Management of Total System Uncertainty in Mine Water Projects

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Abstract
Uncertainty means a lack of knowledge. Regardless of the abundance of available information, data remains restricted in both space and time. In the real world, the total uncertainty of a system is controlled by several sources, like data and parameters, conceptual models, design uncertainty, uncertainty related to the selection of modelling tools, and human behaviour.

This paper intends to address all possible sources of uncertainty by using the theory of system analysis. The system analysis can be implemented by using the so-called Features-Events-Processes (FEP) method, which is a standard approach in the nuclear industry but less known in mining applications. The approach requires the listing of all potential known and unknown features, events, and processes. Based on this comprehensive, transparent, and clear list, the relevance of each element can be evaluated, gaps can be easily identified, and by connecting elements, base case and alternative evolution pathways of a system can be developed.

In this paper a case study is presented for the development of mine-closure scenarios. It is also shown that this approach may provide several costs, business, risk reduction, and QAQC benefits for mine operators.

Keywords: System analysis, uncertainty, scenario development

Introduction

Groundwater assessment and groundwater resources are critical elements in mining operations. Groundwater is a key feature of any mining operation throughout the entire life of the mine, from exploration to the post-closure period. However, assessment of the groundwater regime is always subject to uncertainties of various sources in space and in time, and groundwater systems cannot be described in a deterministic way (Oreskes, Shrader-Frechette, & Belitz 1994). The sources of uncertainty might be, but are not limited to, limited data in space and time, conceptual uncertainty, parameter uncertainty, design uncertainty, and anthropogenic uncertainty.

Recently, there are substatntial developments to manage uncertainty associated with parameter distributions. These approaches assume parameter uncertainties and their management can compensate other sources of uncertainty. However, it is well documented in the literature that the management of one source of uncertainty can not compensate for other sources of uncertainty (Bredehoeft 2005). For example, even in case the most sophisticated statistical approaches are used to manage parameter uncertainty, if the underlying concept is wrong, the results will be invalidated by the inappropriate conceptual model selected. These problems become even more profound as the scale of interest in a particular project gets further away from observation scale in space and in time. Making a useful and applicable prediction for tomorrow is more likely than making a prediction in the scale of tens or even more (hundreds or thousands) years. The same applies to spatial scales: making good prediction at 10m away from a bore (observation) is more likely than at 100m.

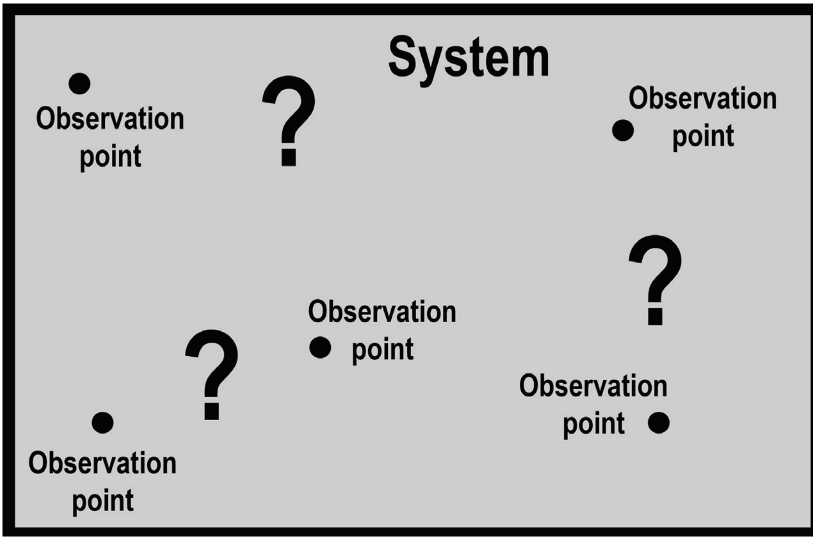

Figure 1 The difference between knowledge and theory. We know the groundwater system at discrete locations (for instance at borehole locations), but we theorise what may go on between observation points (question marks).

In general, it can be stated knowledge in hydrogeology is constrained by the spatial and temporal extent of observations and perceptions (Fig. 1). Any interpretation, interpolation, or extrapolation between the observation points in space and time cannot be fully justified and may form the basis of doubts. Assessment of the unknown is always uncertain and non-unique. As John Allen Paulos quoted, "Uncertainty is the only certainty there is" (Paulos 2003).

Beyond the parametrization of a groundwater system, which is inherently non-unique, it is even more critical to fully understand the system's key characteristics. However, conceptualisation is sometimes subjective, heavily reliant on previous experience and usually non-unique, just like system parameterization. Therefore, a method is required to manage uncertainty associated with the "lack of knowledge" in conceptualisation and with any other potential sources of uncertainty.

System analysis

The nuclear industry has developed the method of features-events-processes method (FEP catalogues) to manage this kind of uncertainty (NIREX 1998). The aim of the FEP analysis process is to provide a systematic framework for identifying all issues relevant to the evolution of a system.

A feature can be defined as an object (e.g., aquifer), structure (e.g., open pit), or condition (e.g., groundwater extraction) that has a potential effect on the system studied. An event can be defined as a natural or human-caused phenomenon that has the potential to affect the system and that occurs during an interval that is short compared to the period of the investigation (e.g., flooding, slope failure, blasting). A process can be defined as a natural or human-caused phenomenon that has the potential to affect the system and that operates during all or a part of the period of the investigation (e.g., groundwater flow, transport, seepage). The processes and events act upon features.

In general, events may define alternative scenarios, while features and processes are usually applicable across several scenarios. To identify scenarios and to develop conceptual models, a database containing the description, properties, and potential impacts of all identified FEPs and the interaction between FEPs is required. The so-called FEP catalogue lists all known, and even unknown or potential FEPs in a comprehensive database with identifiers, definitions, and short descriptions or justifications. An FEP function describes how that component contributes to the system evolution (e.g., rock may transfer fluid) (Andersson *et al.* 2009). A function indicator is a measurable or calculable property of a system component that indicates the extent to which a function is fulfilled (e.g., hydraulic conductivity of rock). A function indicator criterion is a quantitative limit such that if the function indicator to which it relates fulfils the criterion, the corresponding function is maintained (e.g., hydraulic conductivity < 1×10^{-9} m/s – sealing rock). An FEP catalogue is open; the list can be extended as more information and interpretation become available.

It is important to note that even unknown FEP elements must be included, since though these elements may not be observable recently, they may emerge as a critical element in the future. A good example of this problem is the management of climate change.

Key objectives of the FEP catalogue are comprehensiveness, traceability, and clarity (NIREX 1998). Comprehensiveness aims to consider all potential elements of a system studied. Traceability aims to provide a clear and auditable rationale supporting scenario and conceptual model development. Clarity aims to present information in a clear and accessible way such that the basis for decisions and assumptions can be readily understood.

Based on the FEP catalogue, several different system evolution pathways can be developed by using either a top-down approach or a bottom-up approach. A scenario is a description of a possible future evolution of the system; a scenario describes the system components along a potential evolution pathway. A base case scenario is a broad and reasonable representation of the natural evolution of the system and its surrounding environment; it includes all FEPs

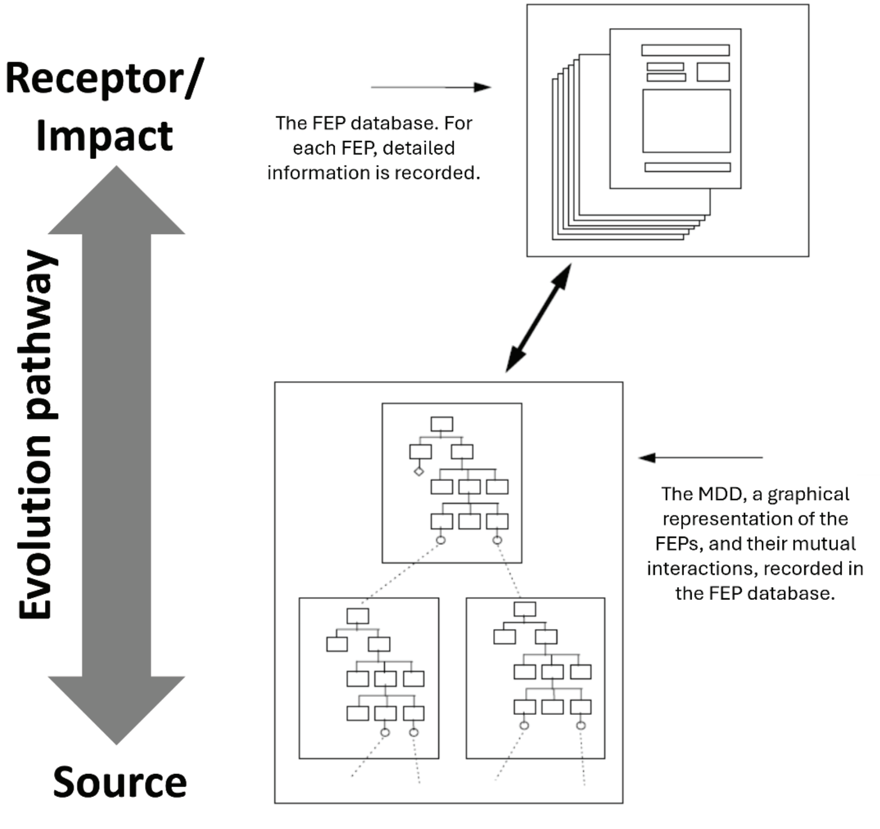

Figure 2 *Development of alternative system evolution pathways by connecting different elements of the FEP catalogue (figure modified after (NIREX 1998)). MDD stands for master directed diagram.*

that are more likely than not to be relevant to the system. Alternative scenarios are any probabilistic system evolution pathways, but the base case scenario. The individual scenarios are developed by connecting elements of the FEP catalogue in a logical way (Fig. 2).

If required, scenarios can be screened out from further analysis (modelling) by considering regulatory, low probability, low consequence or project specific criteria.

Case study

The system analysis approach presented above has been applied to a confidential site in Queensland, Australia. The client requested "the development of a qualitative hydrogeological site conceptual model detailing the potentially complete exposure pathways at the point of mine closure." This request was based on the requirements of the Progressive Rehabilitation and Closure Plan (Department of Environment and Science 2019). Regulatory guidelines usually require that all potential system evolution pathways and associated risks should be evaluated. The use of alternative scenarios (in contrast to relying on one single potential future state) has the advantage that a range of possible evolutions of the system (even including low-probability but high-consequence cases) can be explored. In addition, a good understanding of the relative importance of alternative scenarios will help clients to identify which scenarios may require further consideration (e.g., additional site investigation, modelling, etc.).

Alternative scenarios were developed for the post-closure phase, which assumed that a new hydrogeological "equilibrium" develops ("post-closure steady state") at the site. Note that this phase is different from the post-mining transient phase, which is a transient process between the operational phase and the post-closure steady-state phase. The FEP catalogue developed for the site contains six FEP categories and several elements:

- System categories:
  - General – elements that affect the entire system (e.g., time scale, spatial domain, regulatory framework).
  - Mine infrastructure elements – elements and activities in the mine (e.g., exploration holes, box cut, stockpile).
  - Geological elements (Table 1) – solid underground system (e.g., formations, faults, rock heterogeneity).
  - Hydrogeological (flow and transport) elements – groundwater system (e.g., aquifers, recharge, evapotranspiration).
  - Hydrology elements – surface water system (e.g., surface water bodies, flooding, surface water-dependent ecosystems).
  - Human activity, water use (e.g., new mining activity, site contamination, underground fire).
- Feature, event, process ID.
- Element name.
- Defining if the element is a feature, event, or process.
- Short commentary to provide added context where necessary.
- A short description to note whether the element is part of the base case scenario or not.

The geological elements of the example FEP catalogue are listed in Table 1; the schematic hydrogeological conceptualisations are shown in Fig. 3.

Based on the system element catalogue, three potential alternative scenario models (Fig. 3) have been selected for qualitative description through a series of workshops where all stakeholders were involved:

- Aquifer compartmentalisation.
- Site flooding.
- New mining activity.

A qualitative comparison of the base case and alternative scenarios is summarised in Table 2.

Table 2 clearly shows that assuming different evolution pathways for the site may result in various groundwater flow directions and groundwater quality changes. Therefore, it is critical to fully understand these alternative options to increase confidence in our predictions. Also, it is important to note that these alternative scenarios can be converted into some numerical or analytical calculations to make quantitative predictions about the potential future states of the site.

Table 1 Part of the FEP catalogue listing the geology category.

	FEP IDs	FEP Name	Feature, Event, Process	Comments/Description	Part of the Base Case Scenario?
2.0 Geology	2.1	Quaternary Sediments	F	Alluvial sediments	Yes
	2.2	Tertiary Basalts	F	4 basalt flow	Yes
	2.3	Tertiary Sediments	F	Interlayering with basalt	Yes
	2.4	Fort Cooper Coal Measures	F	Underlying the basalt with unconformity	Yes
	2.5	Moranbah Coal Measures	F	Underlying the Fort Cooper Coal Measures	Yes
	2.6	Coal Seams	F	Part of the Moranbah Coal Measures, three of the nine coal seams are economically viable	Yes
	2.7	Faults	F	Existing thrust faults up to the surface near and away the box cut. Normal faults striking east-west with vertical displacement of 5-10m, thrust faults striking north-south with 3m upthrust to east.	Yes
	2.8	Background Fracturing (Secondary Porosity)	F	Fractures are present in all geological layers.	No
	2.9	Basalt Flow Channels	F	Basalt flow over the Permian sediments.	No
	2.10	Intrusions	F	Some interpretations refer to the presence of intrusions along faults.	No
	2.11	Rock Heterogeneity	F	Basalt-sediment interlayering, sand-silt mud, clay successions.	No
	2.12	Unconformity of Geological Layers	F	Present in all geological formations.	Yes
	2.13	Primary Porosity	F	Property of each rock.	Yes
	2.14	Earthquakes	E	The possibility is considered, not the probability.	No
	2.15	Erosion, Deposition	F	Ongoing process, but no information is available.	No
	2.16	Volcanic Activity	E	The possibility is considered, not the probability.	No
	2.17	Subsidence	P	The subsurface voids may collapse, and backfilled material may get compacted.	No
	2.18	Chemical Alteration of Rocks	P	It can be assumed that waters of different origin may get in contact with various rock types. Also, backfill material may alter locally the groundwater quality. These processes may result in chemical alteration of the rocks.	No

Conclusions

Uncertainty is an inherent part of any hydrogeological project that needs to be considered at all stages of a mining operation. The proposed FEP-based system analysis is widely used in nuclear, water resource, carbon capture and storage, and geothermal projects but less known in mine water studies. In this paper it is demonstrated that developing alternative evolution pathways for a mine site may result in fundamentally different flow patterns and hydrogeological conditions. It is believed that the presented workflow can manage this kind of uncertainty, and the results may help clients in project development in the following ways:

- Consider a wide range of system components and relationships.
- Scenarios can be ranked based on their likelihood in the future in a quantitative way.
- The results may form the basis of future quantitative risk assessments.
- The underlying data set (components (features, events, processes) and relationships) may assist in preparing for alternative groundwater management scenarios.

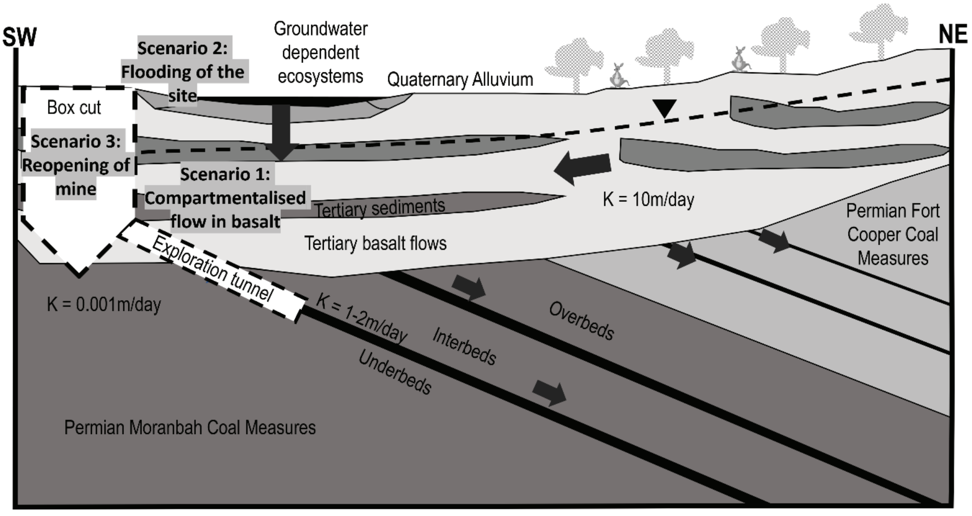

Figure 3 *Visual representation of the base case scenario and alternative scenarios.*

Table 2 Qualitative comparison of the base case and alternative scenarios.

Scenario	Summary of the scenario
Base Case	The box cut material is recharged from the unsaturated zone and the basalt aquifer. The two sources of recharge to the box cut may mix establishing a new blended water quality. At the horizon of the basalt – Permian aquifer interface it is assumed that low salinity basalt water mixes with more saline Permian water. Also, it is likely that water of Permian origin may not up well into the basalt layers due to its higher salt concentration and density. It is likely that this basalt water intrusion may locally dilute the more saline Permian groundwater.
Aquifer compartmentalisation	The limited extent of the aquifer may result in complete localised dewatering of the basalt aquifer during the operational phase. The vertical hydraulic gradients may be reversed leading to upwelling of more saline Permian waters into the lower section of the backfill material and basalt, resulting in water quality deterioration in the basalt aquifer
Site flooding	The local flood water infiltrates down the box cut backfill material, resulting in localised groundwater mounding around the backfilled box cut and intensified water flow back into the basalt and Permian aquifers. Any potential surface contamination may migrate into the underlying aquifers which may result in water quality decline.
New mining activity	The groundwater level declines rapidly as the new mine progresses and a cone of depression around the new mine develops. The mixed basalt-Permian water at the transitional zone of these two aquifers may intrude deeply in the basaltic aquifer resulting in poorer groundwater qualities.

- This may reduce risk and cost caused by using inappropriate water management scenarios.
- The presented system is open; as new considerations emerge, they can be added to the catalogue, and new scenarios can be investigated.

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