# Hydrogeological framework for assessing the possible environmental impacts of large-scale gold mines

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**Abstract:** Hydrogeological information is crucial to the development of a sound environmental impact assessment (EIA) for a proposed mine, as well as the management of potential environmental impacts during and after exploitation. However, the determination of hydrogeological parameters is not customarily included in mineral exploration surveys, with the result that many EIAs end up being rather light in hydrogeological content. Examples from the Tarkwa gold mining district of Ghana illustrate this point. Consequences of such an inadequate hydrogeological understanding are potentially serious, ranging from an inability to predict future problems in water quality after the cessation of mining, to a lack of understanding of hydrogeological controls on slope stability, which is arguably manifest in the catastrophic spill of cyanide-rich processing effluents from a breached tailings dam at Wassa West, near Tarkwa, on 16 October 2001. To redress this deficiency, we propose that a hydrogeological database be assembled during the mineral exploration phase, according to a specified protocol ('check-list'). Using these data, a rational conceptual hydrogeological model for the mine site and its surrounding area can be developed, providing the basis for a thorough consideration of groundwater aspects within the statutory Environmental Impact Assessment, which is (as in most other countries) required by Ghanaian government statute before a mining lease is approved. The resources required to set-up such a database are small compared to the benefits.

Mineral exploration and exploitation is a multimillion dollar business. Even though the risks are very high, the quest for improved living standards and developments in mineral beneficiation technology both stimulate the exploration and development of new sources of mineral wealth (Woodall 1984). The mining industry is both an important source of employment and a major foreign exchange earner in many countries, and this is certainly the case in Ghana, the former 'Gold Coast' of Africa. Although environmental controls during active mining are increasingly stringent, former mining operations have left a long-term legacy of environmental problems on almost all continents (e.g. Hedin *et al.* 1994; Younger 2001; Dzigbodi-Adzimah 1996). Many of these long-term problems arise because of a lack of appreciation of the hydrogeological setting of the mine, resulting in the pursuit of inadequate closure strategies. This lack of hydrogeological appreciation belies the existence of well-established techniques for relatively low-cost development of conceptual hydrogeological models to underpin the process of environmental impact assessment (EIA) (e.g. Pettyjohn 1985; Kolm 1996; Stone 1999).

This paper illustrates the hydrogeological shortcomings of EIA procedures using examples from the Tarwka gold mining district of Ghana. A protocol for hydrogeological data collection to improve the insertion of groundwater system concepts into future site appraisal and management activities is proposed.

## Gold mining and EIA requirements in Ghana

### *Ghanaian gold mining and EIA requirements*

In Ghana, gold mining contributes approximately 30% of the annual foreign exchange earnings and more than 2.3 million ounces of gold is produced by the country annually. Figure 1 shows a simplified geological map of southwest Ghana and the location of large-scale gold mines. A new mining permit can only be issued after the Environmental Protection Agency (EPA) of Ghana has approved an EIA report. The EIA report

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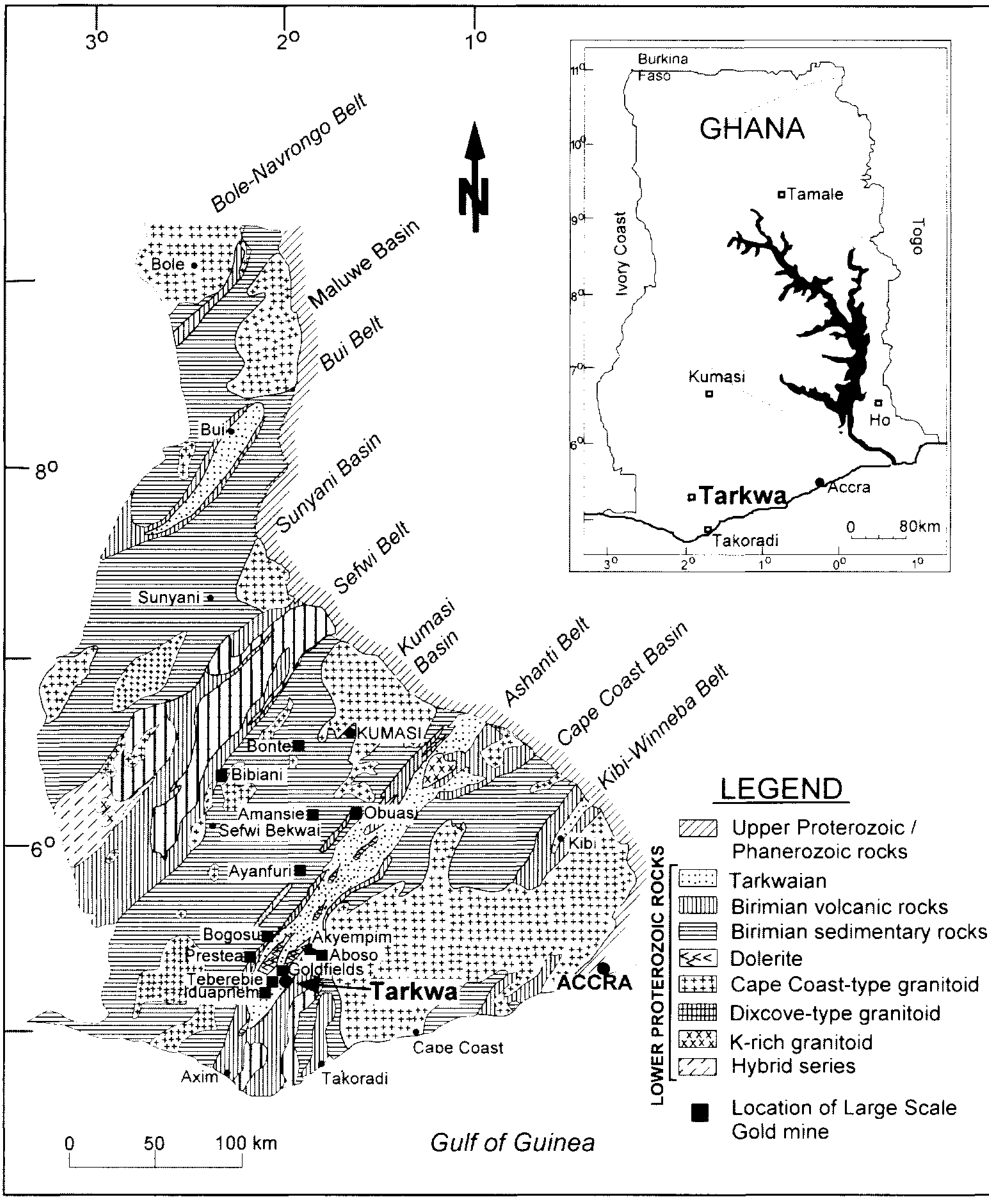


**Fig. 1.** Simplified geological map of Ghana showing the location of large-scale gold mines (adapted from Eisenlohr 1992).

includes, among other requirements, an Environmental Baseline Study, Environmental Impact Statement and an Environmental Management Plan. On-going mining activities are required to submit Environmental Action Plans (EAP) with an annual report (Anon. 1994). During mine operation the EPA also administers a random monitoring programme.

## *Examples of hydrogeological shortcomings in Ghanaian mining EIAs*

Even though the EPA requires water sections in EIA studies, many such studies lack sufficient hydrogeological detail to permit full scrutiny of the intentions of the mining lease permit applicants. Without such detail, the hydrodynamics of the mining areas cannot be conceptualized to the degree necessary to allow adequate safeguards to be put in place to forestall damage of 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 dewatering before blasting could be conducted by the mine' (Amegbey 1996). Even in situations where some hydrogeological information is presented, important aspects are normally absent from the document. For instance an internal report intimated that 'no groundwater recharge information for the area exists' (Anon. 1997).

The ultimate consequence of a lack of hydrogeological data is an inability to manage environmental and geotechnical processes that influence/are influenced by groundwater occurrence, movement and quality. Hence, there still exists no regional groundwater monitoring network in the Tarkwa area that would be needed to independently assess the likely rates of filling of post-mining pit lakes, and/or the positions and quality of mine water decants to the surface environment. Without such information, preventative measures cannot be devised (cf. Younger & Adams 1999; Shevenell 2000). Even before mine closure, groundwater data are critically important in the design of safe pit wall angles, and secure bunds for tailings dams and other structures (see Younger *et al.* 2002). With regard to the latter, inadequate control of sub-dam pore water pressures is suspected to have played a role in the partial failure of a tailings dam, which gave rise to a release of cyanide-rich water in June 1997 (spill from the Teberebie gold mine into the Awunabeng stream) and perhaps also contributed to a similar spill (from Goldfields of Ghana gold mine) on 16 October 2001 that introduced cyanide into the River Essuman, which provides drinking water to the villages of Abekroase and Huniso (Fig. 2).

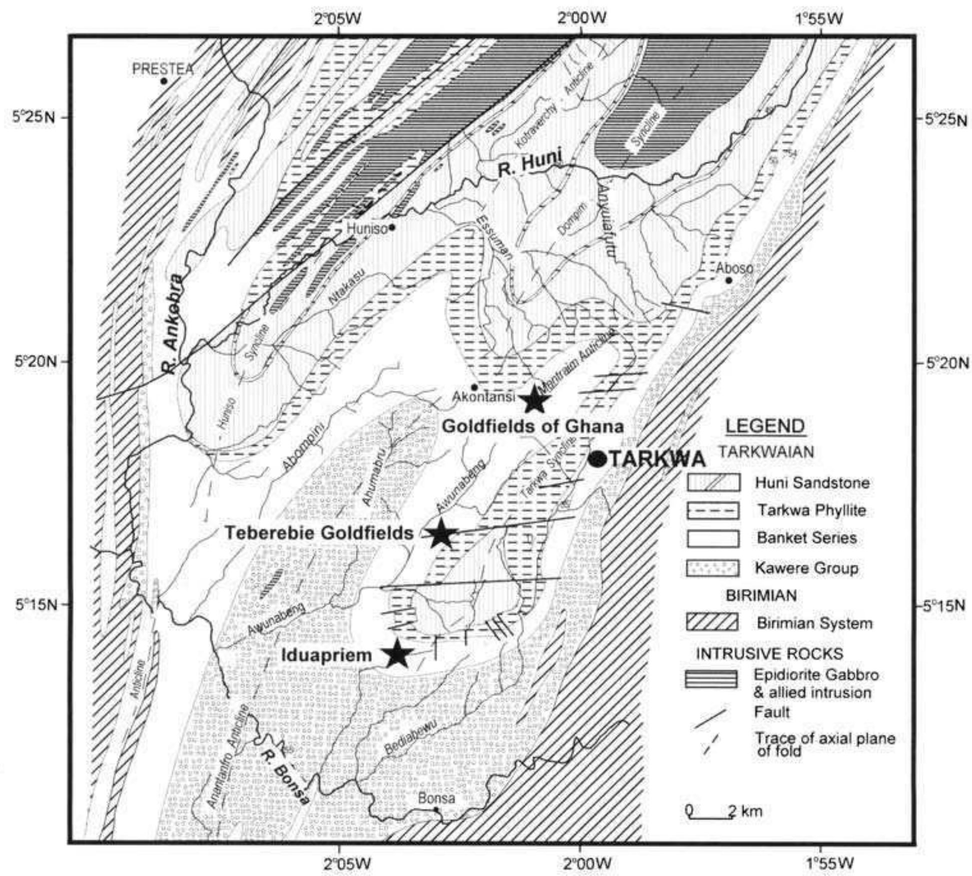


**Fig. 2.** Geological map of Tarkwa area (adapted from Junner *et al.* 1942).

Hence, both short- and long-term environmental management requries hydrogeological understanding. Such an understanding does not necessarily require extensive groundwater mapping to 'First World' standards and it can, in fact, be achieved using an array of relatively simple methods.

## Protocol for low-cost hydrogeological data collection for inclusion in EIA

Groundwater information can be gathered during the phase of mineral exploration, so that it is readily available at the time the EIA is undertaken. Although the following items are described in a segmented manner, it should be borne in mind that they are in reality interconnected. Hence, some of the items covered in one section below are also highlighted in subsequent sections.

### *Physiography*

Historical information on the physiography of the area may be available, but data on current land use, vegetation, relief and drainage information are normally collected early in the preliminary exploration phase by conventional surveying. A map of the physiography at a scale of 1:20 000 or less is normally prepared for the concession, and this scale is reduced as detailed phases of exploration are pursued. Surface water systems provide valuable evidence of groundwater movement (where the two systems are hydraulically connected) and analyses of the surface water system will enable information to be obtained about groundwater flow patterns and water quality (Fetter 1994; Winter *et al.* 1998). In addition, the drainage pattern of an area is normally a reflection of its geological history and structure (Stone 1999). Thus, due consideration given to the study of the drainage pattern will improve an early conception of the groundwater system in the area, for example, identification of recharge and discharge areas.

### *Pedology*

The physical and chemical characteristics of a soil play a vital role in the recharge and chemical evolution of groundwater. This is because soil texture and structure control hydraulic properties, whereas soil mineralogy affects water quality (Hem 1992; Stone 1999). It has, therefore, been advocated that the nature of the soil and the drainage characteristics of an area be closely considered during hydrogeochemical studies (Edmunds 1981). During these studies the type of clay present should be determined by X-ray diffraction (XRD) if possible, as this information can improve knowledge of the possible chemical reactions likely to occur in the shallow subsurface (Appelo & Postma 1993; Head 1997). In addition, the rainfall characteristics, vegetation and land use all influence infiltration of water through soil, and form a critical component of the hydrological cycle (Dingman 1994; Dunne & Leopold 1998).

In undertaking a pedological survey the soil thickness encountered during drilling should be recorded, to delineate the weathered–unweathered boundary of the area. Furthermore, the soil profile and any peculiar textural and structural characteristics in all excavations should be logged. Soil should be sampled in the B-horizon because this is the most critical horizon on which infiltration of precipitation to the groundwater zone depends (Davis & DeWiest 1991). An optimum of 40 soil samples is recommended for determination of particle size distribution (PSD) analysis, bulk and particle densities, and moisture content tests. Soil texture, sorting, changes in lithology, volume changes as a result of compaction and subsidence, and porosity are determined from these tests. Moreover parameters such as porosity, permeability and heterogeneity, together with shape and size of voids, are likely to be of considerable importance in controlling the movement of pollutants through the unsaturated zone (Hounslow 1985). Assessment of groundwater recharge is also aided by using this information.

*Geology.* Knowledge of the lithology, stratigraphy and structure of the rocks in a region is essential to understanding the nature and distribution of their water-bearing properties (Fetter 1994). In a mining environment the presence of lithological logs will greatly enhance knowledge of the subsurface geology, which in turn helps to improve conceptions of the hydrogeology of the area.

Lithological logs are collected during the exploration phase. Normally during the stage of detailed exploration, these logs are acquired at spacings as small as 25 m and in a regular pattern, at least in and around the ore body. These logs should be scrutinized for all the hydrogeologically relevant information that they may contain by means of logging and laboratory tests, which can then form the basis of a hydrogeological model of the concession. Younger (1992) has demonstrated the use of a petrological microscopy in the direct measurement of grain size, pore size and porosity, from which estimates of hydraulic conductivity, specific yield and solute retardation factors have been made. It has also been shown that the storativity of an aquifer can be estimated as function of aquifer lithology and thickness alone (Younger 1993). A probe permeameter could also be employed for making inexpensive permeability determinations on borehole core samples (Eijpe & Weber 1971).

Geological logging and petrological studies of cores enable the prediction of water–rock interactions likely to explain the chemistry of groundwater discharges to streams (Sharp & McBride 1989; Appelo & Postma 1993). The presence of sulphide minerals, which are prevalent in some gold ore fields, deserves particular attention due to their propensity to release acidic, metalliferous leachates (acid mine drainage) after they have been aerated. Early knowledge of their occurrence is useful during planning.

There is a paucity of information regarding the aquifer properties of many mine concessions, even though water boreholes are drilled for processing and other needs (e.g. for local communities on mine concessions and for those who have been resettled) during the feasibility stage of exploration. A little time and effort invested in pumping tests of water boreholes drilled for such purpose can be an invaluable addition to the hydrogeological database. Some of the exploration boreholes can also be adapted as monitoring boreholes to establish pre-mining groundwater trends and background hydrochemical patterns.

### *Hydrology*

Information on the climate may be available for the region as a whole. However part of the concession may have been excluded from further consideration (typically 50% or more). Rainfall, evaporation, temperature and other meteorological data are normally a requirement for site design. Therefore, a simple meteorological station is often installed to aid the estimation of evapotranspiration. Evaporation measurements are also necessary for the design and operation of heap-leach pads, which are employed by most of the gold mines. It is advisable to start routine gauging of major streams in the area (for run-off and recharge estimates) at this time so that this information can be synchronized with meteorological data for future analyses and interpretation. In addition, piezometers need to be economically installed at this time at well-chosen sites in the concession so that the flow regime of the ground water can be determined. Recharge can also be estimated and compared with the value from the stream hydrographs. These piezometers must be kept in working order throughout the life of the mine so that future assessments can be conducted without difficulty.

### *Hydrogeochemistry*

Surveys of streams and springs in and around the concession area, particularly during dry periods when there is no surface run-off to mask groundwater contributions, can provide invaluable information on groundwater chemistry (e.g. Pettyjohn 1985). The data also provide a useful input to the baseline information required in EIA reports. However, where such surveys are undertaken, they often include analysis of only the major ions and/or samples prove to have been poorly collected, so that incomplete and/or contradictory information is provided. We propose the following list of determinands: temperature, pH, Eh, Na, Ca, Mg, K, $HCO_3$, $SO_4$, Cl, $NO_3$, $SiO_2$, Fe, Mn, Al, Co, Cr, Pb, Zn, Cu, CN, Hg, As, DO, TDS colour and turbidity. Further, a major omission is often the assessment of pit-wall or waste rock contribution to discharge water quality and changes that will occur over time (Bowell 2002). This information is normally not collected because an experienced hydrogeochemist may not be included in the exploration team.

At least 5 years (some times up to 20 years) elapse before an exploration prospect actually becomes a mine (Woodall 1984). Therefore, if all the aspects above are conscientiously followed during the exploration stage, a sufficient run of data will have been accumulated to support development of a robust conceptual hydrogeological model of the mine.

## *Example application of the protocol to the Tarkwa gold mining district*

To test the feasibility of applying the above protocol to a real system, it was applied to the Tarkwa mining district in Ghana by means of field surveys between January 2000 and January 2001. The following sections document the findings.

### *Physiography*

The Tarkwa area has a humid tropical climate with an average annual rainfall of over 1750 mm. Rain falls in two main periods in the year: a major wet season from April to July (with a peak in June) and a second minor season from September to November. Air temperature for the area varies in a narrow range (between 28 and 33°C) and relative humidity varies from 83 to 91%. Located in an area transitional between the rain forest and moist semi-deciduous forest, zones of the original vegetation are locally present, while other areas have been cleared for farms, mines and communities (Dickson & Benneh 1988).

The Tarkwa district is located within the Ankobra River basin and is bordered to the west by the southerly flowing Ankobra River (Fig. 2). Both the Huni and Bonsa rivers are major tributaries to the Ankobra, and border the area to the north and south, respectively. The area is highly dissected and of moderate relief with a general decrease in hilltop altitudes towards the south. A series of parallel ridges and valleys oriented along the general NE–SW strike of the rocks define the landscape. This geomorphology is due to pitching fold structures and dip-and-scarp slopes of the Banket Series and Tarkwa Phyllites, which form part of the bedrock (see below). Transverse to the ridges and valleys are smaller tributary valleys and gaps controlled by faulting and jointing (Whitelaw 1929).

### *Pedological characterization*

Infiltration and particle size distribution (PSD) tests were conducted to determine saturated hydraulic conductivities ($K_s$) and textural characteristics, respectively, of soil at 56 sites in the Tarkwa area (Kuma & Younger 2001). These soil tests were conducted in the B-horizon (Table 1). It was observed, in general, that extremely poorly sorted soils exhibit low porosity and relatively higher $K_s$ while relatively better-sorted soils reveal high porosity and low $K_s$ values (Kuma & Younger 2001). The soils are mainly silty-sands, which exhibit $K_s$ values in the $10^{-5}-10^{-8}\,m\,s^{-1}$ range, although this is dominated by those in the narrower band of $10^{-6}-10^{-7}\,m\,s^{-1}$. Minor lateritic patches are located on hilly terrain underlain by Banket Series and Tarkwa Phyllite rocks. Banket soils exhibit the most favourable characteristics for infiltration in the area, in terms of both PSD and $K_s$ values. These soils are located on hills and, therefore, act as the main areas for groundwater recharge. Huni and Kawere soils, located in low-lying areas, display characteristics suggesting that the Huni, with a much better sorting coefficient and $K_s$ value, will admit more precipitation for recharge compared to the Kawere. Soil pH varies from very acidic to moderately acidic, that is 1.72–5.01. The lowest pH values are associated with weathered felsic dykes and are caused by the presence of well-disseminated fine pyrite crystals, which are expected to be a potent source for acid rock drainage when found in the unsaturated zone.

### *Geology*

Sediments of the Tarkwaian System are predominantly arenaceous and were 'deposited by high-energy alluvial fans entering a steep sided basin filled with fresh water' (Kesse 1985). They consist, in general, of coarse, poorly sorted, immature sediments with low roundness typical of a braided stream environment. They have been metamorphosed to low-grade green-schist facies (Kesse 1985). Rocks of the Tarkwaian System, in the direction of younging, comprise the Kawere Group, the Banket Series, the Tarkwa

**Table 1.** *Summary of soil tests conducted in the Tarkwa area*

| Soil type | Texture | Percentage | | | | $K_s$ ($10^{-6}\,m\,s^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Gravel | Sand | Silt | Clay | Min. | Max. | Mean | $S_o$ | $n$ | $W\%$ | $G_s$ | pH |
| Banket | Silty-sand | 2 | 59 | 29 | 10 | 0.21 | 10.56 | 4.45 | 3.74 | 0.38 | 17.5 | 2.66 | 4.92 |
| | Laterite | 69 | 14 | 10 | 7 | 0.01 | 20.75 | 3.46 | 5.85 | 0.22 | 9.8 | 2.67 | 4.86 |
| Huni | Silty-sand | 2 | 55 | 33 | 10 | 0.05 | 7.28 | 1.57 | 2.28 | 0.42 | 12.8 | 2.65 | 5.01 |
| Kawere | Silt sand | 0 | 47 | 40 | 13 | 0.10 | 1.87 | 0.72 | 4.34 | 0.38 | 12.4 | 2.65 | 4.65 |
| Tarkwa Phyllite | Laterite | 62 | 9 | 13 | 16 | – | – | – | 17.8 | – | 14.2 | 2.74 | 5.01 |
| W. Dyke | Silt | 3 | 20 | 64 | 13 | 0.31 | 2.57 | 0.88 | 2.75 | 0.40 | 22.2 | 2.62 | 5.22*<br>1.96† |

$K_s$ is saturated hydraulic conductivity, $S_o$ sorting; $n$ is porosity; $W\%$ is moisture content, $Gs$ is specific gravity; W. Dyke is weathered dyke.
*Mafic.
†Felsic.

**Table 2.** *Subdivision of the Tarkwaian System in the Tarkwa area (modified after Junner* et al. *1942). The bold face characters under 'composite lithology' signify the most abundant and important rocks forming each division*

| System | Series | Thickness (m) | Composite lithology |
|---|---|---|---|
| Tarkwaian System | Huni Sandstone | 1370 | Sandstones, grits and quartzites with bands of phyllite |
| | Tarkwa Phyllite | 120–400 | Huni sandstone transitional beds and greenish-grey phyllites and schists |
| | Banket Series | 120–600 | Tarkwa Phyllite transitional beds and sandstones, quartzites, grits breccias and conglomerates |
| | Kawere Group | 250–700 | Quartzites, grits, phyllites and conglomerates |

Phyllite and the Huni Sandstone (Fig. 2 and Table 2).

Intrusive igneous rocks make up about 20% of the Tarkwaian System in the Tarkwa area. These rocks range from hypabyssal felsic to basic igneous rocks, principally in the form of conformable to slightly transgressive sills, with a small number of dykes. Faults and joints are common in the area and the most prominent joint sets trend ESE–WNW (although NW–SE and N–S trends are also present). The faults are either strike-parallel and closely associated with folding (and may occur as upthrusts) or dip-parallel, and are most often recognized as breaks in the topography (Hirdes & Nunoo 1994).

With shallow-water beds in a braided environment, the thickness of individual members varies considerably. In addition, a fractured and metamorphosed lithology confers aquifers with dual porosity, limited areal extent and storage properties.

## *Hydrology*

Direct recharge (*sensu* Lerner 1990) was identified as the dominant recharge process requiring estimation because precipitation (1803 mm for the year 2000) is the primary hydrological input. In the development of the water balance model, it was assumed that the area is almost hydrologically closed with respect to both surface and groundwater. This is because on three sides of the area, three rivers, i.e. the Bonsa, Huni and Ankobra, effectively act as surface and groundwater divides with no possible intrusion from beyond the river boundaries. On the eastern boundary, the Banket ridge acts as a water divide. The equation for precipitation recharge for the study area is written as:

$$\text{Recharge } (R) = P - RO - AE \pm SMS - SWS \quad (1)$$

where: $P$ is the precipitation (mm year$^{-1}$), $AE$ is the actual evapotranspiration (mm year$^{-1}$), $RO$ is the catchment surface run-off (mm year$^{-1}$), $SMS$ is the soil moisture storage (mm year$^{-1}$) and $SWS$ is the surface water storage (shallow lakes, mm year$^{-1}$).

The Penman–Pan evaporation relationship is strongest in the more humid areas of Ghana and in the wet seasons, because the potential evapotranspiration and pan evaporation values are similar to those yielded by the Thornthwaite and Papadalus formulae (as described by Acheampong 1986). Dunne & Leopold (1998, p. 136) came to a similar conclusion working in Kenya (which is in the tropics, on about the same latitude as Ghana, although higher in altitude). Considering the results of these studies, pan evaporation data were adopted as suitable for describing the potential evapotranspiration (PE) of the study area.

A method adopted by the British Meteorological Office (BMO) for estimating actual evapotranspiration (AE) of a water basin is to classify the various types of vegetation according to their root constants (RC) and proportionately determine the AE from these after calculating the water balance (Shaw 1994). Based on the BMO model, vegetation in the Tarkwa area was classified as having about 65% mature forest (of which 25% was riparian and always transpires at the potential rate), 10% shrubs, 15% crops, and 10% urban and mine area. The mature forest is expected to have the maximum possible root constant of 250 mm, based on both the soil texture and its vegetation (Grindley 1970). Crops farmed are roots and cereals with approximate RC values of 100 and 150 mm, respectively; shrub RC is about 200 mm, and in urban and mining areas it is 25 mm.

The Thornthwaite & Mather (1957) accounting procedure for the water balance method was adopted, and Table 3 shows an example calculation using a root constant of 250 mm. The average actual evapotranspiration obtained

**Table 3.** *Monthly water balance at the Tarkwa area with a root constant of 250 mm**

| Month | Rainfall (mm) | Pan Evap. (mm) | R-PET (mm) | Acc. PL (mm) | ΔST (mm) | ST (mm) | AE (mm) | Deficit (mm) | Surplus (mm) |
|---|---|---|---|---|---|---|---|---|---|
| January | 60.97 | 79.20 | −18.23 | −34.00 | −16 | 218 | 77 | 2 | 0 |
| February | 59.12 | 118.90 | −59.78 | −94.00 | −47 | 171 | 106 | 13 | 0 |
| March | 37.33 | 106.00 | −68.67 | −163.00 | −42 | 129 | 79 | 27 | 0 |
| April | 166.33 | 115.60 | 50.73 | | 50 | 179 | 116 | 0 | 0 |
| May | 293.92 | 102.30 | 191.62 | | 71 | 250 | 102 | 0 | 121 |
| June | 480.01 | 65.00 | 415.01 | | 0 | 250 | 65 | 0 | 415 |
| July | 74.92 | 85.80 | −10.88 | −11.00 | −11 | 239 | 86 | 0 | 0 |
| August | 91.08 | 73.70 | 17.38 | | 11 | 250 | 74 | 0 | 6 |
| September | 123.46 | 73.20 | 50.26 | | 0 | 250 | 73 | 0 | 51 |
| October | 187.18 | 89.90 | 97.28 | | 0 | 250 | 90 | 0 | 97 |
| November | 160.90 | 95.80 | 65.10 | | 0 | 250 | 96 | 0 | 65 |
| December | 68.22 | 84.40 | −16.18 | −16.00 | −16 | 234 | 84 | 0 | 0 |
| Total | 1803.43 | 1089.80 | | −318.00 | 0 | | 1048 | 42 | 755 |

*Acc. PL is the accumulated potential water loss and is defined as the cumulation of negative values of (R-PET). ΔST is the change in soil moisture. The amount by which PE and AE differ each month is the deficit (SMD). Surplus is the moisture surplus.

for the Tarkwa area using these procedures is 1035.18 mm year$^{-1}$.

Three of five major streams and one smaller stream, all in the study area, were gauged in order to estimate their surface run-off and base flows (Fig. 3). The computer program HYSEP (Sloto & Crouse 1996) was employed to separate the stream hydrographs. This program separates the hydrograph into base flow (associated with groundwater discharge) and the surface run-off components (associated with precipitation) (see Pettyjohn & Henning 1979). Total surface run-off for the whole study area for the year 2000 was estimated at 449 mm. Figure 4a–d shows the graph of monthly surface run-off and base flow for the four gauged catchments.

Soil moisture (SM) is held in the soil pores by capillary forces, and it is highly sensitive to changes in precipitation and evaporation, so that changes in soil moisture content occur throughout the year (Chidley 1981). It is generally accepted that the net change in water storage on an annual basis is zero, even though significant differences may occur from one year to the next (Shaw 1994).

Shallow basins under water or marshy conditions during the dry season are significant. Some of these are the result of recent distortions in the landscape due to surface mining while others are natural. Those due to surface mining are either abandoned pits created in the process of mining or else have become unintentionally

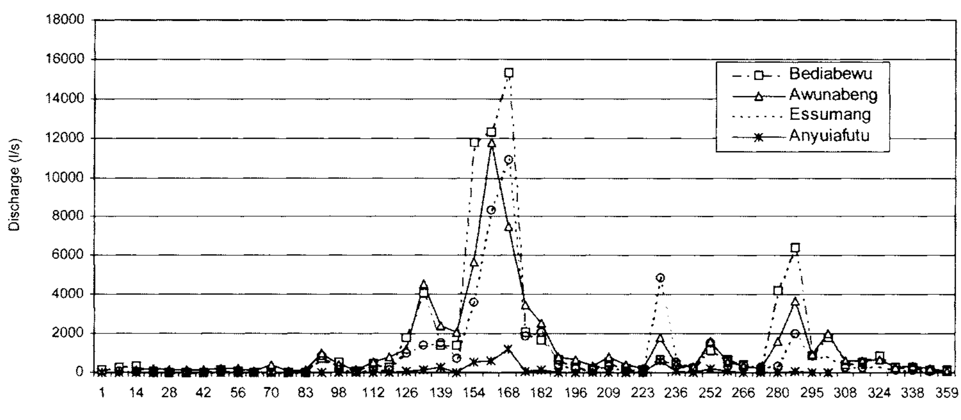


**Fig. 3.** Plot of discharge of four streams in the Tarkwa area.

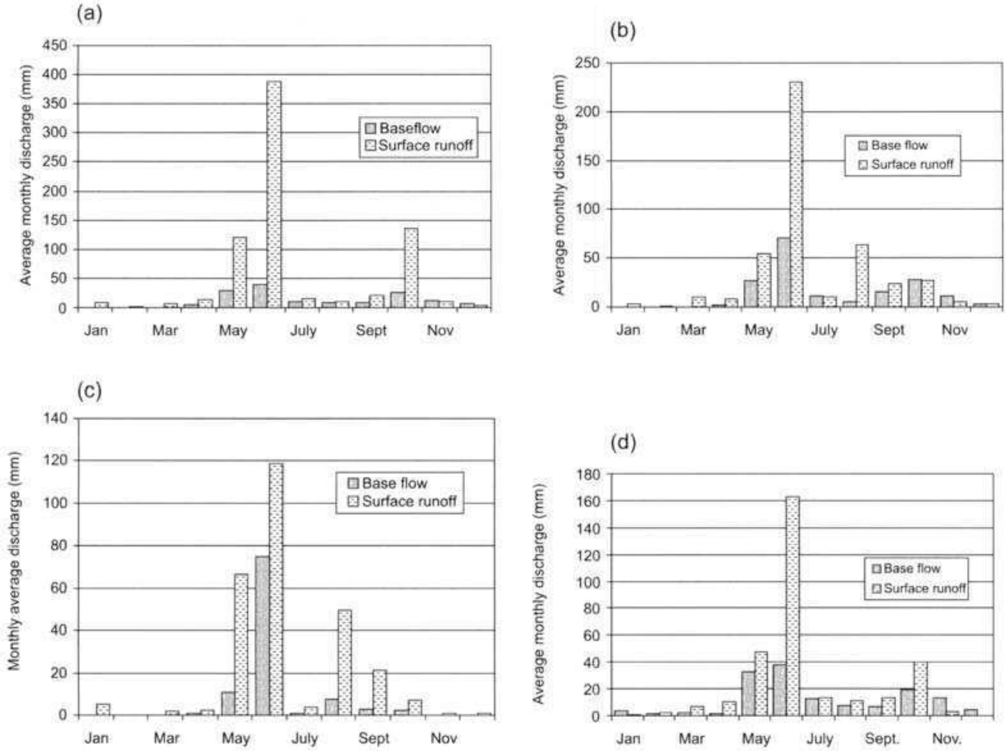


**Fig. 4.** (**a**) Graph of base flow and surface run-off of the Bediabewu catchment. (**b**) Graph of base flow and surface run-off of the Essuman catchment. (**c**) Graph of base flow and surface run-off of the Anyuiafutu catchment. (**d**) Graph of base flow and surface run-off of the Awunabeng catchment.

impounded by earth moved and tipped during mining. Water stored in this way would previously have formed part of local stream flow. The natural pools are surface manifestations of shallow regolith aquifers. The volume of water present in the depressions depends on precipitation and PE. The presence of water at the end of the dry season implies that PE is less than precipitation. A rough estimate of surface water storage (SWS) was made, i.e. about 20 mm year$^{-1}$.

Precipitation recharge (RE) from the above considerations is:

$$(1803.43 - 1035.18 - 449 - 20) \text{ mm year}^{-1}$$

$$= 299.25 \text{ mm year}^{-1}$$

i.e. about 17% of annual precipitation.

Stream hydrograph analysis, from which baseflow is separated, may also be used for the estimation of groundwater recharge (e.g. Meyboom 1961; Rorabough 1964; Bevans 1986; Rutledge 1992). The baseflow estimated from stream hydrographs (using HYSEP; Sloto & Crouse 1996) for the area amounted to 147 mm year$^{-1}$, i.e. about 8% of annual precipitation. For mountainous regions, Mau & Winter (1997) observe that baseflow estimates could provide lower estimates of recharge by about 25%. The moderate relief of the Tarkwa area suggests that, although baseflow is less than recharge, the difference is not as great as 25%. An important reason for the low value of recharge estimated using stream hydrographs compared to the water balance method is that surface mining has distorted the topography such that some of the rainfall is held in mined-out pits and other man-made impoundments, thereby reducing the volume of stream discharge (as noted above). In addition, all three surface mines in the district win gold from the Banket Series, which incidentally has the highest relief in the area. PSD and infiltration tests for the Banket soils revealed they possess the best characteristics for infiltration and provide many recharge areas. Thus, gold mining is inadvertently destroying recharge areas for groundwater. It might be argued that if, for example, recharge estimates were determined ahead of the three surface gold mines commencing production, a better understanding of the groundwater system may have been obtained.

Baseflow index (BFI) is a catchment characteristic and is defined as the percentage of run-off derived from groundwater (Anon. 1980). The BFI determined for four catchments reveal that their storage characteristics are low: Awunabeng (33%), Bediabewu (17%), Essumang (28%) and Anyuiafutu (27%) (Fig. 4a–d). (Stream names are also used to define the catchments in Fig. 2.) Run-off varies with the depth and texture of the soil, and physiography of the catchment (Dunne & Leopold 1998). Therefore, these values have both lithological and topographic significance. The Bediabewu flows more or less between the Banket and Tarkwa Phyllites before going over Kawere rocks. Both Banket and Tarkwa Phyllites form narrow ridges in the area and run-off is swift, resulting in a very low baseflow (Fig. 4a). The Essumang and Anyuiafutu streams, with virtually equal BFI values, are both largely confined to the Huni Sandstone, which has a very gentle topography and, therefore, these values probably reflect a strong soil influence (Fig. 4b & c). The Awunabeng catchment includes the Awunabeng and Ahumabru streams, and is underlain by Banket and Kawere rocks. The Banket terrain is large, and is drained by numerous tributaries of the Awunabeng stream. Despite the fact that mining has destroyed part of the recharge area of the Banket, the Awunabeng catchment still exhibited the highest BFI of the streams gauged (Fig. 4d), confirming the status of the Banket as the best yielding aquifer lithology in the Tarkwaian System.

### *Hydrogeochemistry*

The following water features were identified for investigation:

- Dry weather water samples were collected from all streams in the area at reach intervals of about 3 km. The dry weather (or 'low-flow') period allowed any spatial variations in in-coming groundwater chemistry to be identified (Pettyjohn 1985).
- Temporal variability in stream chemistry was investigated by means of periodic gauging and sampling. All the four streams were sampled over a 12 month period on a weekly basis for pH, Eh, temperature, bicarbonate alkalinity, Cl, Ca, $SO_4$ and $SiO_2$. The suite of major and some minor ions was analysed on a monthly basis.
- Springs and shallow wells give direct samples of groundwater, and boreholes provide samples of bedrock groundwater. (The average depth of the boreholes is 60 m.) During these studies, the lack of depth sampling equipment meant that 'bulk' groundwater samples were taken.

Table 4 summarizes results of the water properties investigated. Spatial and temporal variations are observed, and are attributed to mine water discharging into receiving streams and local community use of the water resources. Some of the important conclusions arrived at are as follows.

Different water types are observed for the different water regimes sampled. The hydrochemical facies identified with water samples from springs, shallow wells and hand-dug wells are dominated by Na–Cl–$HCO_3$–Cl. Streams which were perceived not to be directly or indirectly linked with mine areas are grouped as 'pristine'. Pristine water samples fall into two hydrochemical zones, namely, water with an intermediate chemical character, i.e. no cation–anion pair exceeds 50% and the fresh water facies. These water types are described by Na–Ca–Mg–$HCO_3$–$SO_4$ and Ca–Na–$HCO_3$ chemical facies, respectively.

Streams that have passed through and/or received mine water display Na–$SO_4$–$HCO_3$ and Na–Ca–$HCO_3$–$SO_4$ hydrochemical facies and are identified, respectively, with the Awunabeng and Bediabewu streams. Their water chemistry ranges from slightly saline to saline, with the highest Na sample of 373.6 mg $l^{-1}$ from a tributary of Bediabewu flowing from Teberebie Goldfields concession.

The Essuman stream exhibits a Ca–Na–$HCO_3$ hydrochemical facies, while Anyuiafutu shows equal concentrations of the major cations and almost equal concentrations of $SO_4$ and Cl, i.e. Na–Ca–Mg–Cl–$SO_4$. Low $HCO_3$ water concentration associated with Anyuiafutu is likely due to microbial respiration in the soil resulting in a low annual pH of 6.27. Considering that both Essuman and Anyiuafutu traverse the same lithological unit, the expectation is that both will exhibit broadly similar hydrochemical facies. Differences in their water types are attributed to both artificial and natural influences:

- most of the water in Essuman flows through mine territory and some tributaries receive mine water, this is not so with Anyuiafutu;
- Anyuiafutu, because of its small catchment may be receiving only near-surface

**Table 4.** *Summary of mean chemical characteristics of water in the Tarkwa area*

| | Dry weather water chemistry (spatial variation) | | | Stream gauged water chemistry (temporal variation) | | | |
|---|---|---|---|---|---|---|---|
| | Spring and borehole | Pristine areas | Mine water influenced areas | Awunabeng | Bediabewu | Essuman | Anyuiafutu |
| Facies type | Na–Ca–$HCO_3$–Cl | (a) Na–Ca–Mg–$HCO_3$–$SO_4$ (b) Ca–Na–$HCO_3$ | Na–$SO_4$–$HCO_3$ | Na–$SO_4$–$HCO_3$ | Na–Ca–$HCO_3$–$SO_4$ | Ca–Na–$HCO_3$ | Na–Ca–Mg–Cl–$SO_4$ |
| $HCO_3/SiO_2$ | 1.74 | 2.85 | 11.42 | 7.53/14.85 | 5.29/7.33 | 2.40/3.15 | 0.90/1.48 |
| pH | 5.76 | 6.48 | 7.74 | 7.09/7.68 | 7.04/7.46 | 6.75/6.77 | 6.27/6.58 |
| TDS | 141 | 110 | 536 | 192/348 | 162/227 | 93/97 | 93/116 |
| Remark | (i) Units of TDS is mg $l^{-1}$. | | | (ii) 7.53/14.85 refers to annual/low-flow figures. | | | |

groundwater, explaining its low pH and $HCO_3$ values. However, the pH of Essuman is higher than the average and may be due to mine water discharge.

Another important factor considered during this investigation is the ratio $HCO_3/SiO_2$. A terrain is likely to have undergone silicate weathering if the $HCO_3/SiO_2$ ratio is less than 5, and carbonate weathering if the ratio is greater than 10 (Hounslow 1995). Also, a terrain that has undergone silicate weathering exhibits a low total dissolved solids (TDS) value (in the range 100–200 mg $l^{-1}$), but in carbonate weathered areas, TDS is typically greater than 500 mg $l^{-1}$ (Hounslow 1995).

(a) Dry weather water analyses of perceived pristine areas show $HCO_3/SiO_2$ and TDS values of 2.85 and 110 mg $l^{-1}$, respectively. These values imply that the water in this area has participated in silicate weathering. However, streams passing through mining territory and those that receive mine water show $HCO_3/SiO_2$ ratios of 11.42 and TDS of 536 mg $l^{-1}$, suggestive of carbonate weathering. As the lithology in the mines is not different from that outside of them, this apparent inconsistency can only be due to a direct influence of mine water chemistry on receiving streams, probably by disposal of alkali-dosed waters and/or leakage of spent heap leach pad liquors (de-cyanidized) and/or tailings dam supernatants entering the groundwater system.

(b) The results of (a) apply to streams flowing through and receiving mine water from Ghana Australian Goldfields (GAG) and Teberebie Goldfields Limited concessions. The Essuman stream receives discharges of mine water from Goldfields Ghana Limited, but this stream does not show any significant major ion effect and its chemical facies plot in the fresh water domain, i.e. Ca–Na–$HCO_3$. It is possible to speculate that little or no leakage of unprocessed mine water is released into the Essuman. However, minor and trace ion chemical analysis should be performed on this and all the other streams to ascertain their complete water chemistry (local resources precluded this during the present study).

(c) Mean pH of water in the pristine areas is 6.48, but above 7.00 in streams carrying and receiving mine water from GAG and Teberebie Goldfields (it is 6.77 for Essuman). The higher than average pH values appear to be due to the use of lime in processing gold ore, which seep into streams.

A mean TDS value of $110\,mg\,l^{-1}$ for pristine areas suggests that the residence time of groundwater in the subsurface prior to their emergence in streams is brief, and hence source concentrations are low. In addition, the low TDS value also suggests a region dominated by local-scale flow systems. No change in anionic composition from recharge to discharge points was observed (for streams in pristine areas), which further corroborates small-scale, localized water–rock interactions.

This short study of the major ion chemistry of water from the Tarkwa gold mining district has shown that mining has affected stream water. A long-term monitoring programme undertaken with an expanded analysis including trace and other metal ions would enable the full impact of mining to be stated.

## Using hydrogeological data to assess possible environmental impacts

If all the issues raised are pursued during the exploration and planning phases of mine development, hydrogeological assessment for possible environmental impacts becomes relatively simple and may be conducted by:

- using the hydrogeological model in the EIA report as a baseline for assessment;
- making regular updates to the hydrogeological database during the course of mine operation and production. More monitoring boreholes may then be in operation and can be sampled and gauged for water quality and groundwater head studies, respectively;
- a low-flow water quality and discharge survey conducted in the mine concession leading to hydrogeochemical interpretation to support the baseline report;
- field monitoring of identified poor discharges or problem areas;
- hydrogeochemical studies for possible amelioration.

A summary of the above recommendations is presented in Table 5 and as a flow chart in Fig. 5.

## Discussion and conclusion

This study has outlined the importance of early gathering of hydrogeological information during the mineral exploration phase for new mines. It has identified which datasets should be considered and how they can be obtained at relatively low cost, thus easing the data requirements during hydrogeological assessment for environmental impact assessment purposes later in the development of the mine prospect. All these data are collected one way or the other during groundwater studies for other purposes. In the case considered, i.e. during mineral exploration, the problem is that emphasis is almost entirely placed on "what grade and ore body magnitude are we looking at?'. Therefore, the people involved are either not aware that hydrogeological data are available or, if they are aware, the value of data collection is not realized and it is seen as a waste of time and money.

It might also be argued that at an early stage when the geological resource is not yet fully a reserve, it would be a waste of financial resources and time to collect data that will not directly improve the reserve estimation. However, spending at this time on good quality data collection (which should mean employment of a qualified hydrogeologist) could offset:

- the amount to be spent for employing a hydrogeologist during the preparation of that part of the EIA report. This also means that a more accurate report is produced;
- the cost of hiring a consulting hydrogeologist later on when a hydrogeological problem arises at the mine. This is because the solution can be obtained by analysing the detailed report prepared earlier, or the problem will not arise anyway because the information available has been utilized, preventing its occurrence;
- future problems (environmental, monetary or both) due to ill-conceived planning and construction;
- some of the information is used as input to dewatering design and water management.

It is now the practice to introduce environmental studies into many academic programmes. Therefore, as a permanent solution in the future, and to cut costs, it is suggested that relevant programmes for undergraduates and graduates in the field of earth sciences should incorporate fundamentals of hydrogeology into their curriculum. This should familiarize geoscientists with groundwater hydraulics and the groundwater cycle. In addition to the above, an understanding of hydrogeological soil and rock sampling and logging procedures are essential during lithological core logging. This information can be

**Table 5.** *The recommended phases of mineral exploration most appropriate for hydrogeological data collection and the expected outcomes*

| Hydrogeological aspect | Mineral exploration phase | Hydrogeological outcomes |
|---|---|---|
| Physiography<br>• Relief<br>• Drainage<br>• Land use<br>• Vegetation | Desk studies and during regional reconnaissance. As more detailed surveys are executed, larger-scale maps are obtained. | Maps at a scale of 1:20 000 – 1:5000 are prepared during coventional surveying. Recharge and discharge areas are determined. Preliminary groundwater flow directions and groundwater boundaries are conceptualized. |
| Pedology<br>• Soil logging and sampling<br>• PSD<br>• Moisture content, bulk and particle densities<br>• Infiltration tests | Exploratory, outline and evaluation drilling phases. Pitting and trenching are useful if weathering profile is thin. | Soil thickness map constructed. Soil texture, sorting, porosity and changes in lithology determined. Results are also useful during assessment of groundwater recharge. |
| Geology<br>• Structural<br>• Lithological<br>• Stratigraphic<br>• Thin section and microscopy<br>• Probe permeameter | From the desk study phase through to 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. Three-dimensional (3-D) conceptual hydrogeological model from above information coupled with surface geological mapping and core logging. |
| Hydrology<br>• Meteorological station installed for daily recording<br>• Daily gauging of major streams<br>• Piezometers installed | Some information is available at the desk study phase, but install a meteorological station, install piezometers and start stream gauging – all during evaluation drilling. | Evaporation and evapotranspiration estimation. Use information from soil survey with rainfall, run-off and evapotranspiration data to estimate recharge. Use stream hydrograph to also estimate recharge. Gauging and sampling of piezometers to determine groundwater movement and changes in groundwater quality. |
| Hydrochemistry<br>• Low-flow stream surveys | Regional reconnaissance stream surveys but mainly during feasibility studies. | Hydrochemistry of the area determined. Weekly or monthly hydrochemical sampling of major stream(s) to determine temporal changes in chemistry of groundwater. |

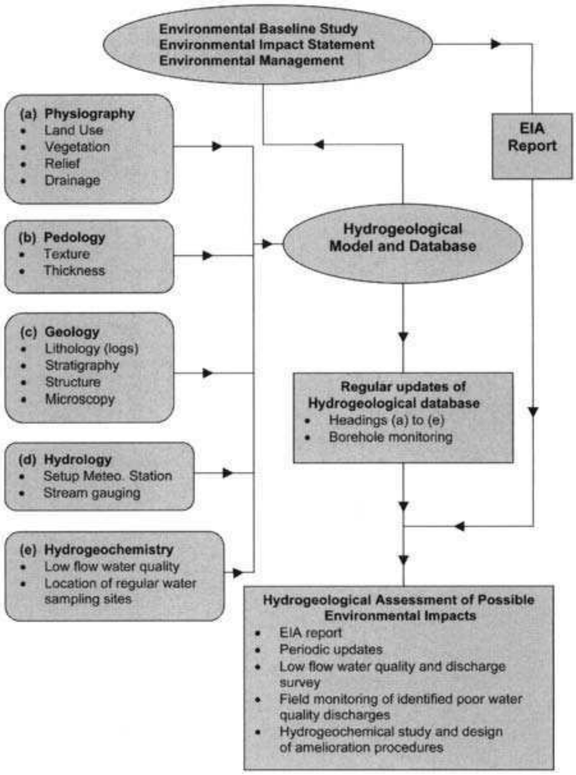


**Fig. 5.** Proposed flow chart of the hydrogeological framework for assessing environmental impacts of large-scale gold mines.

gathered at the same time and consciously built into a database for later interpretation.

The fact that hydrogeological data are available at such an early stage means that it can be included in the EIA report when presented to the EPA for evaluation before a lease for mining is granted. Interpretation of these data could be a useful input to dewatering design and groundwater management. Any water borehole drilled by a mine should be seen as an opportunity for carrying out test pumping so that aquifer properties can be determined. Piezometers installed for water monitoring need to be kept in working order and measurements taken regularly for valuable data to be available for later assessment.

The onus is, therefore, on the regulation agency to make it a policy for all prospective mines to include vital hydrogeological information in their EIAs to enhance knowledge of the hydrogeology of the area in question. The argument for this procedure is that once the decision is made for detailed drilling to commence, it implicitly means that the prospect is of interest and that it also warrants a hydrogeological assessment. The hydrogeological information can be integrated with the EIA document. This actually eliminates the tendency of looking at time as a constraint and, therefore, precludes a half-hearted (or absent) hydrogeological section in the report. This procedure may also be employed in areas where 'incomplete' EIA reports are a common occurrence.

## References

ACHEAMPONG, P.K. 1986. Evaluation of potential evapotranspiration methods for Ghana. *GeoJournal*, **12**, 409–415.

AMEGBEY, N. 1996. *West Coast Explosives (Ltd) EIA on the Bulk Emulsion Explosive Plant at Nsuta-Wassaw.* West Coast Explosive Ltd., Tarkwa, Ghana.

ANON. 1980. *Low Flow studies.* Institute of Hydrology, Wallingford, Research Report, **1**.

ANON. 1994. In: LAING, E. *Ghana Environmental Action Plan (Vol. 2), Technical Background Papers by the Six Working Groups.* Environmental Protection Council (EPC), Ghana.

ANON. 1997. *Drilling of Production Boreholes and Monitor Boreholes at the Tarkwa Mine.* Internal SRK Report, **229708**.

APPELO, C.A.J. & POSTMA, D. 1993. *Geochemistry, Goundwater and Pollution*. A.A. Balkema, Rotterdam.

BEVANS, H.E. 1986. Estimating stream–aquifer interactions in coal areas of eastern Kansas by using streamflow records. In: SUBITZKY, S. (ed.) *Selected Papers in the Hydrologic Sciences*, US Geological Survey, Water Supply Paper. Vol. **2290**, 51–64.

BOWELL, R.J. 2002. The hydrogeochemical dynamics of mine pit lakes. In: YOUNGER, P.L. & ROBINS, N.S. (eds) *Mine Water Hydrologogy and Geochemistry*; Special Publications. Geological Society, London Vol. **198**, 59–185.

CHIDLEY, T.R.E. 1981. Assessment of groundwater recharge. In: LLOYD, J.W. (ed.) *Case Studies in Ground Water Resources Evaluation*. Butler & Tanner, London, 133–149.

DAVIS, S.N & DEWEIST, R.J.M. 1991. *Hydrogeology*, reprint edn. Krieger, Florida.

DICKSON, K.B. & BENNEH, G. 1988. *A New Geography of Ghana*. Longman, London.

DINGMAN, S.L. 1994. *Physical Hydrology*. Prentice-Hall, Englewood Cliffs, New Jersey.

DUNNE, T. & LEOPOLD, L.B. 1998. *Water in Environmental Planning*. W.H. Freeman, New York.

DZIGBODI-ADZIMAH, K. 1996. Environmental concerns of Ghana's gold booms: past present and future. *Ghana Mining Journal*, **2**, 21–26.

EDMUNDS, W.M. 1981. Hydrogeochemical investigations. In: LLOYD, J.W. (ed.) *Case Studies in Ground Water Resources Evaluation*. Butler & Tanner, London, 87–111.

EIJPE, R. & WEBER, K.J. 1971. Mini permeameter for consolidated rock and unconsolidated sand. *American Association of Petroleum Geologists Bulletin*, **55**, 307.

EISENLOHR, B.N. 1992. Conflicting evidence on the timing of mesothermal and paleoplacer gold mineralisation in Early Proterozoic rocks from southwest Ghana, West Africa. *Mineralium Deposita*, **27**, 23–29.

Fetter, C.W. 1994. *Applied Hydrogeology*. Prentice-Hall, Upper Saddle River, New Jersey.

Grindley, J. 1970. *Estimation and Mapping of Evaporation*. IASH publication No. 92. *World Water Balance*, **1**, 200–213.

HEAD, K.H. *Manual of Soil laboratory testing. Soil Classification and Compaction Tests*; Pentech Press, London, Volume 1.

HEDIN, R.S., NAIRN, R.W. & KLEINMANN, R.L.P. 1994. *Passive Treatment of Coal Mine Drainage*, US Bureau of Mines Information Circular, Vol. **9389**, 35.

HEM, J.D. *Study and Interpretation of the Chemical Characteristics of Natural Water*, United States Geological Survey, Water Supply Paper, Vol. **2254**, 263.

HIRDES, W. & NUNOO, B. 1994. The Proterozoic paleoplacers at Tarkwa Gold Mine, SW Ghana: sedimentology, mineralogy and precise age dating of the main reef and west reef, and bearing of the investigations on source area aspects. *BGR Geol Jb*, **D100**, 247–311.

HOUNSLOW, A.W. 1985. Strategy for subsurface characterisation research. In: WARD, C.H., GIGER, W. & MCCARTY, P.L. (eds) *Ground Water Quality*. John Wiley, New York, 356–369.

HOUNSLOW, A.W. *Water Quality Data: Analysis and Interpretation* CRC Lewis, New York.

JUNNER, N.R., HIRST, T. & SERVICE, H. 1942. *The Tarkwa Goldfield*, Gold Coast Geological Survey, Memoir, **6**, 75.

KESSE, G.O. *The Mineral and Rock Resources of Ghana*; Balkema, Rotterdam.

KOLM, K.E. 1996. Conceptualization and characterization of ground water systems using Geographic Information Systems. Engineering. *Geology*, **42**, 111–118.

KUMA, J.S. & YOUNGER, P.L. 2001. Pedological Characteristics Related to Ground Water Occurrence in the Tarkwa Area, Ghana. *Journal of African Earth Sciences*, **33**, 363–376.

LERNER, D.N. 1990. Techniques (Part III). In: LERNER, D.N., ISSAR, A.S. & SIMMERS, I. (eds) *Groundwater Recharge; A Guide to Understanding and Estimating Natural Recharge*, International Association of Hydrogeologists. Vol. **8**, 99–228.

MAU, D.P. & WINTER, T.C. 1997. Estimating ground water recharge from streamflow hydrographs for a small mountain watershed in a temperate humid climate, New Hampshire, USA. *Ground Water*, **35**, 291–304.

MEYBOOM, P. 1961. Estimating groundwater recharge from stream hydrographs. *Journal of Geophysical Research*, **66**, 1203–1214.

PETTYJOHN, W.A. 1985. Regional approach to ground water investigations. In: WARD, C.H., GIGER, W. & MCCARTY, P.L. (eds) *Ground Water Quality*. John Wiley, New York, 402–417.

PETTYJOHN, W.A. & HENNING, R. 1979. *Preliminary Estimate of Ground Water Recharge Rates Related Streamflow and Water Quality in Ohio*. Water Resources Center, Ohio State University, Project Completion Report, Vol. **552**, 333.

RORABAUGH, M.I. 1964. Estimating changes in bank storage and ground water contribution to streamflow. *International Association of Science & Hydrology, Publication*, **63**, 432–441.

RUTLEDGE, A.T. 1992. Methods of using streamflow records for estimating total and effective recharge in the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic provinces. In: HOTCHKISS, W.R. & JOHNSON, A.I. (eds) *Regional Aquifer Systems of the United States, Aquifers of the Southern and Eastern States*, American Water Research Association Monograph Series. Vol. **17**, 59–73.

SHARP, J.M. & MCBRIDE, E.F. 1989. Sedimentary petrology – a guide to paleohydrogeologic analyses, example of sandstones from the northwest Gulf of Mexico. *Journal of Hydrology*, **108**, 367–386.

SHAW, E.M. *Hydrology in Practice*, Chapman and Hall, London.

SHEVENELL, L. 2000. Analytical method for predicting filling rates of mining pit lakes: example from the Getchell Mine, Nevada. *Mining Engineering*, **52**, 53–60.

SLOTO, R.A. & CROUSE, M.Y. 1996. *HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis*, United States Geological Survey, Water Resources Investigations Report, Vol. **96–4040**, 46.

STONE, W.J. *Hydrogeology in Practice. A Guide to Characterizing Ground-water Systems*, Prentice-Hall, Englewood Cliffs, New Jersey.

THORNTHWAITE, C.W. & MATHER, J.R. 1957. *Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance publications in Climatology*, (3) Centerton, New Jersey Vol. 5, 185–311.

WHITELAW, O.A.L. 1929. *Geological and Mining Features of the Tarkwa–Aboso Goldfield*, Gold Coast Geological Survey, Memoir, Vol. 1, 46.

WINTER, T.C., HARVEY, J.W., FRANKE, O.L. & ALLEY, W.M. 1998. *Ground Water and Surface Water: A Single Resource*, United States Geological Survey, Circular, Vol. 1139, 79.

WOODALL, R. 1984. Success in mineral exploration: a matter of confidence. *Geoscience Canada*, **11**, 41–46.

YOUNGER, P.L. 1992. The hydrogeological use of thin sections: inexpensive estimates of groundwater flow and transport parameters. *Quarterly Journal of Engineering Geology*, **25**, 159–164.

YOUNGER, P.L. 1993. Simple generalized methods for estimating aquifer storage parameters. *Quarterly Journal of Engineering Geology*, **26**, 127–135.

YOUNGER, P.L. 2001. Mine water pollution in Scotland; nature, extent and preventive strategies. *Science of the Total Environment*, **265**, 309–326.

YOUNGER, P.L. & ADAMS, R. 1999. *Predicting Mine Water Rebound*; Environment Agency, R&D Technical Report, **W179**.

YOUNGER, P.L., BANWART, S.A. & HEDIN, R.S. 2002. *Mine Water: Hydrology, Pollution, Remediation*. Kluwer, Dordrecht.