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Expanding the hydrogeological base in mining EIA studies A focus on Ghana

Jerry S. Kuma[a,b,*], Paul L. Younger[b], Rob J. Bowell[c]

[a]*KNUST School of Mines, P.O. Box 237, Tarkwa, Ghana*
[b]*Department of Civil Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU, England, UK*
[c]*SRK, Summit House, 9-10 Windsor Place, Cardiff CF10 3SR, Wales, UK*

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Abstract

Conducive economic policies have led to a vibrant minerals and mining sector in Ghana, with the establishment of 12 new large-scale gold mines since 1988. The Environmental Protection Agency (EPA) has been strengthened and a robust monitoring regime is in place to prevent abuse of the environment. Insufficient attention has been paid, however, to the necessary hydrogeological detail of statutory environmental impact assessments (EIAs). This should be specified in order to furnish concise knowledge of the pre-mining groundwater conditions. Although such information is normally obtained through pumping tests, the cost involved has hitherto precluded its use. Yet hydrogeological data can be estimated from thin section and other studies on borehole cores obtained during routine mineral exploration. Combined with other "regional" methods of gathering groundwater information, these estimates provide a sound basis for baseline condition evaluation for less than 0.1% of the average expenditure incurred in locating an economic deposit. Apart from improving mining EIA practices, the proposed approach can also yield dividends for the mine operator, in terms of helping to find water for mine needs, and minimising water ingress to workings and associated pollutant release.

Keywords: Predictive; Mining EIA; Hydrogeology

* Corresponding author. Department of Civil Engineering, University of Newcastle upon Tyne, Newcastle upon Tyne NE1 7RU, England, UK.
E-mail address: j.s.y.kuma@ncl.ac.uk (J.S. Kuma).

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1. Introduction

Mining changes the hydrodynamics of both surface and groundwater systems. The effect of these changes is more noticeable in areas where the mine is located upstream of residential areas. Unchecked mining can cause water contamination and other environmental problems (e.g., forest degradation and air pollution). There is plenty of evidence from all continents that active and abandoned mines cause severe pollution (e.g., Kempe, 1983; Hedin et al., 1994; Banks et al., 1997). Jarvis and Younger (2000) have detailed the pollution of rivers by water from abandoned mines in the UK and have proposed some procedures for improving environmental impact assessment (EIA)-related impact quantification of mine waters and their remediation. In Ghana, Dzigbodi-Adzimah (1996) and Smedley et al. (1996) among others have highlighted water pollution problems related to mining. Attempts to check the degradation of the environment have resulted in the formation of government agencies, for example, the Environment Agency in Britain, the US Environmental Protection Agency (EPA), and analogous regulatory bodies in other countries, which enforce laws regulating the activities of industries (mining included) with a view to minimising their impact on the environment.

Major changes in the Ghanaian economy were initiated in 1983, including mining laws and fiscal measures, which considerably affected the mining industry. These changes culminated in the promulgation of the Ghana Mining and Minerals law in 1986 which promoted large-scale capital investment (Anon, 1986; Sraku-Lartey, 1993; Pohl, 1998). Realising that recent policies were likely to have serious environmental consequences, the government of Ghana published a working document entitled the "Ghana Environmental Action Plan" (vols. 1 and 2: Anon, 1991 and 1994a, respectively), and strengthened the EPA. In addition, the Minerals Commission was set up to monitor and regulate mining activities in the country. These developments led to the establishment of 12 new large-scale gold mines (as at 2001), and at the peak of the gold boom, in 1997 alone, 62 prospecting licences were issued to exploration companies. Scores of servicing companies also came into operation. Currently, about 40% of the country's annual foreign exchange earnings come from mineral exports, with gold contributing more than 90% of this figure. The total production of gold has now exceeded 2.3 million ounces per year.

Before a mining lease is awarded to prospective mining companies in Ghana, the EPA requires an EIA report that must be officially approved (Anon, 1994b). While the EPA has a robust regime in place for enforcing the environmental laws of the country, the hydrogeological reporting required by the guidelines is not sufficiently detailed to allow the intentions of mining lease permit seekers to be properly scrutinised. As a result, some EIAs reveal little about the hydrodynamics of mining areas prior to the commencement of mining, which means that adequate safeguards cannot be put in place to prevent damage to water resources. There are even times when little or no hydrogeological information is presented. For example, one recent EIA reported that "very little hydrogeological information was available. Groundwater seems to be abundant as there was the need for de-watering before blasting could be conducted by the mine" (Amegbey, 1996). Even in situations where some hydrogeological information is presented, important aspects are often neglected in the report. One recent internal report intimated that "no groundwater recharge information for the area exists" (Anon, 1997).

This paper examines the coverage of hydrogeology in the guidelines for mining EIA reporting in Ghana. It identifies inadequacies that seem to promote substandard groundwater sections in most mining EIA studies in the country. A format is suggested whereby the current Mining and Environmental Guidelines document (Anon, 1994b) can be altered to include a detailed but low-cost procedure for groundwater studies, which prospective lease permit seekers should be required to adopt. These guidelines could be applied in other countries, particularly those with inadequate groundwater studies. The purpose of this paper is to contribute to the nurturing of a philosophy in mining operations, from the exploration phase onwards, in which pollution prevention becomes the norm rather than an afterthought.

2. Current scope for hydrogeological investigations in Ghana's mining EIA

Gray (1975) has exhaustively investigated the scope of hydrogeology in the literature and adopted the following definition. Hydrogeology is the study of

1. "the occurrence and movement of aqueous solutions through porous and permeable rock media, regardless of the phase or concentration of the solutions;
2. the modifications caused to the chemical composition of the solutions, of other subsurface fluids and of the rock media by their mutual interaction."

Stone (1999), quoting from May (1976), defined hydrogeology more succinctly as "the science that applies geologic methods to the understanding of hydrologic phenomena."

These definitions indicate that geologic tools can be effectively employed to study the occurrence, movement, and chemical composition of aqueous solutions in rocks. All three aspects of the solutions (occurrence, movement, and chemistry) will be significantly affected by mining. Therefore, an assessment of the condition of the pre-mining groundwater system is necessary to enable the prediction of its likely level of distortion during and after mining. This in turn will suggest ways of formulating strategies to plan and manage the water regime in order to minimise any negative impacts that might be foreseen.

In the case of proposed mining developments in Ghana, a reconnaissance licence is awarded for 1 year and, if merited, renewed for an additional year. After this stage, a prospecting licence is awarded for a maximum area of 150 km^2 for 3 years in the first instance. This licence is also renewable for a period not exceeding 2 years and a further 2 years is permitted, although 50% of the concession must be given up (Anon, 1986). Drilling and excavation are not permitted at the reconnaissance stage but are integral parts of the prospecting phase. Successful reconnaissance and prospecting phases, therefore normally span 9 years, and proof of a mineable deposit leads to a request for a mining lease. A lease application is supported by reports of feasibility and EIA studies, which are reviewed by the Minerals Commission and EPA, respectively. Anon (1994b) is the working document, which addresses how much information is required in mining EIA studies. Aboagye (1993) explains how this information is to be presented in a feasibility report.

Environmental issues are addressed from the exploration phase and a "comprehensive" guideline is presented for all prospective new mines in Anon (1994b). The most important aspects of the 1994 document regarding water issues are considered in the *Soil and Mine Rock Geochemistry*, *Water Management*, and *Discharges to Water* sections.

The Soil and Mine Rock Geochemistry section states:

• "...identify ore and waste rock quantities which are chemically reactive and determine: potential for acid generation, total element composition and potential contaminants, contaminant solubility and leaching potential...."

The Water Management and Discharge sections state:

• "...identify all water sources...categorise catchments according to the quality of drainage water...develop a water management plan to prevent both surface and groundwater pollution, as far as possible, and agreed between company and EPA."

These statements appear to expand on the regulations that are in place to prevent pollution of the environment by a holder of a mineral right (Anon, 1986). The groundwater studies required by these guidelines are broadly adequate because they address the rock chemistry and water systems. The point at which such information is expected to be collected is normally at the feasibility stage of work; however, most of the data needed for groundwater studies are best gathered during the preceding exploration phase (Kuma et al., in press). In addition, the consultants who prepare the feasibility report are not those who conduct the exploration. Although in principle a link between the two exists through the Exploration Manager, the foci of work of these two groups are different. The result is that some elements required in the water studies are overlooked in earlier exploration phases, or inadequately evaluated because of costs. This means that the water sections in EIA reports can be incomplete and of little value.

Another problem is that even though the guidelines are considered to be "comprehensive, and not all requirements will be relevant to every type of mining project," it is stated elsewhere that they "are intended to define the minimum scope of the EIA and a proponent can include additional information if appropriate." While these two statements appear to be contradictory, the second implies that some activities can be included or omitted from the study at the discretion of the lease seekers. Consequently, they may willfully, or by genuine omission, present incomplete reports. Of course the discretionary inclusion of further material by applicants is not to be discouraged but experience shows that inclusion of superfluous detail is far less common than the omission of crucial hydrogeological information.

3. Addressing the issues

Although the existing regulations clearly require mining EIA studies to include investigations of surface and groundwater systems, the need for more prescriptive guidelines on hydrogeological content has been highlighted. This section discusses the components of the hydrogeological framework and the stages of exploration in which groundwater information can be obtained. It also evaluates the additional expenditure associated with the collection and processing of data which is not directly gathered during routine exploration. The sequential exploration model (SEM) which divides exploration into seven phases (Westerhof, 1999) is adopted as a basis for this discussion (i.e., *Desk studies*, *Regional reconnaissance*, *Detailed survey*, *Exploration drilling*, *Outline drilling*, *Evaluation drilling*, and *Feasibility study*).

3.1. Physiography

Physiography comprises land use, vegetation, relief, and drainage of an area. This information will normally be available on a relatively large scale, and is obtained during desk studies. However, in the course of reconnaissance survey work, all aspects of the data constituting the physiography will be gathered on a more appropriate scale and these should be carefully collated. These data provide the basis for building a hydrogeological database for the prospective mine and conceptualising the flow characteristics of the region. The main reasons for this are as follows:

1. Drainage patterns reveal important aspects of the geologic makeup and structure of an area (Stone, 1999).
2. Analysing the relief will help to delineate the flow characteristics and boundary conditions for the flow systems (Domenico and Schwartz, 1998).
3. Surface water systems are normally indicators of groundwater movement when both are hydraulically linked (Winter et al., 1998).
4. Land use and vegetation types affect runoff and evapotranspiration estimates (Dunne and Leopold, 1998).

No additional field activity is necessary apart from that already carried out during the land survey. Therefore, there is no extra expenditure involved.

3.2. Pedology

Soil is important because it often hosts the shallowest aquifer (regolith), which is normally hydraulically unconfined and thus frequently exploited for small-scale water supplies, particularly in tropical African countries (Wright, 1992). The shallowness is also reflected in its high vulnerability to pollution. According to Davis (1994), however, soil hydrogeology has been neglected in many groundwater studies and where it has been assessed, only the top 2–3 m are normally investigated, for agricultural purposes. Hydrogeologically, the soil zone includes poorly consolidated and unconsolidated rocks as well as soils. Precipitation infiltrates the soil to the water table, whose configuration is generally a subdued replica of the relief of the land surface.

Pedological data are obtained from the exploratory drilling to evaluation drilling phases when drilled holes are logged. However, in situations where the weathering profile is not thick, trenching and pitting during detailed survey also contribute to improving the database. The soil component can then be extracted and presented as a soil thickness map. Textural characteristics of the soil are determined to enable one to make an informed assessment of the importance of infiltration, and coupled with some elements of the physiography, the direction of movement of shallow groundwater may be inferred (e.g., Kuma and Younger, 2001). The surficial aquifer may be the sole water resource tapped by local communities and its destruction can cause serious problems. Furthermore, this aquifer may be linked directly with deeper bedrock aquifers. The soil activities are therefore:

1. Visually describe the soil profile and log any peculiar textural and structural characteristics it may exhibit in all excavations.
2. Identify and log the weathered–unweathered boundary in every drill hole and, where applicable, in pits and trenches.
3. An optimum sampling interval needs to be determined and this depends on pit and borehole density. About 40 soil samples are recommended (Kuma and Younger, 2001) and these should be taken in the B horizon because this is generally the most critical horizon on which infiltration of precipitation depends (Davis and DeWiest, 1991). The recommended tests are particle size distribution (PSD) analysis, bulk and particle densities, and moisture content. From these tests, soil texture, sorting, changes in lithology, volume changes as a result of compaction and subsidence, and porosity, are determined. In addition, other measurements are correlated or verified (Cullen and Everett, 1994).

The additional cost involved in carrying out these activities is associated with (3) alone. Since the position of all drill locations will not be known in earlier phases of work, it is advisable to take and keep soil samples (sealed) until a clearer picture of pit and drill-hole density is obtained, before tests are conducted, so that a fair sampling distribution is guaranteed. Interest in the concession would be high at the phase when the tests are conducted, and the importance of this whole exercise would be appreciated. The total cost (2001 prices) of the three tests conducted in a geotechnical laboratory in Ghana is about US$40/sample × 40 samples, that is, US$1600.

3.3. Geology

One of the reasons for conducting pumping tests is to define the size, extent, and yield of an aquifer (the latter being determined by measuring its hydraulic conductivity, specific yield, and storativity). The key hydrological parameters are controlled by the geological characteristics of the rocks as determined by their lithologic, stratigraphic, and structural properties. These properties are in turn obtained during mineral exploration at the surface geological mapping phases and when holes are drilled essentially for sampling and assaying.

Kuma et al. (in press) have demonstrated that the core logs retrieved from drilling represent a good opportunity for measuring the hydraulic properties of the rocks by the use of thin section analysis and the probe permeameter. Properties such as grain size, pore size, and porosity are measured, from which hydraulic conductivity, specific yield, and solute retardation factors are determined (Younger, 1992). In addition to these, the storativity of an aquifer is estimated as a function of aquifer lithology and thickness (Younger, 1993). Correlation of fractures in the cores will also help to estimate the effect (if present) of dual porosity on the overall aquifer properties. This is particularly important in some Ghanaian terrain, notably the Tarkwaian where surface geological mapping, including aerial photo and aeromagnetic maps, show multiple fractures (Kuma, 1994).

An added advantage during thin section studies on the cores is that it is possible to predict water–rock interactions, with the result that the effect of the rocks on the chemistry of discharges during mining can be rationally estimated. For example, pyrite is present in and around some intrusives in the Tarkwaian and a threat of acid generation may be perceived depending on the proximity of the intrusives to the ore body, the degree of crystallinity of the pyrite, and the sulphur content. Twenty per cent of the thickness of the Tarkwaian in the gold mining district in Tarkwa is made up of intrusive rocks of which the basic type is dominant (Hirdes and Nunoo, 1994). In the Birimian, sulphides form an integral part of the gold-bearing mineralisation in both the ore zone and parts of the host rocks. The degree of influence of these ore minerals on the chemistry of groundwater, especially in the unsaturated zone, can be estimated early and incorporated in the design of some mine facilities. A conscious effort to gather and apply all the information discussed above will form the basis of a reliable 3-D conceptual groundwater model of the target area.

The activities to be undertaken are:

1. Detailed surface geological mapping.
2. Detailed core logging to map primary and secondary features.
3. Probe permeameter for permeability determinations on cores.
4. Prepare standard thin sections in blue resin and use a petrological microscope to determine mineralogical composition. Measure grain size, sorting and the structure and dimensions of pore spaces and grain contacts. Conduct point counting, volume-percentage composition and porosity for each analysis with a minimum of 300 points (Emery and Robinson, 1993).
5. Use porosity determined from (4) to estimate specific yield and storativity of aquifers (Younger, 1993).

Extra costs are associated with (3) and (4). A typical scenario would be:

- In a reputable laboratory, a test for permeability determination costs US$10 per rock sample. Assume that 200 tests are conducted, that is, US$2000.
- Preparation of a thin section costs US$10 and for say 200 sections, this works out at US$2000.
- Interpretation of each section for the items in (4) costs US$40 per section, that is, US$8000 in total for 200 samples.

The extra cost of these activities would be US$12,000.

3.4. Hydrology

Meteorological data (especially rainfall, temperature, and humidity) are widely available and are obtained for the region during the desk studies phase. However, just as in the case of the physiographic data, this information may not be located exactly in the prospect. Since topographic features can cause significant local variations in some of the meteorological data and because, currently, almost all prospects are developed for surface operations, the magnitude and variation of evaporation is vital, especially where heap leach technology is to be employed to extract gold. It is therefore important to install a meteorological station in the proposed mining area. This is normally installed during the feasibility stage, but it would be far better to establish it during evaluation drilling when interest in the prospect is high. The risk in this decision is reduced if an arrangement between the Meteorological Services Department (MSD) and EPA can be struck on behalf of the Exploration Company so that the MSD will take over the meteorological station if work in the prospect is terminated. This also has a wider importance, since Anon (1994a) has revealed that the density of meteorological stations is low in most parts of Ghana. The Exploration Company incurs no loss because the cost of this operation would be recovered in the event of nonproduction.

Major stream gauging should coincide with the installation of a meteorological station so as to synchronise data for runoff, recharge, evapotranspiration, and other hydrological estimates, because at least 3 years of data are required to make credible estimates of hydrological parameters. According to Knutsson (1988), it is necessary in a study of groundwater recharge to use more than one technique for result verification. At this stage of exploration, renewal of the prospecting licence has usually been effected, implying that the area under study is reduced to 75 km^2.

Stream gauging is generally not part of the exploration activity and would thus incur extra cost. Assume that two streams are gauged daily up to and including the period of feasibility studies. That the technician in charge of the weather station could be trained with an assistant to carry out stream gauging.

- The price of a flow meter varies from US$700 to more than US$2000.
- Salary for an assistant for 3 years, say US$100 per month $\times$ 36 months, is US$3600.[1]

The overall expenditure in this section would be US$5600.

3.5. Hydrochemistry

During the feasibility study phase of ore exploration, water samples are often collected at strategic locations in the prospect. This helps to define the pre-mining concentration of elements as baseline information for future hydrogeological impact assessment investigations. Attention should be paid to the seasonality of sampling, since groundwater forms the bulk of stream flow in the dry season (e.g., Pettyjohn, 1985). Kuma et al. (in press) observe that very often only major elements are measured, or poorly collected or incomplete or contradictory information is provided. Therefore, all the protocols relating to sample collection, storage, and analyses should be followed. The chemical analyses should also include the major elements as well as those minor and trace elements whose concentrations are likely to be affected by mining (Younger et al., 2002). No extra cost is incurred in carrying out this activity because all the above are expected anyway.

[1] Salary is based on current conditions on the Ghanaian employment market. All other costs are international rates.

4. Discussion

Just as some scientists assume that geophysics is synonymous with the seismic reflection method, so it is with the misconception among others who equate hydrogeology solely with pumping tests. Many EIA studies lack hydrogeological detail, probably because of the high cost of conducting pumping tests, and since mineral exploration is such a high-risk undertaking, one can do without a hydrogeological budget because it has no link with estimating the mineral resource (Kuma et al., in press). Pettyjohn (1985) suggests that even though test drilling is required in most hydrogeological studies, because the costs are high, there is a need for other sampling methods and techniques to be developed to evaluate the subsurface. He concludes that "it might be a good idea to prohibit all drilling until the final report is prepared." This suggestion presupposes that it is possible to conduct a hydrogeological study without resorting to test drilling, that is, by employing non-point source or areal examination techniques. However, during mineral exploration, drilling on a large scale normally forms part of the detailed exploration phase. This is a welcome opportunity for gathering point-source hydrogeological information to supplement non-point source techniques because very little extra expenditure is involved. Some hydrogeologists have advocated this type of hydrogeological data collection in other water resources studies (Younger, 1992, 1993). In the case of mineral exploration, it should be seen as a useful and convenient way of obtaining a thorough picture of the groundwater system of the area in question. An advantage of pursuing this line of study is that the occurrence, movement, and chemical composition of identified aquifers can be quite accurately determined. Lehr (1985) corroborates this view when he observes that groundwater moves within relatively distinct boundaries in predictable directions. Therefore, areas of preferential groundwater flow that may lead into important aquifers could be identified early, the risk of their destruction assessed, and alternative action or precautions built into the mine design to forestall contamination. In addition, aquifers that may be starved of recharge water could be identified and mitigating plans and other management mechanisms put in place.

Drilling tests are conducted in mine concessions to explore for water in order to feed processing plants and other needs of the mine. In some instances, several dry water holes are drilled, necessitating the use of geophysics before success is achieved. Both of these undertakings are necessary but expensive. However, employing the proposed procedure would significantly cut the cost of these tests.

Another advantage of this procedure is that the consultants who prepare the feasibility reports would no longer have to sift through "geologic information" to prepare a hydrogeologic section: the cause of inadequate water resources sections in mining EIA studies. Neither would they have to "duplicate" geological activity which has already been executed in a bid to get more hydrogeological information (giving rise to an extra budget, although this rarely happens).

The estimated additional expenditure needed to implement this procedure is less than US$ 20,000. Woodall (1984) noted that an in-depth study of metals exploration between 1955 and 1978 revealed US$16 million as the average cost of discovering a deposit in Australia under 1980 conditions. According to Westerhoff (1999), modest-sized epithermal gold deposits required an investment of between US$25 and US$125 million during the 1980s and 1990s. If a conservative minimum figure of US$20 million is taken as the amount required for finding an economic deposit under current market conditions, an additional figure of less than 0.1% of the cost of exploration is worth spending. This is because the information and its interpretation are useful not only for EIA studies. In addition to the benefits already noted, a vital ancillary database for pit-wall stability, water ingress into pits, and mine closure assessment studies is obtained (for details of such applications of these data, see Younger et al., 2002). This database is also the basis on which any environmental hydrogeological audit would be conducted during the course of mining.

Kuma et al. (in press) propose that aspects of environmental hydrogeology should be built into undergraduate and graduate earth science curricula to enable students in these fields to acquire the necessary skills that will help them undertake tasks of data and information gathering and management. Ghana has sufficient middle- and high-level manpower resources in the earth sciences. With the consent and involvement of the EPA of Ghana, short courses could be organised for those already in the exploration field to familiarise them with the water cycle and elementary groundwater hydraulics. A period of time may be allowed for training field geologists before implementing this procedure. All the geological and geotechnical tests that need to be conducted are available in reputable laboratories in the country.

5. Conclusion

The Ghanaian EPA has a strong and effective monitoring regime to safeguard the environment, and Anon (1994b) has spelt out the extent of groundwater studies required in mining EIA studies. As noted, however, a number of EIA reports lack the necessary groundwater detail. This is because data necessary for an effective evaluation are not collected and assessed early enough during the course of exploration, but only at the feasibility phase, with the result that valuable information is lost. In addition, contradictory signals in the EIA guidelines may be interpreted by some lease seekers to their own advantage, minimising hydrogeological investigation and thus endangering the environment.

This paper has itemised and discussed the essential components required to form the basis of a groundwater section in mining EIA studies in Ghana. It has suggested ways of expanding the scope of such studies to include invaluable point source data, hitherto ignored. Benefits to be derived if this procedure is adopted are:

- A better groundwater conceptual model for a mineral concession is obtained for presentation in mining EIA studies. The occurrence, movement, and quality of identified aquifers are quite precisely determined and areas of preferential groundwater flow into or out of important aquifers are identified early, the risk of their destruction assessed, and a groundwater management plan incorporated into the mine design to forestall contamination. Water–rock interactions are predicted through thin section studies resulting in a rational estimate of the effect of host rocks on the chemistry of discharges during mining.

Table 1
The recommended phases of mineral exploration most appropriate for hydrogeological data collection and the additional costs incurred at each stage

Hydrogeological aspect	Mineral exploration phase	Hydrogeological outcomes	Extra expenditure
Physiography • Relief • Drainage • Land use • Vegetation	Desk studies and during regional reconnaissance. As more detailed surveys are executed, larger scale maps are produced.	Maps at a scale of 1:20,000 to 1:5000 are produced. Recharge and discharge areas are determined. Preliminary groundwater flow directions and groundwater boundaries are conceptualised.	None
Pedology • Soil logging and sampling • PSD • Moisture content, bulk, and particle densities • Infiltration tests	Exploratory, outline, and evaluation drilling phases. Pitting and trenching are useful if the weathering profile is thin.	Soil thickness map, soil texture, sorting, porosity, and changes in lithology. Results are also useful during assessment of groundwater recharge.	US$1600
Geology • Lithological • Structural • Stratigraphic • Thin section and microscopy • Probe permeameter	From the desk study phase through evaluation drilling, surface mapping, and core logging.	From thin section analysis of rock samples, determine: mineralogical composition, grain size, sorting, and porosity (by point counting). Use porosity to estimate specific yield and storativity (Younger, 1993). Permeability determined from probe permeameter. Prediction of rock–water interactions for assessment of possible discharges to streams. 3-D conceptual hydrogeological model from above information coupled with surface geological mapping and core logging.	US$12,000
Hydrology • Meteorological station installed for daily recording • Daily gauging of major streams	Some information is available at the desk study phase. But meteorological station installed and stream gauging conducted: both during evaluation drilling.	Evaporation and evapotranspiration estimation. Use information from soil survey with rainfall, runoff, and evapotranspiration data to estimate recharge. Use stream hydrograph to also estimate recharge.	US$5600
Hydrochemistry • Low-flow stream surveys	Regional reconnaissance stream surveys but mainly during feasibility studies.	Hydrochemistry of the area determined.	None
		Total expenditure=US$19,200	

- A vital ancillary database for pit-wall stability, dewatering of pits, and mine closure assessment studies, is obtained. This database is also the basis on which any environmental hydrogeological audit would be conducted during the course of mining.
- The cost of implementing this procedure is low, that is, 0.1% of the average mineral exploration budget, and should therefore appeal to all who desire to protect the environment from contamination and pollution during mining.

It is advisable for the government to amend the current Mining and Environmental Guidelines document (Anon, 1994b) and include this procedure for groundwater studies. The government should require exploration companies to build a water resources database and to submit an elaborate groundwater section in their quarterly and annual reports. Although quarterly water sections may not show any significant changes from the previous report because water events are on yearly scales, they would nonetheless keep the regulating agencies abreast of all the water activities of the company. Most exploration companies use commercial software such as *SURPAC*, *DATAMINE* and *TECHBASE*, all of which can handle groundwater data. Table 1 summarises the likely phases of mineral exploration when hydrogeological data may be most appropriately collected and the additional costs likely to be incurred.

The cleanup budget for a mine with serious environmental problems is very high and these problems are normally only acknowledged after a serious environmental accident, when a mine goes bankrupt or is decommissioned. The budgetary constraints due to inadequate financial resources and competing demands in developing countries means that working in a pre-emptive capacity by devising stringent, yet user-friendly and low-cost methods likely to prevent water pollution problems, is the best action to undertake. This also helps to build a sustainable livelihood for communities that are situated close to mines. This predictive procedure is also recommended for adoption in countries with similar cases or in situations where, although enough groundwater information is presented in mining EIA studies, a predictive strategy is now desirable.

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