Technical note

Guide to groundwater monitoring for the coal industry

MR Barnes* and PD Vermeulen
Institute for Groundwater Studies, University of the Free State, PO Box 339, Bloemfontein 9300, South Africa

Abstract

It is well established in literature that the environmental impacts associated with the coal industry are numerous. In respect of South Africa's groundwater resources the major impact of the coal industry is a reduction in groundwater quantity and quality. There is therefore a need to proactively prevent or minimise these potential impacts through long-term protection and improved water management practices. One such initiative is to implement monitoring programmes in various sectors of the coal industry for groundwater quality and quantity. Groundwater monitoring requires sophisticated interlinked stages which are often overlooked or not fully understood. Consequently a methodical approach must be undertaken in order to have an effective and economical groundwater monitoring system. This paper provides a comprehensive guide to the establishment of a groundwater monitoring programme for environmental practitioners in the coal industry. An inclusive 7-stage methodology is presented describing the different stages of establishing a groundwater monitoring programme, focusing on the 'why', 'how', and 'who' of groundwater monitoring.

Keywords: coal industry, monitoring programme, water management, environmental impact, acid mine drainage, conceptual model, risk assessment, geophysics, drilling methods, borehole construction.

Introduction

Coal was first discovered in South Africa in 1838 and 1859 in the provinces of Mpumalanga, KwaZulu-Natal, and the Eastern Cape (Roux, 1998). Since then coal has played a vital role in South Africa's economy, satisfying the majority of the country's primary energy requirements, as well as bringing foreign investment into the country. Coal, according to Roux (1998, p. 136) is a 'readily combustible sedimentary rock containing more than 50 per cent by weight and 70 per cent by volume of carbonaceous material, and is formed by the accumulation, compaction, and induration of variously altered plant remains'. Coal is found in South Africa in 19 coalfields throughout the country. The majority of the coal reserves are located in the provinces of KwaZulu-Natal, Mpumalanga, Limpopo, and the Free State, with lesser reserves in Gauteng, North West and the Eastern Cape (Jeffery, 2005).

Both underground and opencast mining takes place in South Africa**.** About 37% of South Africa's coal production comes from underground mines and about 63% from surface mines (GCIS, 2007). Though South Africa has the benefit of widespread reserves, it is highly dependent on its coal reserves. Coal is South Africa's primary source of electricity production, contributing over 75% of the country's power supply (Fourie et al., 2006). The extensive utilisation of coal in South Africa, coupled with continual population growth, is resulting in a ever-growing demand and impact on South Africa's scarce freshwater resources. There is, therefore, a need to proactively prevent or minimise potential impacts on groundwater through long-term protection and improved water management practices. One proactive step to managing the coal industry's impact is that of developing a groundwater monitoring programme.

Impacts of the coal industry

The coal industry impacts on groundwater resources in two main ways, affecting both water quality and quantity. There are a number of chemical reactions that result in the degradation of the quality of groundwater. When water and oxygen come into contact with sulphide-bearing mineral species during coal mining, a reaction resulting in what is termed 'acid mine drainage' occurs (Hodgson and Krantz, 1998). In some sulphide-bearing rocks, sulphides constitute a major proportion of the chemical composition of the rock, for example, in metallic ore deposits, coal seams, oil shales, and mineral sands (Lottermoser, 2010). Pyrite is a typical mineral that is associated with acid mine drainage. The simplified 3-step reaction of pyrite oxidation and mine drainage is presented below:

- **Step 1**: Pyrite reacts with water and oxygen, forming dissolved ferrous iron, acidity and sulphate.

  $$4FeS_{2(s)} + 14O_{2(g)} + 4H_2O_{(l)} \text{-->} 4Fe^{2+}_{(aq)} + 8SO_4{}^{2-}_{(aq)} + 8H^+_{(aq)}$$

  The reaction initiates once pyrite has come into contact with oxygen and water.

- **Step 2**: Ferrous iron is oxidised to ferric iron.

  $$4Fe^{2+}_{(aq)} + O_{2(g)} + 4H^+_{(aq)} \text{-->} 4Fe^{3+}_{(aq)} + 2H_2O_{(l)}$$

  Constructed silt traps/ponds and aerobic wetlands promote this reaction.

- **Step 3:** Ferric iron is hydrolysed to insoluble iron hydroxide (yellow boy).

  $$4Fe^{3+}_{(aq)} + 12\ H_2O_{(l)} \text{-->} 4Fe(OH)^{3}_{(s)} + 12H^+_{(aq)}$$

  Yellow boy is an insoluble precipitate which coats stream beds and forms thick yellowy-orange sludges in water bodies.

---

* To whom all correspondence should be addressed.
☎ +27 11 794 7534; fax: +27 11 794 6946;
e-mail: Michael@cabangaconcepts.co.za

Received 20 February 2012; accepted in revised form 27 September 2012.

http://dx.doi.org/10.4314/wsa.v38i5.25
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 38 No. 5 October 2012
ISSN 1816-7950 (On-line) = Water SA Vol. 38 No. 5 October 2012

With each step, more and more hydroxides are released into the system, further adding to the acidity of the solution. Once at the third step, the hydrolysis of iron hydroxide from ferric iron can be self sustaining as long as ferric iron is present within the system. This means that, once the third step has initiated, oxygen is no longer a driving force for acid generation. The typical consequences of acid mine drainage are water with very low pH values (< 2) as well as highly-elevated amounts of dissolved metals and salts. The environmental impacts associated with acid mine drainage are degradation or death of plants and animals, reduction in drinking water quality, and corrosion of man-made structures. Iron precipitate furthermore results in the smothering of benthic organisms and clogging of fish gills, reduction in light penetration of the water column, and encrustation of man-made structures (Ritchie, 1994).

A second impact is the loss of groundwater quantity. This is caused by the removal of water that has entered mining operations. This removal results in a depression cone (decrease in hydraulic head) surrounding the mine workings, caused by dewatering of the surrounding aquifers. The depression cone alters the natural underground hydrological conditions by diverting the natural flow of groundwater, through the creation of paths of less resistance, which results in water entering the mining area. Once the mine workings intercept aquifer systems, water from these systems enters the open pit or underground workings, and a working mine, therefore, has to continuously pump excess water from its workings. The dewatering of aquifers can have a number of implications for surrounding water uses, such as lowering of the static water levels in boreholes, directly impacting on borehole yields, and drying out of rivers and wetlands.

Implementation of a groundwater monitoring programme

Before one commissions a monitoring programme clear management objectives must be established. Objectives act as the 'ruler' to measure the effectiveness of a monitoring programme and set out what exactly needs to be achieved. The management objectives must be set out with a practical and efficient mindset, as complex and drawn-out objectives can merely result in extra expenditure and confusion. By revolving the monitoring programme's objectives around 3 questions of 'why', 'how', 'who', as prescribed by Steele (1987), one can then set obtainable objectives that are meaningful and achievable.

A successful monitoring programme, as stated by Nielsen (2006), is one that consists of an adequate number of wells that are installed at targeted locations and depths. Monitoring programmes must also yield sufficient groundwater samples from the aquifer that represent the quality of up-gradient groundwater, which has not been affected by a facility, and that represent the quality of groundwater down-gradient of the facility.

Figure 1 shows the 7 stages necessary for achieving a holistic and representative monitoring programme. A methodological approach must be followed, as a monitoring programme in which boreholes are installed at random locations, are poorly constructed and maintained, and where improper sampling techniques are practiced, are far too common. This can result in the company facing potential costly impacts that they are not aware of due to inadequate monitoring. The recommended 7 stages for a groundwater monitoring programme are listed below:

- Stage 1: Conceptual model and site selection
- Stage 2: Risk assessment
- Stage 3: Drilling of targeted monitoring boreholes
- Stage 4: Borehole construction
- Stage 5: Sampling of monitoring boreholes
- Stage 6: Water quality analyses and interpretation
- Stage 7: Review and update of database

With each stage an appropriate approach to health and safety must be used to avoid any damage to person or property.

Stage 1: Conceptual model and site investigations

Developing a conceptual model is the first stage when establishing a groundwater monitoring programme. In order to develop a conceptual model various forms of site investigation need to be conducted. The triangulation method encompasses a wide range of sources in order to accurately conduct a site investigation. Figure 2 shows the triangulation method which makes use of maps, observations, and geophysics.

Maps or cartographical sources are the starting point when commencing with site investigations. These sources provide background data for the investigation and aim to minimise the use of extensive study areas, by highlighting focal points for the surveys and traverses to be conducted during the geophysical investigations. Cartographical sources include photographs, images, maps, and background literature.

Figure 1
Groundwater monitoring programme stages

http://dx.doi.org/10.4314/wsa.v38i5.25
Available on website http://www.wrc.org.za
ISSN 0378-4738 (Print) = Water SA Vol. 38 No. 5 October 2012
ISSN 1816-7950 (On-line) = Water SA Vol. 38 No. 5 October 2012

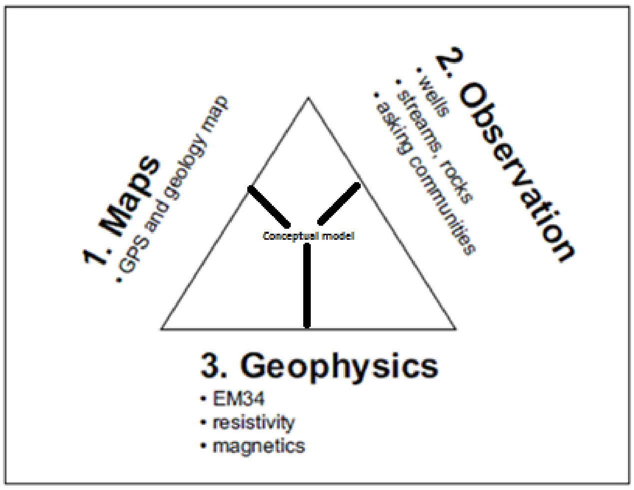

Figure 2
Triangulation method

Observations are conducted through reconnaissance of the site as well as the immediate areas surrounding the site. The benefits of taking a site walk-over include confirming the accuracy of existing information, identifying local geological anomalies, and providing more insight regarding the local geology. Talking to the local community is also a valuable source of additional information.

Geophysics, the last step in the triangulation method, is a tool used to assist with solving geotechnical and hydrogeological problems by obtaining information regarding the subsurface. With respect to groundwater, geophysics is used to identify anomalies such as faults, intrusions, and zones of weathering, by identifying contrasts within the subsurface. There are two categories of geophysical methods, namely, passive and active systems. Active systems measure the subsurface responses to electric, electromagnetic and seismic energy. Passive systems measure the subsurface's ambient magnetic, electric and gravitational characteristics (USEPA, 1999). Each geophysical method measures a different characteristic of the subsurface and thus the methods are often used in conjunction with each other. By utilising more than one method a number of physical parameters can be measured and a clearer indication of the subsurface condition can be realised, further increasing the likelihood of siting a successful monitoring borehole. The two more commonly utilised methods for groundwater investigations in the coal industry are magnetic and electromagnetic methods.

Based on the information obtained through the triangulation method a conceptual model of the site can be established. The conceptual model is the most important step in developing a monitoring programme. It serves as a mental model of the site.

Stage 2: Risk assessment

The risk assessment forms the basis for a monitoring programme and further refines the site's conceptual model. According to Hodgson and Krantz (1998), the main aim of a risk assessment is to provide the preliminary design of the monitoring facilities that can be prescribed according to the results of the risk assessment. The results of the risk assessment will also provide a guideline to identifying target areas and to determining the density and location of monitoring points. With respect to risk, the principle is based on three components: source, pathway and receptor. Numerous phases of the coal industry produce sources of pollution, whether physical mining or extraction, processing, transportation, or final utilisation of the coal.

Two main types of sources exist, described by DWAF (2006) in the Best Practice Guideline G3 as point and diffuse pollution sources. A point source is a single identifiable source of pollution, such as a pipeline, culvert, channel or a container from which pollutants may be discharged. Diffusive sources are much more difficult to identify and are associated with runoff, leachate, seepage, and atmospheric deposition. There are numerous sources of pollution in the coal industry, such as underground mining, opencast mining discard and ash dumps.

A pathway is the link between the source and the receptor and is described by Leeson et al. (2003, p. 200, 55) as 'the route along which a particle of water, substance or contaminant moves through the environment (for example, the route contaminants are transported between the source of landfill leachate and a water receptor)'. It must be remembered that the groundwater resource itself can be considered a receptor in its own right. Assessing potential pathways requires an assessment of the site's geological and hydrogeological aspects, previous investigation reports, and any available surface and groundwater monitoring data.

The receptor is the receiver of the pollution that has migrated along the pathway from the source. When one thinks of a receptor one often does not think of water; however, if water becomes polluted it has a direct impact on the surrounding flora and fauna. The most commonly referred receptor is that of human beings. Humans are identified through their presence. When identifying potential receptors, the aim is to identify down-gradient receptors such as towns, settlements, agricultural or recreational areas, farm boreholes, etc. Sensitive receptors such as wetlands and nature conservation areas must also be delineated.

Once the conceptual model has been developed and refined by the risk assessment, the conceptual model can provide vital information including the location of target sites relative to proposed monitoring boreholes, groundwater flow, aquifer systems, down-gradient receptors, potential pathways, etc. Once the conceptual model is fully visualised and all of the sources, receptors and pathways identified, the number and location of the monitoring boreholes to be drilled can be established.

Stage 3: Drilling of targeted monitoring boreholes

Before commencing with a drilling programme there are a number of factors that must be taken into account. These factors can be logistic, economic, or related to drilling considerations, and can all impact on the number and location of the proposed monitoring boreholes.

There are a number of drilling methods, and each may be more applicable to overcome a specific geological condition than others. However, the most commonly-used drilling method in the coal industry is rotary-percussion air drilling, which is the most economical method of drilling boreholes in hard rock and semi-consolidated formations (Woodford and Chevallier, 2002). A major advantage is that when different aquifers are intercepted during drilling water immediately flows to the surface, and as consecutive aquifers are intercepted the overall discharge rate (blow yield) increases. This allows the hydrogeologist to identify different aquifers and to monitor any changes in the quantity or quality of the different aquifers. Rotary-percussion air drilling further allows for easy recovery of the rock material resulting in accurate geological logging and sampling. Boreholes can be drilled quickly and several can be installed in a single day.

During the drilling of boreholes it is important to note a number of vital pieces of information. Data that needs to be recorded includes: penetration rate, water strikes, and logging of geological chip samples. The main aim of data collection is the identification of water-bearing zones (aquifers) during drilling.

Before borehole construction is addressed the physical nature of the borehole, i.e. diameter and depth, must be decided. The borehole diameter must take into account the lowering of sampling and testing equipment. The most common diameter for monitoring boreholes in the coal industry is 165 mm. This diameter provides sufficient space for smaller diameter pumps, casings, gravel packs, etc. DWAF (1998, p. 6-5) states that 'A monitoring hole must be as such that the section of the groundwater most likely to be polluted first, is suitably penetrated to ensure the most realistic monitoring result'. If the potential pollution source is located on surface (discard dump) the depth of the monitoring borehole, for example, must intersect the uppermost or target aquifer. In the case of a discard dump, the weathered aquifer system (5–15 m) will be the first aquifer to become polluted and hence must be the target for monitoring. A second example is that of opencast mining, where the target monitoring depth is that of the lowest coal seam mined. Preferably, piezometers can be installed in the monitoring boreholes where a number of aquifer systems can be simultaneously monitored for pollution.

Stage 4: Borehole construction

Once the borehole has been drilled the next stage is that of construction. Delleur (1999) states that 'the purpose of a groundwater monitoring well is to provide access to the target monitoring zone for collection of a representative sample of groundwater'. The 'target monitoring zone', as mentioned by Delleur, refers to the upper or target aquifer system that will be affected by a given activity; as this aquifer will be impacted it must be monitored. When sampling this target zone the representativeness of the sample can be altered by the manner of borehole construction. Therefore the primary consideration when selecting construction material is to select appropriate material that minimises any alteration in the chemical or physical characteristics of the groundwater sample.

Selection of the type of casing to be used is the first step. The main purpose of the casing is to prevent the borehole from collapsing. Solid casing is less expensive than perforated casing and can be used for the majority of the borehole. Perforated casings' screen diameters allow water to enter the borehole; a screen size of 2−4 mm is recommended. In the coal industry the water that is monitored may be highly acidic and it is recommended that a PVC (polyvinyl chloride) casing be used. PVC casings have a number of benefits over regular steel casings, being completely resistant to galvanic and electrochemical corrosion, lightweight for ease of installation, displaying high abrasion resistance, requiring low maintenance and being flexible and workable for ease of cutting and joining (USEPA, 1992).

The gravel pack, or filter pack, is installed after the casing has been fitted. The gravel pack must consist of an inert material to prevent the gravel pack altering the water quality entering the borehole. Quartzitic gravel is commonly used in monitoring boreholes. The gravel must be well rounded, with a diameter of 6−10 mm (DWAF, 2008). The diameter of the gravel is vital and should not be smaller then the screen diameter, else the gravel will enter the borehole or block the screens.

Piezometers can also be considered during the construction stage and are smaller diameter casings that are utilised for isolating specific aquifer systems whilst preventing cross contamination. Hodgson and Krantz (1998) describe piezometers as access tubes that are installed within a monitoring borehole at different horizons (sample points), such as at the weathered zone near the surface and at a deeper fracture intersected in the fractured rock aquifer. The diameter of the piezometers must be considered with the diameter of the sampling equipment in mind. Different piezometers are then separated from one another by an impermeable layer such as bentonite or concrete. These layers prevent interaction of water from different aquifers.

Once the casings and gravel pack have been installed the different forms of borehole protection must be considered. Borehole protection comprises two main components: (i) the protection of the actual borehole from physical harm, which is usually achieved by placing a cap and lock mechanism, and by placing a marker post on the borehole and surrounding it with a fence, and (ii) the protection necessary to prevent contaminated surface water from entering the borehole. To prevent surface water from seeping into the borehole a sanitary or surface seal is installed after the borehole has been constructed. Surface seals can be a simple concrete slab (100 cm x 100 cm x 30 cm) surrounding the surface of the borehole casing.

Lastly, after the borehole has been drilled and constructed the borehole must be developed. Borehole development aims at restoring the aquifers characteristics in terms of both yield and water quality. Delleur (1999,p. 9-25) states that the 'principal purpose of well development is to remove the fine materials adjacent to the well bore, to increase porosity and hydraulic conductivity of the aquifer and gravel pack, to remove any mud cake or compacted zone that results from the actual drilling, and to minimise or eliminate sand pumping'. Greases, glues and other chemicals used during borehole construction can also be flushed out of the borehole during well development.

Stage 5: Sampling of monitoring boreholes

Water levels must always be recorded as a first step in monitoring boreholes. This provides valuable information on the exploitation, overall management and recharge of the aquifer. Sampling of the borehole should only be done after the well has been sufficiently developed as possible contamination from drilling and borehole construction will result in water chemistry that is not a true reflection of aquifer conditions. Deterioration in groundwater quality and quantity can be monitored by field measurements and sampling. A number of steps are involved in a sampling programme: field inspection, borehole purging, sample collection, sample storage and sample handling.

The first step in sampling is that of the initial field inspection at each monitoring borehole. During the field inspection one has to check the site for any hazardous conditions surrounding the borehole. Secondly, when arriving at each monitoring borehole one has to inspect the physical condition and construction of the borehole in order to identify damage to or tampering with the borehole, missing locks or caps, and any other changes to the borehole or the surrounding area. Once the borehole and immediate area has been inspected various field measurements can be taken, including water level, pH, and total dissolved solids.

Sample collection must be done correctly as it forms the crux of the entire groundwater investigation. The correct method of sample collection from boreholes is subject to debate. Numerous authors (USEPA 1992, Weaver et al., 2007 and Wilde 2006) state that borehole purging is necessary as water in the borehole becomes stagnant and may not represent *in-situ* groundwater quality. This is based on the assumption that water in the borehole does not interact with water in the aquifer. Historically, large amounts of water would be removed from the borehole before sampling would take place, in order to overcome this problem. However, purging too much water at high rates may result in the mixing of water from zones of different quality, resulting in potential contamination of non-contaminated zones. However, Nielsen (2006), Puls and Powell (1992) and Puls et al. (1992) state that water moving through the formation also moves through the well screen. Thus, the water in the screen is representative of the formation. The water surrounding the screen can then be sampled using low-flow purging. However the abstraction rates in low-flow purging can even be too high for the majority of the boreholes drilled into fractured rock aquifers, where the common yield of a borehole can be as low as 0.001 ℓ/s. In these cases, no type of purging is possible and as a result the borehole must be sampled without purging.

Once the method of sampling has been decided the sample frequency must be chosen. Sample frequency can be influenced by a number of factors, such as the stage of mining, budget constraints, and even the type of pollution source. As a general rule all monitoring boreholes should be sampled on a monthly basis at least for the first year of monitoring (Lee Jones, 1983). After the first year of monitoring the frequency can then be reassessed. For long-term monitoring throughout the general life span of a mine, and after the first year, sampling can be conducted on a quarterly basis until an impact is noted.

Once the water has been sampled it must be placed in a container. This stage too can be difficult and can lead to the accidental contamination of a sample. There are two commonly-used sample containers: glass and plastic (Weaver et al., 2007). Glass containers are usually used for biological sampling whilst polyethylene or polyvinylchloride (PVC) plastic bottles are used for inorganic sampling. It is recommended that the sample containers be requested from a certified water analysis laboratory.

Depending on the purpose of analysis the water sample may have to be filtered. Filtration of the water sample can be regarding as a pre-treatment to the sample. The benefit of filtering the water sample is to determine if a constituent is truly dissolved in water (Nielsen, 2006). Filtration is conducted by passing the raw water sample through a filter medium, of selected pore size. Filtering makes it possible to determine actual concentrations of dissolved metals in groundwater. If a water sample is not filtered and preserved with acid, the acid will leach metals from the surfaces of colloids and suspended particles, resulting in an artificially-elevated dissolved metal concentration within the samples. It is recommended that two water samples be taken, one for the analyses of dissolved metals and the second for the other constituents.

It is very unlikely that a water sample is taken and analysed by a laboratory immediately; therefore, all samples must undergo some form of preservation to retain the water samples original properties. ‘Preservation methods are intended to: retard biological activity, retard chemical reaction and reduce volatility’ (Weaver et al., 2007, p. 112). Sample preservation can either be done chemically or physically. Physical preservation is done by storing samples in portable ice chest. It is recommended that the chest be filled with ice as it is inexpensive, usually close at hand, and will not freeze samples. Samples should be stored at temperatures around 4°C (Weaver et al., 2007; Hodgson and Krantz, 1998; DWAF 2006). When sampling numerous boreholes, which are likely to be both contaminated and non-contaminated, it is vital that all equipment that has come into contact with water from a borehole be decontaminated to prevent cross-contamination of the next sample.

Laboratory results can often contain errors, which can lead to misinterpretation. A common source of errors is poor quality control during the sampling run. Quality control and verification is a vital step during sampling and can be achieved by calibrating equipment on a regular basis, submitting blank or spiked samples, etc. It is always advisable to submit a blank (deionised water) or spiked (prepared sample using certified reagent grade chemicals of known concentrations) sample to the laboratory with one’s water quality samples to ensure that quality control is in place. Common methods of verifying data integrity are conducting consistency checks, checking ionic balances, and identification, confirmation and rejection of outliers (DWAF, 2006). The simplest version of data verification can simply be to regularly review entered data to highlight any absence, duplication, or transcription errors within the data set.

Stage 6: Water quality analyses and interpretation

There is a wide range of chemical constituents to analyse for. In order to have an efficient monitoring programme and to prevent unnecessary analysis and costs it is critical that one is aware of what parameters need to be monitored. For the first year of sampling it is recommended that a more comprehensive list of parameters be assessed. Hodgson and Krantz (1998) state that for new monitoring boreholes, a more comprehensive analysis must be conducted to ensure a wide range of background parameters. This usually includes a complete macro-analysis as well as an analysis for trace elements. These background parameters will always serve as the water quality ‘bar’ which water samples will be compared to throughout the life of the operation. After the first year discussions can be held with interested and affected parties and the local authorities to discuss the narrowing of the focus of analyses to water quality indicators such a pH, Eh, electrical conductivity, sulphates and iron. This will keep laboratory costs to a minimum whilst still providing adequate information to identify possible sources of contamination as a result of the operation.

Water chemistry and its evolution is one of the most complex natural systems to predict (DWAF, 1998); however, by utilising various diagrams water chemistry can be effectively interpreted and trends can be identified, aiding prediction. Piper and expanded Durov diagrams are simple chemical interpretation diagrams that assist in evaluating ‘families’ of different groundwater chemistry (USEPA, 2004). The Piper or Triliner diagrams are one of the simplest and most valuable methods that may be used to evaluate groundwater quality data. The expanded Durov diagram represents the different water types that can be expected to be found within the coal industry. Like the Piper diagrams the Expanded Durov Diagram can also be used to indicate trends in water quality. Other diagrams that can be utilised to interpret water quality include stiff diagrams, line and bar diagrams, box and whisker plots.

Stage 7: Review and updating

The last stage in the development of a groundwater monitoring programme is the reviewing of the monitoring programme itself. Once a groundwater monitoring programme has been established it must be reviewed and updated on a regular basis (annually, if site conditions remain constant. A suitable database, recognised by the coal industry, e.g. WISH or HBASE, should be used. Review is undertaken to ensure the monitoring programme is both cost-effective and representative of site conditions.

Review includes: sampling locations, sampling frequency, and water quality parameters analysed. Sampling locations must be reviewed and updated as per site-specific needs. The operation that the monitoring programme was developed for is not stationary, but changes on a daily basis. These changes can include the construction of new opencast pits, new discard dumps, or expansion of existing ash dumps. With the development of new activities, new sources will be created, followed by new pathways being identified, and potential receptors being affected. The groundwater monitoring programme needs to be a diverse and continually growing programme to ensure that it will always be one step ahead of newly constructed activities.

Conclusions

South Africa is a water-scarce country and sources of fresh drinking water need to be protected for the sake of all terrestrial and freshwater ecosystems. The coal industry impacts on this vital resource in terms of both quantity and quality. Fresh groundwater can become acidic with highly-elevated amounts of dissolved metals and salts, thus becoming toxic for both domestic and livestock consumption. Furthermore, mining excavations result in the diversion of natural flow systems of groundwater and the dewatering of aquifer systems. Once groundwater becomes contaminated it requires long-term and expensive mitigation measures. Therefore with respect to groundwater, it is better to implement the philosophy of ‘prevention is better then the cure’ (Institute of Petroleum, 2002). A groundwater monitoring programme serves as a measuring tool and informs the industry’s role players on how well their pollution control structures are working. The development and implementation of a groundwater monitoring programme becomes the first line of prevention and enables the Industry to readily identify and mitigate any potential sources of contamination.

Recommendations

The aim of this study was to support role-players in the management of the groundwater resources in and surrounding coal industry operations and to provide clear guidance on the processes to follow. This paper aims to support stakeholders in overseeing groundwater investigations rather than in conducting the investigations themselves. Groundwater movement, chemistry and contamination is a highly complex field of study and as a geohydrologist must always be called upon to assist in the development of the groundwater monitoring programme.

Acknowledgements

I wish to thank the personnel of the Institute for Groundwater Studies (South Africa) for their expert advice and guidance.

References

DELLEUR J (1999) *Handbook of Groundwater Engineering.* Springer Verlag, Berlin.

DWAF (DEPARTMENT OF WATER AFFAIRS AND FORESTRY, SOUTH AFRICA) (1998) Minimum Requirements for Water Monitoring at Waste Management Facilities (2nd edn.). Department of Water Affairs and Forestry, Pretoria.

DWAF (DEPARTMENT OF WATER AFFAIRS AND FORESTRY, SOUTH AFRICA) (2006) Best Practice Guideline G3. Water Monitoring Systems. Department of Water Affairs and Forestry, Pretoria.

FOURIE CJS, DU PLESSIS SJ and HENRY G (2006) New airborne geophysical data from the Waterberg Coalfield – South Africa’s major future energy source. CSIR, Auckland Park.

GCIS (GOVERNMENT COMMUNICATION AND INFORMATION SYSTEM, SOUTH AFRICA) (2007) *South Africa Yearbook 2006/2007.* URL: http://www.gcis.gov.za/docs/publications/yearbook.htm (Accessed 11 June 2010).

HODGSON FDI and KRANTZ RM (1998) Investigations into Groundwater Quality Deterioration In The Olifants River Catchment Above The Loskop Dam With Specialised Investigation In The Witbank Dam Sub-Catchment. WRC Report No. 291/1/98. Water Research Commission, Pretoria.

INSTITUTE OF PETROLEUM (2002) *Guidelines for Soil, Groundwater, and Surface Water Protection and Vapour Emission Control at Petrol Filling Stations.* The Institute of Petroleum, London.

JEFFERY LW (2005) Characterisation of the coal resources of South Africa. *J. S. Afr. Inst. Mining Met.* **105** (6) 95-102.

LEE JONES RF (1983) A composite-grab of water pollution control sampling. *Water Pollut. Control Fed.* **40** (3) 492-498.

LEESON J, EDWARDS A, SMITH JWN and POTTER HAB (2003) *Hydrogeological Risk Assessments for Landfills.* Environment Agency, Bristol.

LOTTERMOSER BG (2010) *Mine Wastes: Characterization, Treatment and Environmental Impacts.* Springer-Verlag, Berlin.

NIELSEN DM (2006) *Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring.* Taylor and Francis Group, Boca Raton.

PULS RW and POWELL RM (1992) Acquisition of representative ground-water quality samples for metals. *Ground-Water Monit. Rev.* **12** (3) 167–176.

PULS RW, CLARK DA, BLEDSOE B, POWELL RM and PAUL CJ (1992) Metals in groundwater: Sampling artifacts and reproducibility. *Hazardous Waste Hazardous Mater.* **9** (9) 149–162.

RITCHIE AIM (1994a) The waste-rock environment. In: Jambor JL and Blowes DW (eds.) *Environmental Geochemistry of Sulfide Mine-Wastes.* Mineralogical Association of Canada, Nepean. (Short course handbook **22** 133–161).

ROUX PL (1998) Aggregates. In: Wilson MGC and Anhaeusser CR (eds.) *The Mineral Resources of South Africa.* Council for Geoscience Handbook 16. Council for Geoscience, Pretoria. 40–45.

STEELE TD (1987) Water quality monitoring strategies. *Hydrol. Sci. J.* **32** (2) 3.

USEPA (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY) (1992) *RCRA Ground-Water Monitoring: Draft Technical Guidance.* United States Environmental Protection Agency, Washington.

USEPA (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY) (1999) Chapter 3: Surface Geophysical Methods. URL: www.epa.gov/oust/pubs/esa-chap3.pdf (Accessed 10 June 2010)

USEPA (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY) (2004) Recording, interpretation and analysis of monitoring results. ERA 75 – Waste disposal. United States Environmental Protection Agency, Queensland.

WEAVER JMC, CAVE L and TALMA AS (2007) Groundwater Sampling: A Comprehensive Guide for Sampling Methods. Groundwater Sciences, CSIR, Pretoria, South Africa.

WILDE FD (2006) National Field Manual for the Collection of Water-Quality Data. Chapter A4. United States Geological Survey, Reston.

WOODFORD AC and CHEVALLIER L (2002) Hydrogeology of the Main Karoo Basin: Current Knowledge and Future Research Needs. WRC Report No. TT 179/02. Water Research Commission, Pretoria.

---

http://dx.doi.org/10.4314/wsa.v38i5.25
Available on website http://www.wrc.org.za