Integrated groundwater management model for underground coal gasification plants

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Abstract

Underground coal gasification UCG is an unconventional mining method that produces a cavity with residue products that have the potential to leach into the surrounding aquifers. Like all mining activities, UCG has to be monitored and regulated to safeguard water resources from the harmful effects of mining. There is currently lack of cohesion in terms of a regulatory framework for UCG sites and this is partially due to lack of groundwater contamination studies in these sites. This study takes into account learnings from an active UCG site in South Africa and develops a framework for an integrated groundwater management model for UCG sites.

The UCG process takes place within the targeted coal seam with the coal seam aquifer being consumed as part of high temperature reactions. The process results in inorganic and organic residue products that have the potential to cause groundwater pollution. The risk to groundwater was assessed by subjecting these sources to the following tests; mineralogical and hydrochemical analysis, petrography and leaching tests. The assessment of the risk was incorporated into an integrated groundwater management model that can be applied to UCG sites across the world.

The pathways that pollution from the UCG geo-reactor can be transmitted through were identified as natural faults, heat induced fractures and other production wells. All these pathways were assessed for hydraulic connections with the spent gasification chamber via stable isotopes studies and hydrochemistry. The receptor aquifer was periodically monitored for water quality and levels were found to be generally similar to background resulting in the conclusion that no contamination had occurred during the period of monitoring.

This research has laid a foundation in understanding groundwater contamination from UCG operations. The study however had limitations that can be explored by further research, especially for new UCG operations where background geochemistry can be comprehensively investigated before the gasification stage. This research is aimed at assisting UCG operators and regulators in decision making especially concerning groundwater issues.

Introduction

Underground coal gasification (UCG) is an unconventional mining method that converts in situ coal into fuel gas using high temperature conversion reactions. This process uses a panel of injection and production wells drilled into the coal seam to achieve gasification and transportation of the gas to the surface, Fig. 1. Oxidants in the form of a mixture of oxygen and steam are transported into the gasification zone via injection wells and take part in UCG reactions. The gasification process converts solid coal into a combustible gas composed mainly of methane, hydrogen and carbon monoxide, collectively referred to as synthetic gas. The gas escapes through production wells to the surface where a number of gas scrubbing plants are installed to achieve the desired gas that can be used for electricity production. The mass transfer of solid coal to gaseous phases leaves a cavity in the coal seam that gets partially filled with residue products (ash and char) and eventually groundwater once the gasifier is shutdown.

Underground coal gasification can have less surface environmental impact than conventional coal mining as most of the waste handling and coal processing is eliminated (Imran et al. 2014). In traditional coal mining techniques, coal is mined and transported to the point of use where it is stockpiled before processing. All these processes have unfavourable environment effects such as groundwater contamination, surface disturbance and atmospheric pollution. At the tail end of the coal value chain is the waste handling of ash which also adds to the environmental risk and cost. UCG technology has advantages that include improved health and safety of mining, reduction in coal processing and waste handling and less surface damage from mining activity. Carbon capture and sequestration technology can be incorporated into UCG by utilizing the cavity as a carbon dioxide storage chamber hence further reducing the environmental effects from UCG activities (Bhutto et al. 2013).

Effects of underground coal gasification on groundwater

The UCG process takes place within the targeted coal seam with the coal seam aquifer being consumed as part of geochemical reactions. The gasifier consumes water from the coal seam aquifer together with moisture within the overburden and underburden sections, which then produces a cone of depression in the coal seam aquifer. If there are faults/fractures that link the coal seam aquifer with overlying aquifers, then water will be drained from the shallower aquifers as the fractures provide a hydraulic connection. The heat from the gasification process can also induce secondary fractures in the surrounding strata. Groundwater monitoring in a UCG facility should cover all the identified aquifers around the gasification zone, before, during and post gasification. The monitoring programme should be both qualitative and quantitative. The quantitative groundwater monitoring of the shallow aquifer can indicate if a change in groundwater levels drops and this might be an indicator that water drainage to the coal seam aquifer is taking place. The deeper aquifer systems may also be confined, leading to piezometric surface that equilibrates within the overlying aquifer. The confined nature of deep aquifers suggests that pollutants can be transported to overlying aquifers if hydraulic connections exist. The groundwater monitoring programme should therefore cover all the overlying aquifers, the coal seam aquifer and the underlying aquifers beneath the gasification zone. A detailed review of groundwater monitoring at UCG

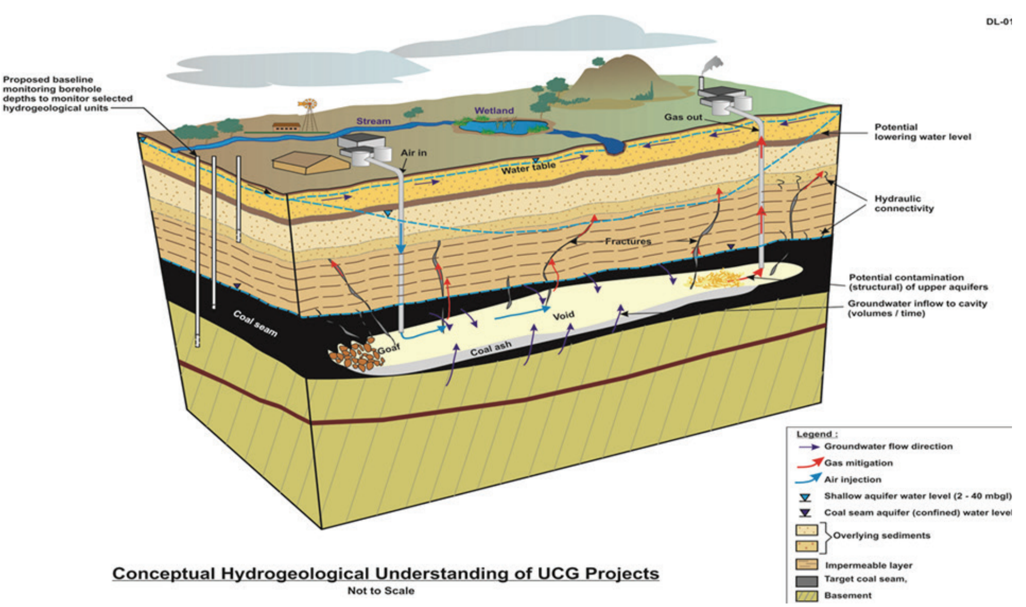

Figure 1 Conceptual hydrogeological model of a UCG plant adapted from (Pershad et al. *2018)*

sites is given by (Van Dyk et al. 2018) which also proposed the frequency of sampling depending on the period of UCG operations.

As previously stated UCG produces a cavity with residue products that have the potential to leach into the surrounding aquifer. The potential of acid rock drainage (ARD) from the spent UCG cavity stems from the fact that the overburden, ash, char and the coal seam floor inherently possess sulfide minerals due to the coalification process that occurs in a reducing environment. Sulfide minerals such as pyrite form under reducing conditions where S2- is the dominant redox form of sulfur and since these minerals are not stable when exposed to molecular oxygen, will undergo oxidation and dissolve when exposed to atmospheric oxygen or groundwater with dissolved oxygen (DO) (Deutsch 1997). The UCG process introduces oxidants in the form of air or oxygen gas during the gasification stage and post gasification surface water can be introduced in the cavity as a form of assisted quenching. Acid base accounting was used to assess the risk of acid generation at the Majuba UCG pilot plant with results indicating minimum risk of acid generation (Mokhahlane et al. 2018a).

Assisted quenching has been utilized in the Majuba UCG geo-reactor by injecting water from the surface into the gasification zone (Pershad et al. 2018). This method of quenching is depended on the hydrogeological conditions as high permeable strata may not need assisted quenching. For example, if the coal seam aquifer has high hydraulic conductivity there will be substantial groundwater flow into the UCG cavity after gasifier shutdown and this will assist with cooling of the cavity, however strata with low hydraulic conductivity requires injection of water to quench the gasifier. Post gasification the groundwater gradient will eventually rebound and water will begin to flow through the cavity (Liu et al. 2007). The hydraulic head will re-establish within the coal seam aquifer as the UCG process conditions (pressure and temperature) shutdown with the result that the pre-gasification groundwater regime slowly develops. The geochemical interactions in the cavity have the potential for ARD especially if the sulfide quantities are adequate for acid generation.

Heat penetration can alter the overlying rocks and create fractures that result in the coal seam aquifer becoming hydraulically connected to the shallow aquifer, which then leads to the draining of the shallow aquifer into the gasification zone (Fig. 1). The confined nature of the coal (deep) seam aquifer allows its water levels (head) to stabilize at shallower levels above the coal seam depth (Dvornikova, 2018). The hydraulic connections can ultimately transmit water contaminated with inorganic and organic UCG products from the gasification zone to the shallow levels where subsequent contamination of pristine aquifers can occur. UCG operators have to ensure the site is well characterized and that the coal seam has limited connectivity with other water sources (Imran et al. 2014).

Subsidence of the overburden above the UCG burn void can also result in serious groundwater contamination via fractures that result in aquifers cross connections. This can result in the transmission of pollutants generated from the burn zone to overlying aquifers (Liu et al. 2007). Overburden failure can create joints and fractures (Ghasemi et al. 2012), similar to the ones seen in Fig. 1, and this can be pathways for contaminants to migrate from the UCG cavity to the shallower aquifers. The environmental risks to groundwater pollution from UCG activities are mostly site specific. Appropriate site selection can mitigate most of the potential risks to groundwater contamination as factors such as depth of cover and competency of overlying rock play an important role in roof collapse (Ghasemi et al. 2012, Imran et al. 2014). If there is no hydraulic connection between the shallow aquifers and the coal seam aquifer, from which gasification is undertaken, there remains little risk of groundwater contamination. Usually the coal seam aquifer is of poor quality and not used for any domestic or agricultural use. However if faults and fractures exists within the natural strata, a hydraulic connection can be created between the coal seam aquifer and the shallow aquifer as seen in Fig. 1.

Stratification is the vertical distribution of salinity, pH and temperature of groundwater into a stepwise or layered dissemination (Ryuh et al. 2017). Stratification within an underground cavity associated with coal mining is common in the Karoo coal-bearing formations (Johnstone et al. 2013). UCG creates an underground cavity as a result of coal being gasified in situ and upon completion of the gasification process, groundwater levels are expected to rebound in the gasification zone and groundwater flow to resume. The geochemical evolution of the UCG cavity will be a result of interactions between groundwater and the various residue products contained in the cavity including ash, unburned coal, heat affected surrounding strata and hydrocarbons. Assessment of stratification in the UCG cavity is an important aspect as it may point to chemical processes such as diffusion which may influence the evolution of contaminants. Johnstone et al. (2013) reported stratification in the cavity of coal mines in Ermelo Mpumalanga, which showed groundwater quality evolves from sulfate type water to sodium type water due to sulfate reducing bacteria. This stratification led to the scrapping of the planned water treatment plant for discharging groundwater from the mine void, this was due to the water quality on top of the cavity being better than water at the bottom of the cavity. Stratification was also reported in the boreholes at the Majuba UCG site in South Africa in the boreholes intercepting the gasification zone (Mokhahlane et al. 2018b). There was stratification in all the boreholes (monitoring and verification) assessed in terms of EC and temperature. The stratification in EC shows that the quality of water that is sitting on top of the well is better than that in the bottom. This trend suggest that in the event of fractures forming due to roof collapse or any other event that could possibly create a flow path between the cavity water and the shallower strata, the water quality will not be uniform throughout the hydraulic connection. Better water quality will preferentially be at the shallow levels with low quality water concentrated at the bottom (Mokhahlane et al. 2018b).

Integrated groundwater risk assessment model for UCG sites

Groundwater contamination can be assessed using the source-pathway-receptor model in which polluted groundwater travels through a flow path in order to affect a receptor or user of the resource. The knowledge attained through this work has provided for a simple but comprehensive groundwater risk assessment for a spent UCG chamber via an integrated model.

The model follows the source-pathway-receptor arrangement where groundwater contamination sources are identified as ash, char, roof and floor. The risk to groundwater pollution is then assessed by subjecting these sources to the following tests; mineralogical and elemental analysis, petrography and chemical assessment, leaching tests and acid-base accounting (Mokhahlane et al. 2018a). Post gasification groundwater enters the spent geo-reactor and is able to transport contaminants to secondary locations. The pathways that pollution from the UCG geo-reactor can be transmitted through were identified as; natural faults, heat induced fractures, boreholes, local aquifers. All these pathways will have to be assessed for hydraulic connections with the spent geo-reactor via stable isotopes, hydrochemistry and stratification analysis and all the results have been presented in previous studies by the author (Mokhahlane et al. 2018b, Mokhahlane et al. 2018c). Finally, the receptor aquifers (e.g. shallow aquifer) will have to be monitored periodically to determine if contamination has occurred. This is summarized by a simple flow diagram showing the integrated groundwater risk assessment model, that can be followed for any UCG site (Fig. 2).

The flow diagram can be expanded to bring the analyses to a risk test, Fig. 3. After identifying sources of groundwater contamination at UCG sites and performing the analytical tests, the model can then subject the process to a risk assessment. If for example, the analytical leaching results show unacceptably high levels of toxic cation release, then those sources will be profiled to pose a "groundwater risk". However, if negligible mobilization is recorded, then the risk test will report "no groundwater risk" and hence no further investigation is needed. Where sources of groundwater contamination have been verified, then existence of pathways to receptors will have to be established. If no pathway exit, then the risk test will

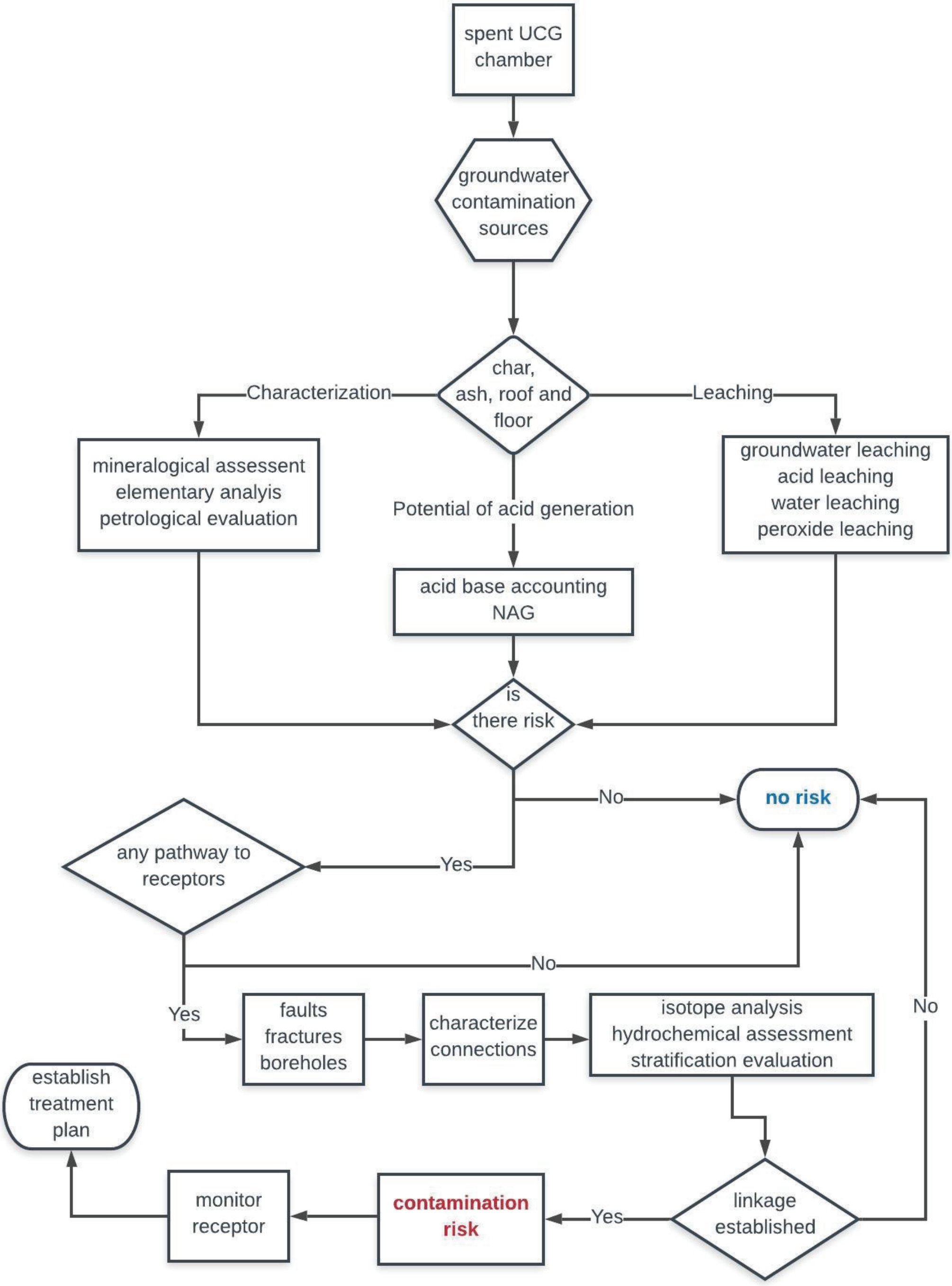

Figure 2 *Expanded integrated groundwater risk assessment model for UCG sites*

report "no groundwater risk" and hence no further investigation is necessary. However, is pathways do exist then those channels will have to be examined using appropriate methods including but not limited to stable isotopes, hydrochemistry and stratification analysis in order to establish the groundwater risk. If the connection do not pose any risk, then no further investigation is necessary.

However, if the connection prove that elements are indeed transmittable between the source and the receptor then the model will report that contamination is a real possibility and periodic monitoring of the receptor should be implemented, considering the risk profile of the source. A treatment plan for the spent UCG geo-reactor should then be established and implemented to avoid contamination of the receptor. This study has laid a foundation in understanding groundwater contamination from UCG operations and provided a practical mechanism for assessing groundwater contamination risk for active UCG operations. It is also envisioned that this research can go some way in helping UCG operators and regulators in conducting their work effectively and to provide confidence in decision making especially regarding groundwater matters.

Acknowledgement

This paper for WVTF | IMWA 2024 emanates from my PhD thesis at the University of the Free State.

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