directly applicable. Spatially variable three-dimensional anisotropy may be used to align with the dips and strikes of formation bedding and/or structures, and modelling of discrete features and fracture zones may also be required. Zones may also have high variability in hydraulic properties over very short distances. The use of discrete hydrostratigraphic zones may need to be replaced with interpolation surfaces and numerical functions.

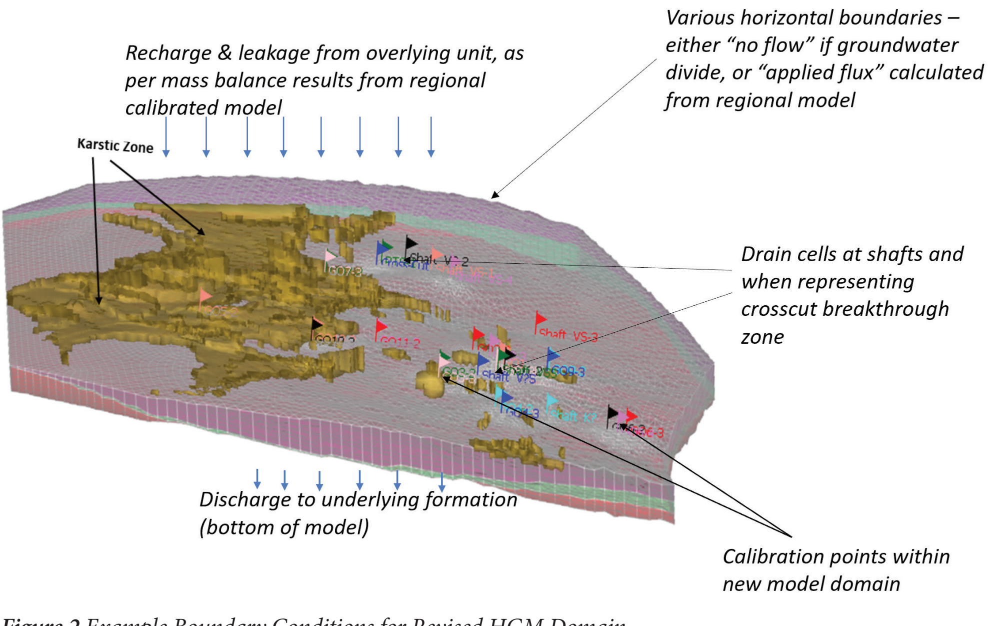

Figure 2 Example Boundary Conditions for Revised HGM Domain

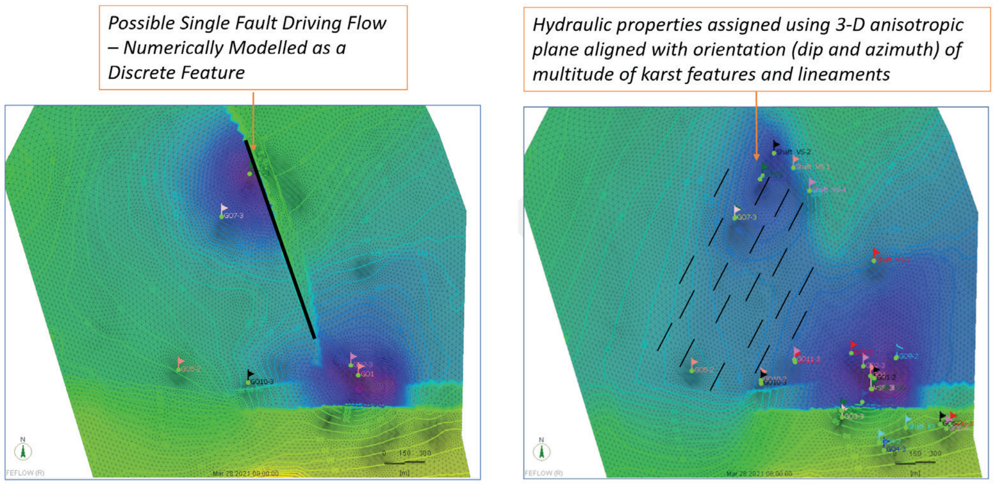

Figure 3 *Example Hydrostratigraphic Zoning Methodologies Tested during Hazard Modelling Scenarios*

Additionally, different methodologies may be required to represent the same area for different scenarios, and flexibility is required in the HGM so as to represent the various conceptual model hypotheses. **Figure 3** illustrates this concept by showing an example of two different zoning methodologies used for test scenarios of inrush responses.

- *Calibration*. Calibration requirements for HGM modelling require careful upfront consideration, including calibration priorities. Inflows and mass balance are often of primary importance. Local head pressures are relevant but may not be easily measurable at the site and thus thorough analysis of the local observation data is required. Calibrating to previous responses to events, such as a breakthrough event, will greatly enhance model confidence. Note that there will not necessarily be a direct correlation between the HGM and regional model parameterisation due to the REV assumptions, as discussed in the previous point, and thus the two models should not be forced to align in this regard.
- *Predictive scenarios*. Model scenarios need to be focussed on the model objectives. Model outputs will form a key input to the detailed hazard mapping and other groundwater management and monitoring advice, as discussed in the following sub-sections.
- *Uncertainty*. Sensitivity and uncertainty are a key aspect of the HGM scenarios. Consideration should be applied to the use of deterministic, stochastic, or a hybrid approach, for the model scenarios. Confidence in the underlying geological model is a critical consideration for any uncertainty analysis given the risks associated with poorly constrained or unknown geological structures.

Detailed Hazard Mapping

Datasets of contributing factors form inputs to a more detailed hazard mapping exercise designed to predict where hazard-related risk is spatially greatest. Spatial values for each contributing factor are informed by a combination of base data (e.g., extent and age of workings) or outputs from the numerical modelling exercise (e.g., permeability distribution). Datasets are given weightings using an analytical hierarchy process and are spatially and statistically analysed using multi-criteria decision analysis. This is typically undertaken on a GIS platform whereby combinations of factors can be analysed spatially (Donglin et al 2012; Wu et al, 2008).

This approach uses several criteria considered to be contributing factors. By way of example, take five contributory factors; i. the distance between a potentially hazardous aquifer (in this case, a dolomitic limestone in the hangingwall) and a mine development,

ii. the distribution of faults, iii. the hydraulic behaviour of each fault (i.e., whether the structure is behaving as a flow barrier or a flow conduit), iv. the permeability/degree of karstification within the aquifer and v. the proximity of the recharge zone to the aquifer. An Analytical Hierarchy Process can be applied and an overall relevance modifier value calculated for each factor. The composite probability of water inrush can then be calculated on a geospatial basis to produce, in a GIS environment, a spatial inundation probability map.

In potash mines and other evaporite environments there are specific criteria associated with, for example, the creep deformation characteristics of evaporite minerals, the strength of overburden strata, the natural 'anomalies' within the evaporite strata and the characteristics of groundwater in the overlying strata. Broad factors for consideration in any mine environment include:

- Natural geological conditions
- Mine design, layout and age of working
- Rock mass response due to mining
- Regulatory criteria
- Backfilling and other mitigation measures
- Monitoring systems, both surface and underground
- Management, expertise and 'expert' knowledge.

Managing the Hazard

The outputs from the monitoring and modelling exercises inform the hazard management process via one or more broad action routes:

- Inform Management Decisions Based on the preceding analysis management can make targeted decisions around future actions and assess the level of urgency required in applying these actions. The key benefit of this workflow approach to hazard analysis is that it is informed and focused. The aim is to reduce uncertainty where possible, but also to expose and highlight areas of lower certainty (and hence heightened risk) to allow targeted action accordingly.
- Mine Planning Changes to mine designs are often required to reduce inflow risks in the light of new hazards. Responses can include measures such as installing more pumping capacity, installing bulkheads, adjusting mine layouts and increasing barrier pillars.
- Future monitoring requirements Ongoing monitoring is intended to avoid an inundation or inrush event by identifying potential problems in advance. The hazard assessment workflow enables augmented monitoring to be established that targets the specific high-risk factors identified and informs the Hazard-Specific TARPs (Triggered Action Response Plans).
- Hazard-Specific TARPs should be reviewed and modified to ensure they reflect the specific outputs from the targeted hazard assessment. New TARPs should be drafted where a specific hazard type has previously not been identified.

The benefit of the workflow approach presented here is that the hazard management strategy is tailored to specifically manage the potential or identified hazard, rather than it being a more general and less targeted, strategy which is commonly the case.

Summary and Conclusions

The workflow and methods outlined in this paper provide a recommended approach to proactive groundwater-related hazard assessment. This approach uses objective-focussed models, tools and methods to inform appropriate action to reduce the likelihood of future potential catastrophic groundwater-related failures at mine sites. The approach is targeted to specific hazards and is structured and comprehensive. As such it has many advantages over more generic approaches, and is particularly effective in managing and mitigating hazards associated with unexpected and unpredicted events.

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