HYDROGEOLOGICAL CHARACTERISATION AND WATER-SUPPLY POTENTIAL OF BASEMENT AQUIFERS IN TROPICAL AFRICA[1]

by

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ABSTRACT: Crystalline basement rocks, with a mantle of weathered alteration products, occur beneath very extensive areas of tropical Africa. Low-productivity aquifers are widely, but rather unpredictably, present in this formation. They yield small water supplies vital to the rural population for domestic purposes and for livestock watering. On a more localised basis, a potential may exist to develop larger supplies that are adequate for small towns or for small-scale irrigation. This paper reviews advances in the understanding of this extensive hydrogeological system, resulting from British research and experience since 1980.

RÉSUMÉ: Les roches cristallines du socle, avec leurs altérites, occupent de très grandes surfaces en Afrique tropicale. Des aquifères à faible productivité sont fréquemment présents dans ces formations, mais de façon plutôt imprévisible. Ils alimentent de petites adductions d'eau, d'intérêt vital pour la population rurale, pour les usages domestiques et pour les troupeaux. De façon plus localisée, il peut exister des possibilités de captages plus importants, convenant à de petites villes ou pour des réseaux d'irrigation peu étendus. Cet article passe en revue les progrès dans la connaissance de ce système hydrogéologique étendu, sur la base des recherches et de l'expérience britanniques depuis 1985.

RESUMEN: Las rocas cristalinas basales aparecen cubiertas por una capa de productos de alteración bajo áreas muy extensas del África Tropical. Acuíferos de baja productividad se encuentran presentes en esta formación de forma extensa, aunque de modo impredecible. Estos suministran pequeñas cantidades de agua que son vitales para el abastecimiento humano y animal de la población rural. De modo más localizado, existe potencial para desarrollar suministros mayores, adecuados para pequeñas ciudades o para regadío a pequeña escala. Este artículo revisa los avances en el conocimiento de este extenso sistema hidrogeológico como resultado de la investigación y la experiencia británicas acumuladas desde 1985.

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[1]Originally presented as invited paper to IAH XXIV Congress in Oslo, Norway, 2 July 1993

INTRODUCTION

The aim of this paper is to review advances in understanding of the hydrogeological character and water-supply potential of basement aquifers in the humid and arid regions of tropical Africa. This review is based mainly on published British work and draws primarily on the results of major groundwater research and rural water-supply programmes undertaken by British hydrogeologists in Malawi, Zimbabwe, Botswana, and Nigeria during the 1980's.

Geological and Geomorphological Setting

The crystalline basement of the African continent is formed by major suites of mainly Pre-Cambrian rocks, more than 550 Ma in age. The predominant lithological types are granitic gneisses and lower-grade metamorphic rocks derived from volcanic and sedimentary deposits. Amongst the latter, greenstone belts of ultrabasic volcanic origin are especially prominent in some areas. The basement also includes some large areas of more recent anorogenic intrusive rocks (Key, 1992).

The ancient land surface has been exposed to prolonged weathering, which has resulted in the formation of a mantle of alteration products, normally more than 10 m thick. This regolith includes both the residual soil and the saprolite (figs. 1 and 2). The latter is derived from in-situ weathering and has become largely disaggregated. The residual soil has developed from the underlying saprolite by further dissolution and leaching, combined with other chemical, physical, and biological processes. Over very long periods, infiltrating acidic rainfall has reacted with alkaline minerals, leaching the more soluble and mobile components and reprecipitating less mobile minerals, with the formation of kaolinite and Fe-Al oxides.

In the extreme, kaolinite dissolution also occurs and only quartz sand is left. The weathering process has spanned numerous climatic and tectonic cycles, which have determined the relative levels of land surface and water table and thus controlled the rate and depth of weathering. These cycles have also controlled the frequency and scale of surface runoff, and thus soil erosion and inselberg formation (fig. 1).

The relative depth and degree of weathering also depends on the mineral grain size of the crystalline rocks, their intensity of fracturing, and the relative proportions of Fe-Mg minerals. The transition to unweathered bedrock is generally gradual, and occurs over a few metres, with saprock (remnants of unweathered bedrock set in an altered matrix) as the intermediate condition (fig. 1).

Differing hypotheses have been proposed concerning the origin of the African land surface. It appears likely (McFarlane, 1992) that slow subsidence, resulting from the leaching and eventual collapse of the saprolite, has dominated over direct erosion by surface runoff, under most climatic conditions. These processes are not exclusive, however, and during periods of drier climate and sparser vegetative cover, direct soil erosion by surface runoff occurs. Colluvial redistribution of residual materials downslope has occurred, and land surface depressions (known variously as dambos, vleis, fadamas, and bas-fonds) have been formed.

Occurrence and Significance of Basement Aquifers

Certain zones within the regolith and the underlying bedrock have sufficient permeability to yield small water supplies to appropriately designed and constructed wells on a widespread basis. Hydrogeological investigations for village water supplies in Malawi (Chilton and Smith-Carington, 1984) indicated that the basal part of the regolith, together with the deeply-weathered bedrock (saprock), are likely to provide most of the yield to successful boreholes. Further, the presence of a relatively thick saturated regolith in the more humid regions is of critical significance in terms of aquifer storage and available drawdown. A preliminary conceptual model of the aquifer system was developed from this work by Foster (1984). This work drew attention to potentially important differences in maximum well yield and the sustainability and quality of supply, related to the position of the water table, which was expected to vary with both geomorphological position and climatic type (fig. 2).

These low-productivity aquifers are of major importance in tropical Africa (Wright, 1992), because:

(1) They have widespread occurrence in areas of relatively high rural population density.

(2) Their groundwater is sufficiently shallow to allow exploitation at relatively low cost and with simple technology, appropriate to the low level of economic development.

(3) Surface-water resources are generally unreliable, with no readily available or economically viable source of water of adequate quality.

In order to focus on practical issues related to water-supply development, this review is structured in three sections that deal with:

(1) The extent to which hydrogeological parameters can be shown to influence the success of village-well

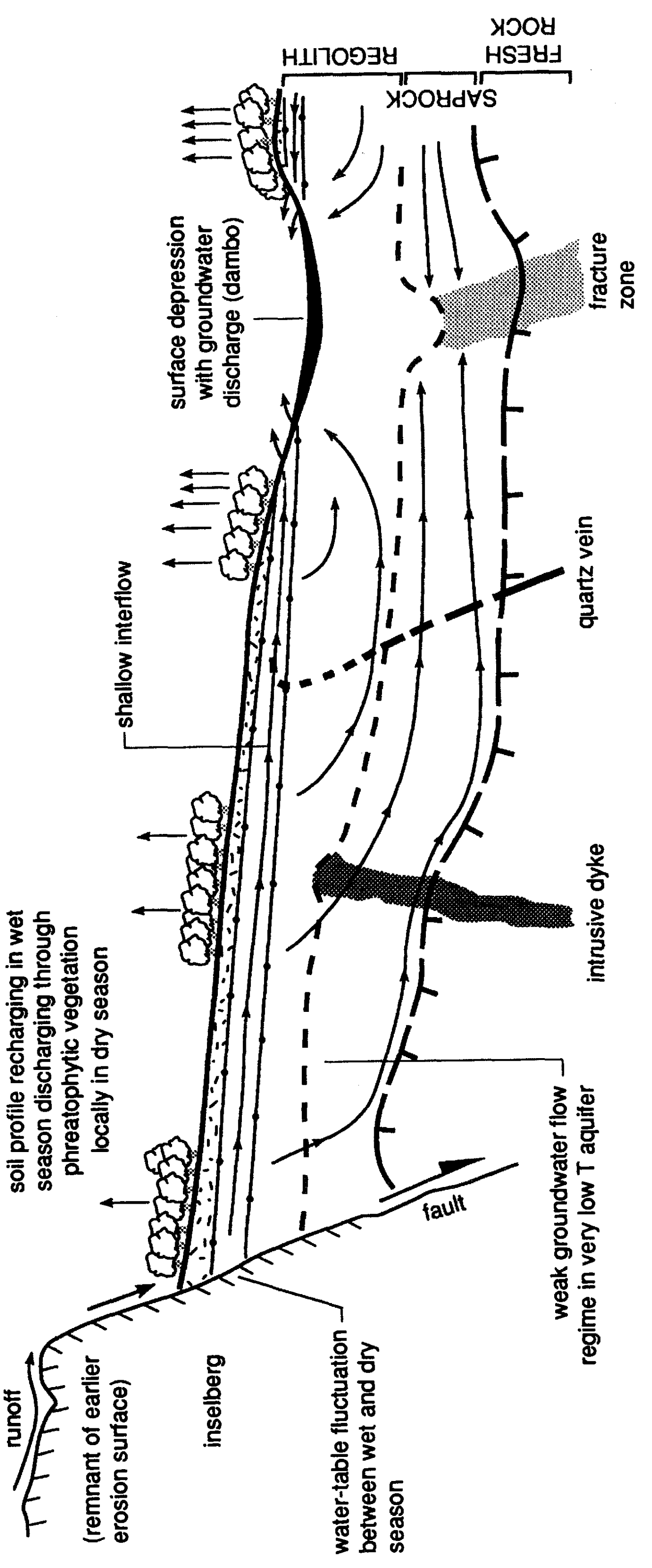

Figure 1. Generalised section of the groundwater flow system in the weathered crystalline-basement aquifer in Malawi.

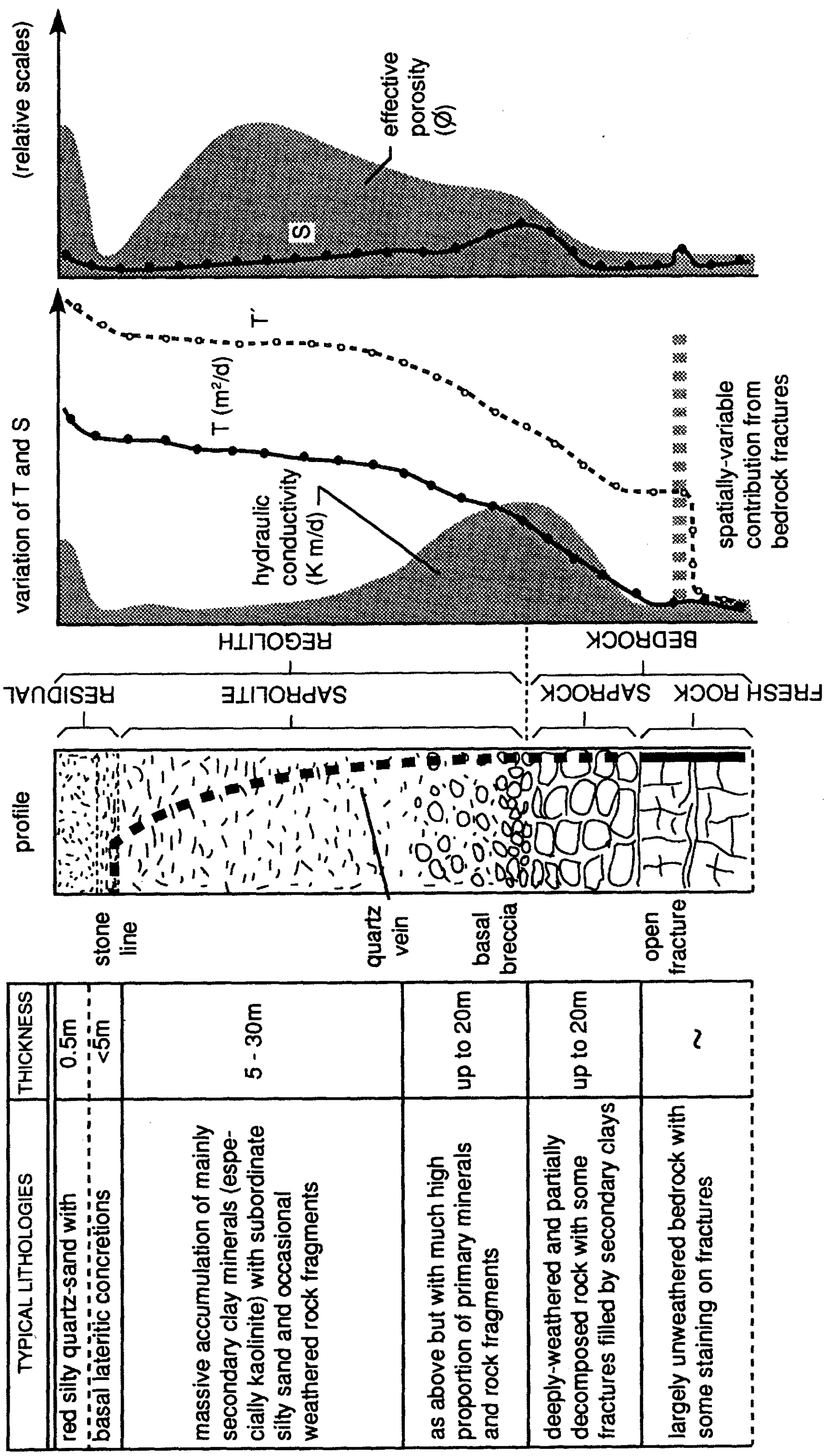

Figure 2. Conceptual hydrogeological model of the weathered crystalline-basement aquifer in Africa (modified from Chilton and Smith-Carington, 1984; and Foster, 1984. With data from Wright, 1992; Barker et al., 1992; and Hazell et al., 1992).

siting, where the requirement is for individual boreholes (or dug wells) with sufficient yield to support hand-pump or windlass-bucket abstraction, normally taken as 0.2 l/s.

(2) The constraints on development of larger water supplies for small towns or small-scale irrigation through boreholes with motorised pumping plants, requiring a minimum yield of 1 l/s.

(3) The considerable variation of groundwater quality and the potential problems this presents for domestic water supply or livestock watering.

Two aspects of groundwater exploitation and development in basement aquifers receive only limited discussion because of space constraints:

(1) Surface geophysical surveying techniques for well siting.

(2) Well-design factors and construction methods.

It is, however, recognised that improving the efficiency of water-supply development and achieving the full potential of this low-productivity aquifer often depends on the use of appropriate geophysical exploration techniques and on relating well design closely to hydrogeological conditions.

In particular, the main subdivisions of the weathered basement profile (fig. 2) have distinctive specific electrical resistivities: saturated regolith, 100-300 ohm-m; saprock, 300-3,000 ohm-m; and fresh bedrock, greater than 3,000 ohm-m. However, the shallow unsaturated surface layers exhibit wide variations, from less than 50 ohm-m (dambo clays) to more than 1,000 ohm-m (lateritic concretions).

CONTROLS ON SUCCESS OF VILLAGE-WELL SITING

Stratigraphic Position and Potential of Productive Zones

The conceptual model that was based on early investigations (Foster, 1984), with the most productive zones at the base of the regolith and the top of the weathered bedrock (saprock), has been confirmed with relatively minor modifications (fig. 2) by workers in various countries (Jones, 1985; Acworth, 1987; Wright, 1992; Barker et al., 1992; Hazell et al., 1992). Further quantitative evidence has been collected in the form of incremental borehole yields with depth and permeability distributions from Zimbabwe (fig. 3) and from Malawi (table 1), respectively.

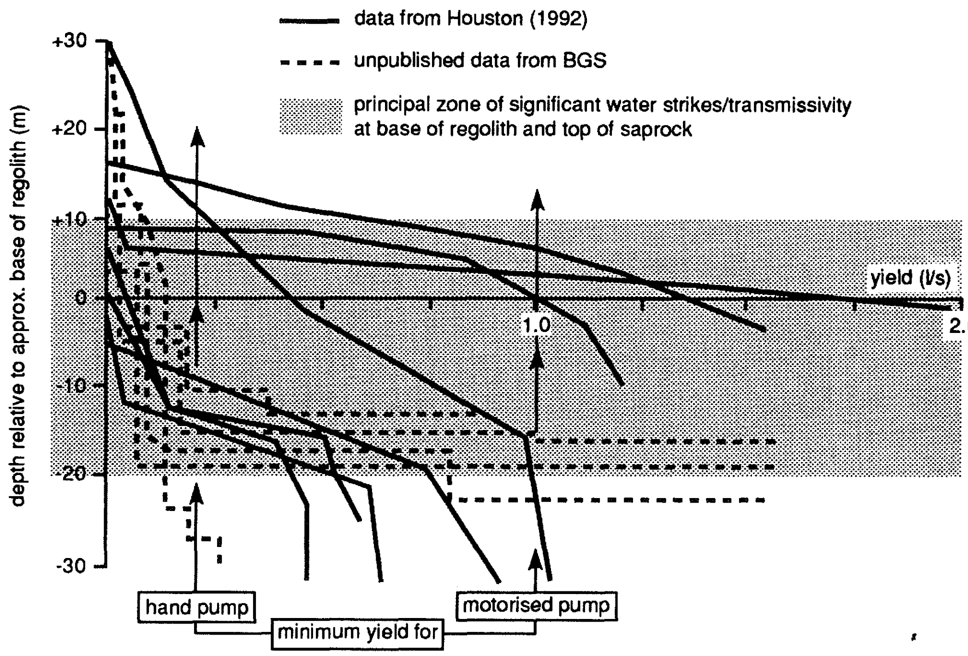

Figure 3. Relation between test yield and depth relative to base of regolith, selected small-diameter boreholes in the weathered crystalline basement of Masivingo Province, Zimbabwe.

Table 1. Results of hydraulic testing of sections of crystalline basement at Chimimbe, Malawi (derived from McFarlane, 1992).

Lithologic unit	Number of tests	Sections tested, using two methods		Horizontal component of hydraulic conductivity, m/d	
		Number	Thickness, m	Minimum	Maximum
Residual subsoil	2	2	4	0.0001	0.005
Saprolite	12	6	8	.04	.4
Saprock	6	3	4	.08	.7

Enough pumping tests have now been conducted to confirm that the aquifer system generally has very low overall transmissivity (1-5 m^2/d), with occasional values as much as an order of magnitude lower and higher than the end values in this range (table 2). Such low values imply that, although basement aquifers have an essentially regular occurrence in any given area, they are likely to exhibit significant local variations in yield and response to abstraction. The low values are due to the poor connectivity of bedrock fractures and low permeability of parts of the saturated regolith. These variations reduce the success rate for construction of low-yielding boreholes and the consistency of specific-capacity data (fig. 4).

Spatial and Temporal Variations of Water Levels

In higher-rainfall areas, water levels generally occur within the regolith (fig. 1), whereas in the driest areas, the water table may be below the regolith for all or most of the year. Seasonal fluctuations in potentiometric level are generally 1-5 m. Continuous records from several sites in Malawi show a rise in water levels 2-3 months after the beginning of the rainy season to peak levels at the end of the rainy season (in March-April), followed by a steady recession through the dry season.

In general, water levels reflect in subdued fashion the surface topography, implying aquifer recharge on the broad interfluves and groundwater discharge in surface depressions. Detailed investigations of two sections in Malawi provided little evidence of perched groundwater bodies, and variations in potentiometric head with depth were small. The vertical component of head was downward from the centre of the interfluve as far as the dambo edge, and predominantly upward within the dambo. These observations support the flow regime shown in figure 1.

A component of infiltration moves quickly down from the interfluve at shallow depth within the residual soil in the rainy season, and a deeper, slower component of flow moves through the saprolite. This flow pattern may have important implications for groundwater quality, because the shallow flow component is often characterised by low mineralisation and the deeper component is more strongly mineralised (McFarlane, 1992).

Hydrogeological Properties of Regolith

Subdivision of the regolith into distinct units with somewhat different hydraulic properties and hydrogeological significance is now possible as a result of recent research (McFarlane, 1992; Wright, 1992).

The residual soil is formed by the collapse of the underlying saprolite, due to intensive leaching and bioturbation. This soil includes tropical oxysols, characterised by kaolinite, quartz, and oxidised Fe minerals, and is underlain locally by laterite beds or stone lines (fig. 2). This layer, which is almost always in the vadose zone, is mainly of significance in relation to recharge. Whilst the relatively sandy surface deposits on the interfluves have moderately high infiltration capacity, this capacity reduces rapidly with depth, although pathways for preferential flow are likely to be present and active.

The saprolite itself may be subdivided into an upper and lower layer related to intensity of weathering. The upper layer has a high proportion of the secondary clay mineral kaolinite, and the lower has a greater abundance of primary minerals and intermediate weathering products (fig. 2). The boundary with the underlying saprock is relatively sharp against coarse-grained massive crystalline rocks or more transitional in finer-grained or banded rocks. A basal brecciated zone is often present with rock fragmentation but with little mineralogical change, and this zone is often misidentified as saprock in borehole logs.

The relationship of the weathering process to permeability development is complex. Dissolution of minerals and leaching must tend to increase porosity, permeability, and specific yield, but the decomposition of secondary clay minerals could tend to reverse this process (Wright, 1992). In theory at least, bedrock type might be expected to exert a major control, with coarser-grained,

Table 2. Results of hydraulic tests on production boreholes in regolith, Malawi and Zimbabwe.

Area	Number of boreholes tested	Transmissivity[1], m^2/d		Saturated thickness of regolith[2], m
		Mean	Range	
Malawi[3]				
Livulezi	**134**	**5.5**	**1-20**	**17.6**
Dowa West	**81**	**2.1**	**0.2-5**	**16.1**
Zimbabwe				
Masvingo (a)[4]	**64**	**5.2**	**1-60**	**13.3**
Masvingo (b)[4]	**27**	**3.4**	**2-10**	**22.3**
Various sites[5]	**6**	**4.6**	**0.2-40**	**12.9**

[1] Geometric mean; reduces bias associated with occasional exceptionally high values (greater than 20 m^2/d)
[2] Includes any productive zones in the saprolite-saprock transition
[3] After Chilton and Smith-Carington (1984)
[4] After Houston and Lewis (1988); refers to regolith derived from intrusive granite (a) and granitic gneiss (b)
[5] After Wright (1992)

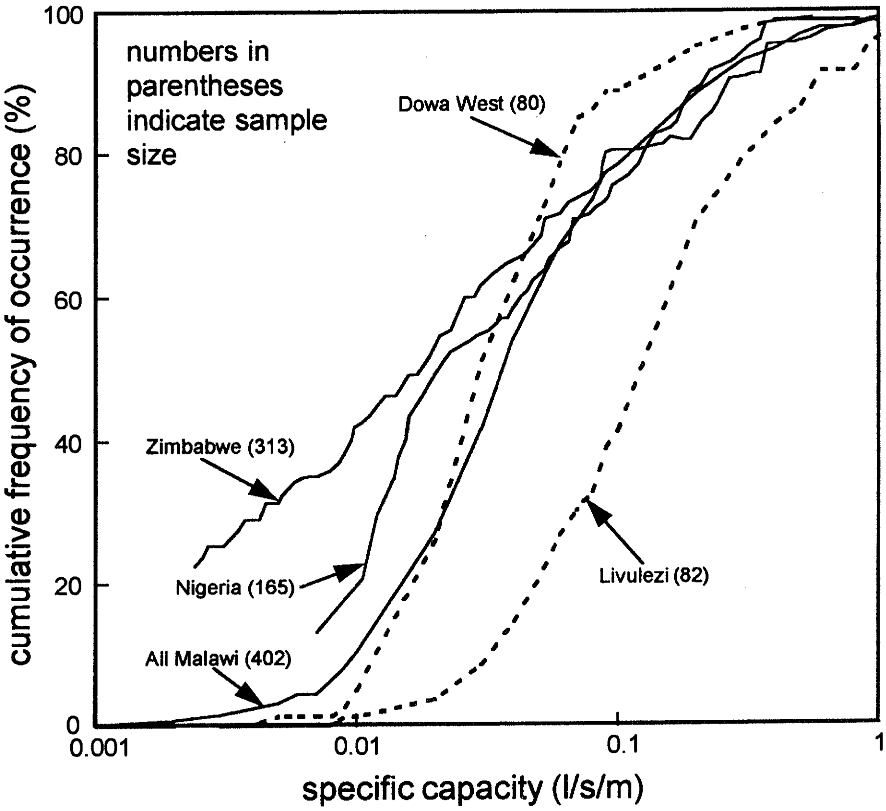

Figure 4. Cumulative distributions of specific capacities of small-diameter boreholes in weathered crystalline-basement aquifers in Zimbabwe, Nigeria, and Malawi, including distributions for boreholes in two districts in Malawi.

quartz-rich, crystalline rocks developing a higher-permeability regolith. However, more schistose metamorphic rocks, and also zones of tectonic disturbance, are likely to promote deeper weathering and a thicker regolith, although the presence of abundant Fe-Mg minerals (such as biotite), which readily weather to secondary products, is likely to further reduce permeability.

Only limited data exist on regolith permeability from discrete tests (table 1). Values probably do not average more than 0.1 m/d, and thus a saturated thickness substantially greater than 10 m would be needed for the regolith alone to act as a useful aquifer for village water supplies. Such conditions are generally fulfilled in the more humid regions, which have a shallow water table, especially on the African erosion surface where the deepest uniform weathering has occurred. In more arid regions with deeper water tables and/or in areas below this erosion surface, the saturated regolith is generally too thin to provide, by itself, sufficient yield for hand-pump boreholes. In the most arid regions, such regolith as is present is commonly entirely above the water table.

Nevertheless, the saturated thickness of the regolith is a major controlling factor on the success rate of village water-supply boreholes. This productivity does not arise primarily from its transmissivity, but more importantly because it provides the dominant element of aquifer storage and determines the available drawdown to the most productive aquifer zone.

The relative positions of water table and regolith base also effectively dictate the approach to groundwater development. Shallow water levels and substantial thicknesses of saturated regolith may permit simple approaches to borehole siting, with abstraction either from dug wells, shallow screened boreholes, or collector wells (fig. 5). Deeper water levels with thin saturated regolith necessitates a more costly and complex approach to borehole siting, aimed at locating structures in the largely unweathered bedrock, and the drilling of deeper (often more expensive) boreholes into the basement to intercept these structures (fig. 5).

Hydrogeological Character of Bedrock

The bedrock includes both the weathered saprock and fresh variably-fractured rock (figs. 1 and 2). Fracture systems may be the result of surface decompression, producing subhorizontal joints, which often predominate to depths of about 40-50 m; or, these systems may be the result of tectonic forces, which usually generate subvertical fractures (Houston, 1992). The orientation of regional stress fields determines where the latter systems are in tension or compression. This evaluation may give, in theory, an indication of permeability, but the complex tectonic history of many areas, with reactivation of per-existing fractures, complicates the picture (Wright, 1992).

The effect of tectonic structures on water-bearing properties is becoming clearer in generic terms. Brittle deformation has a positive effect on transmissive properties, and cataclastic deformation has a negative effect. Nevertheless, the width and inclination of the zone of influence of individual structural lineaments and their effect on water-bearing properties is still difficult to predict when attempting to optimise borehole siting.

The permeability of individual fractures is a function of aperture, which decreases with depth. The permeability of fracture systems is dependent on aperture and is also correlated with connectivity and frequency. Both of the latter also normally decrease with depth (Houston, 1992). However, the data available on which to base conclusions are very limited, and it is possible that fracture sealing through the deposition of secondary clay minerals in some lithological types may in practice reduce overall permeability in the weathered bedrock.

Extensive test pumping of boreholes tapping bedrock in Zimbabwe showed a very wide range of transmissivity (0.5-100 m^2/d), although most values are within the range 2-5 m^2/d (Wright, 1992).

Problems of Yield Correlation and Success Evaluation

Many authors have taken a statistical approach to the analysis of the relative significance of various environmental factors (such as bedrock type, regolith thickness, geomorphological situation, depth to water table, and rainfall) on borehole yield. Such methods are fraught with many difficulties, primarily associated with the subjectivity of the yield value itself. Measured yield has a wide variation at any given site as a result of differences in borehole lining and hydraulic efficiency , depth of borehole penetration, and lack of uniformity in testing protocol. It is not surprising, therefore, that few, if any, attempts at regression analysis result in significant correlations (e.g., Houston and Lewis, 1988; Wright, 1992; McFarlane et al., 1992). Specific capacity is an improvement over yield for such purposes, but still suffers from most of the same inherent inconsistencies. The nearest approaches to correlation (fig. 6) are normally those between specific capacity and saturated regolith thickness (or depth to bedrock in areas of low relief).

Thus, despite the regional coherence of factors such as bedrock type, geomorphological situation, and climatic regime and history, the variability of well response to abstraction suggests an overriding influence of local factors, such as detailed well construction/efficiency or small-scale lithological and structural features.

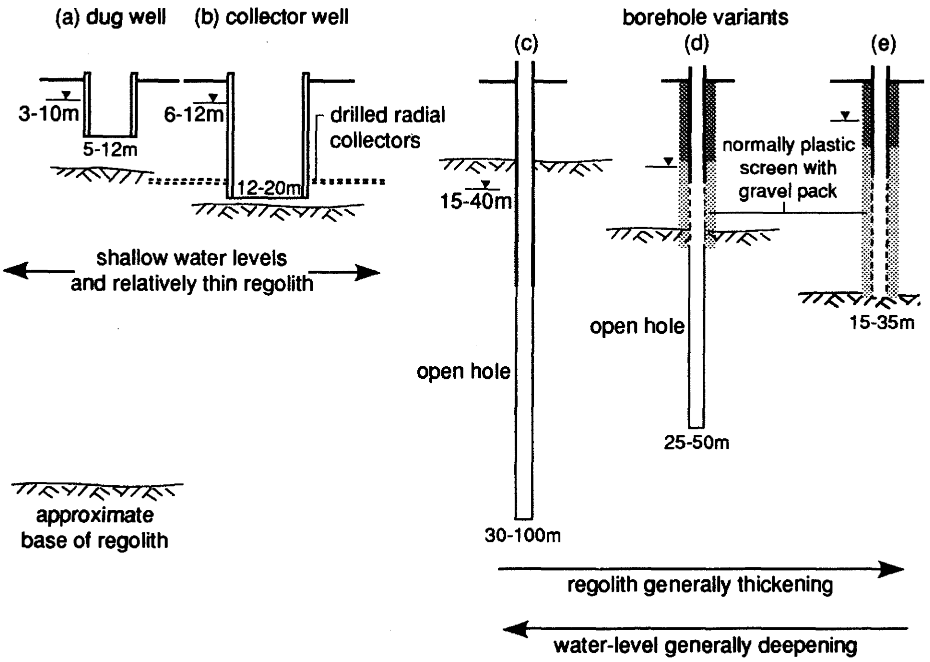

Figure 5. Preferred well-construction approaches to the development of weathered basement aquifers.

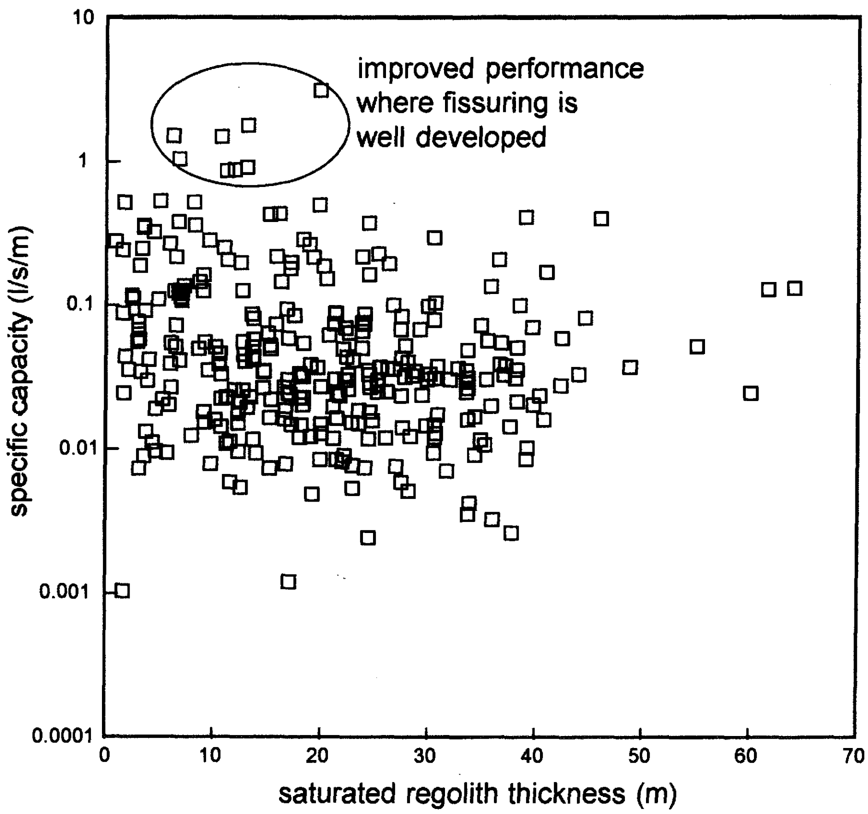

Figure 6. Relation between specific capacity and saturated regolith thickness for small-diameter boreholes in the weathered basement aquifers of Malawi.

Similar difficulties are often encountered when trying to assess the success of the various well-siting techniques for village boreholes. A given technique is only justified if it increases the chances of subsequent boreholes meeting the success criterion, namely that the overall unit saving in drilling costs in the long run is greater than the unit cost of the siting technique (Farr et al., 1982). Thus, reliable data on wildcat drilling success rates are required to assess the success of controlled well siting by a given technique. In many areas, such data are simply not available. It is clear, however, that a greater investment in scientific siting techniques is justified in areas where the wildcat drilling success rate is suspected to be low.

The maximum economic expenditure on investigation and development is set, in theory, by the cost of equivalent alternative water sources. In practice, however, this expenditure is set by project budgetary constraints, which normally only allow US$ 3,000-5,000 per village well, given the relatively low level of economic development of the communities involved.

DEVELOPMENT OF LARGER WATER SUPPLIES

Possibilities of Increased Well Yield

The preceding discussion suggests that the weathered basement aquifer generally provides only modest yields from individual production boreholes (normally less than 1 l/s). More intensive development of groundwater resources is possible only where higher abstractions are technically feasible and economically justified by the eventual water use. Higher yields to support motortised pumping and water reticulation can be obtained at locations where favourable lithology, structural features, and weathering are combined. Exploration to locate restricted zones of higher transmissivity involves increasingly sophisticated exploration methods and a much larger capital investment. In some circumstances, modifications to well design by increasing diameter to make use of well storage, by using collector wells with drilled laterals, or by hydrofracturing, can help to obtain yields sufficient for limited irrigation or for small-town supply (fig. 5).

Sustainability of Abstraction

Dispersed exploitation through modest-yielding hand-pump wells, to provide adequate domestic water requirements, implies overall groundwater abstraction rates equivalent to 1-3 mm/a for typical rural population densities (Foster, 1984). Consideration of the groundwater resources available to meet this demand becomes important only in very dry areas with rainfall below 500 mm/a, or in times of unusually prolonged drought. An understanding of where and how aquifer recharge occurs may, however, help in well siting, especially in drier areas (Wright, 1992).

In situations where higher yields have been confirmed by appropriate test pumping, an evaluation of groundwater recharge becomes necessary to ensure sustainability of the supply through drought conditions. Methods of estimating recharge are subject to significant uncertainty in most hydrogeological situations. The magnitude of uncertainty is increased in basement areas, because of the heterogeneity and discontinuity of the aquifer and the resulting complexity of the groundwater flow system (fig. 1). Several of the conventional methods of recharge estimation have been used in recent studies in Malawi in areas of annual rainfall of 800-1,200 mm/a, but all present difficulties when applied to basement areas (table 3).

Estimation of recharge by baseflow separation has the advantage of directly identifying the groundwater component. Application of this method to 26 catchments in Zimbabwe and Malawi (Farquharson and Bullock, 1992) produced baseflow estimates ranging from 0-25 per cent of annual rainfall, equivalent to recharge of up to 370 mm/a. As would be expected, a strong correlation exists between baseflow and rainfall, but additional correlations with relative relief and dambo density were also apparent. Thus, catchments with higher relief, characteristic of the Post-African erosion surface in Zimbabwe and the Rift Valley shoulder in Malawi, have significant baseflow, whereas catchments draining the more subdued topography of the African erosion surface have less baseflow.

Assessments of groundwater recharge from baseflow should be considered as minimum estimates, because water can be lost to evaporation by various processes before reaching the flow gauging station. This is a particularly important consideration because groundwater moving from broad low interfluves (fig. 1) discharges as seepages or is lost by evapotranspiration from the relatively green dambo vegetation in the dry season (Chilton and Smith-Carington, 1984). In these circumstances, a gauging station farther down the catchment may significantly underestimate groundwater recharge. For the catchment of the Bua River in Malawi, with 21 per cent dambo cover, estimated dry season evapotranspiration losses were equivalent to 78 mm over the catchment, compared to a baseflow estimate of 18 mm (table 3).

Estimates of groundwater recharge can also be made by the chloride balance method, which assumes that groundwater chloride concentrations represent the chloride content of the infiltrating rainfall, concentrated by evapotranspiration in the unsaturated zone (Edmunds, et al., 1988). Application of this simple approach to

Table 3. Estimates of groundwater recharge by different methods, basement-aquifer areas of Malawi (Chilton and Smith-Carington, 1984; and Wright, 1992).

Location in Malawi	Recharge, mm/a		Seepage evapo-transpira-tion, mm/a	Dambo density
	Base-flow method	Chloride-balance method		
Livulezi	145	114-234	–	Negligible
Bua	18	118-134	78	High
Diampwe	75	97-152	150	Moderate

estimating recharge is, however, constrained by uncertainties in areal distribution and chloride content of rainfall. A more important constraint is the complexity of groundwater flow systems in the basement, which causes variations in travel times and degree of vadose-zone concentration (Wright, 1992). In spite of these difficulties, when applied in Malawi and Zimbabwe, the method gave comparable results to baseflow for catchments without significant dambos, and it supported the higher recharge estimates based on seepage and evapotranspiration losses in catchments with a significant area of dambos (table 3).

Other approaches to recharge estimation based on flow-net analysis and water-level fluctuations suffer from major uncertainties in relation to transmissivity and storage coefficient, respectively. Such methods gave values mainly about 10-30 mm/a for various small catchments in the Dowa West area of Malawi, compared to 20-80 mm/a by other methods (Chilton and Smith-Carington, 1984). It is possible, however, that the transmissivity values used at times of maximum water level and hydraulic gradient are too low.

The difficulties inherent in estimating recharge to basement aquifers make it desirable that more than one method should be used, with emphasis given to those that appear most appropriate for local circumstances and for which data can most easily be obtained.

QUALITY CONSTRAINTS ON AQUIFER DEVELOPMENT

Natural Groundwater Chemistry

Groundwater from basement aquifers has generally been considered to be of good natural chemical quality, although its potential to be corrosive has been known for many years. The more comprehensive data collection and fuller analyses carried out in recent investigations have generally supported this view, but some specific quality concerns have been raised.

Deep regolith profiles have developed by prolonged aggressive weathering and differential leaching, in which the movement of infiltrating groundwater has played the dominant role. The natural groundwater chemistry is the product of various weathering processes, and varies with the pH and Eh. Thus, vertical differences in chemical composition might be expected because the regolith profiles contain varying mineral assemblages pertaining to different stages of weathering and leaching.

In the case of the African surface in Malawi, leaching of interfluve profiles has produced chemically distinctive groundwater at shallow and greater depths (McFarlane, 1992). After heavy rain, a shallow throughflow (fig. 1) with low salinity and dissolved silica moves downslope, where it is intercepted by shallow wells and discharges to seepage zones close to dambo edges (table 4). At this particular dambo, seepage continued in the dry season from a somewhat deeper component of flow with higher concentrations of all determinands. In contrast, samples from drilled wells in the dambo floor and discharge from crescent springs (table 4) reflect upward discharge of much deeper groundwater, which has moved more slowly through the saprolite toward the dambo (fig. 1).

The complexity in detail of groundwater flow and weathering processes is illustrated by extreme variations in groundwater quality over short distances. In the Dowa West area of central Malawi, for example, groundwater sulphate concentrations of more than 2,000 mg/l and less than 400 mg/l occur within a few hundred metres of each other (Chilton and Smith-Carington, 1984). The sulphate is presumed to originate by oxidation of pyrite and pyrrhotite locally present within basement gneisses. The extreme variations may be accentuated by groundwater taking different flow paths through the oxidised and unoxidised parts of the basement profile.

Table 4. Chemical analyses of groundwater samples obtained at the margins of the Linthembwe dambo, Malawi[1].

Determinand	Source[2] and value (concentrations are in mg/l)		
	Shallow wells	Seepage zones	Crescent springs
pH	6.0-6.3	5.9-6.6	6.7-7.0
Sodium	4-17	64-71	67-163
Calcium	1-14	95-114	143-555
Magnesium	1-7	57-104	78-343
Chloride	--	4-16	5-19
Silica (SiO_2)	7-14	10-23	24-41
Sulphate (SO_4)	2-21	368-639	528-2,490

[1] Data from McFarlane (1992), but omitting apparently highly anomalous sample
[2] From left to right, increasing depth of groundwater circulation

A widespread characteristic of basement areas is high iron concentration in abstracted groundwater. While not itself damaging to health, this high concentration may lead to public unacceptability of groundwater supplies because of bitter taste and food discolouration. The beneficiaries of improved water supplies may instead continue to use unprotected sources with severe bacteriological contamination (Lewis and Chilton, 1984). A detailed survey of iron concentration suggested that the use of plastic materials in borehole completion and pump manufacture could significantly reduce this problem (Lewis and Chilton, 1989).

Prolonged and extensive leaching of interfluve profiles results in major mobilisation of aluminium, but high concentrations of aluminium are not observed in groundwater. McFarlane (1992) suggested that the method of filtering and acidification normally used for chemical sampling may mitigate against detection if aluminium is present in adsorbed colloid form.

Elevated dissolved organic carbon and total coliform counts have been reported from locations in the humid tropics, in areas that appear to be free from surface contamination. Their occurrence suggests that these constituents may, in fact, arise naturally and be related to the universally deep and biologically-active soil profiles.

Aquifer-Pollution Vulnerability

Basement aquifers may be more vulnerable to pollution from anthropogenic activities than their generally low permeability suggests. This vulnerability is because the vadose zone is often thin, and preferential flow through regolith cracking and macropores can occur (Foster, 1993). In more arid situations, despite the deeper water table, the clayey regolith may be absent and fractured bedrock may be exposed at the surface.

Faecal contamination of shallow wells and boreholes in the weathered basement aquifer of Malawi is widespread (Lewis and Chilton, 1984), and severe faecal and nitrate pollution of village water supplies in eastern Botswana has also been reported (Lewis et al., 1980). In the former example, improved small-diameter boreholes of the type shown in figure 5 produced water of generally high microbiological quality, compared to the water from both traditional open and protected dugwells. Sound sanitary completion and careful siting in relation to potential pollution sources can provide a high degree of protection for groundwater supplies in basement aquifers.

Little information is available on the vulnerability of weathered basement aquifers to contamination from agricultural cultivation practices. Some evidence suggests that traditional rotations of subsistence crops have little impact on quality. However, attempts to intensify cultivation and introduce highly-productive monocultures is likely to lead to soil compaction, increased runoff, and soil erosion or soil breakdown and excessive leaching of nutrients.

CONCLUSIONS

1. The basement aquifer is now well proven as a vital resource to the rural population of tropical Africa. These aquifers can be tapped widely at relatively low cost and with relatively simple technology.

2. Water-supply potential of the basement aquifer is strictly limited by its generally low transmissivity. Permeability development is related in a complex way to geological structure and geomorphological evolution.

3. The situation is more favourable in humid than arid regions, because of the presence in humid regions of a much thicker regolith and shallower water table, providing a larger available drawdown to productive aquifer horizons and a significant aquifer storage component.

4. The depth to water table and thickness of saturated regolith should dictate the approach to, and thus determine the relative cost of, well siting, design, and construction.

5. Despite the coherence of factors such as bedrock type, geomorphological situation, and climatic regime, local conditions dominate yield and well response at a given site. Reliable predictions of potential well yield cannot be guaranteed even by putting considerable effort into the assessment of existing data and the use of a variety of siting techniques.

6. The development of larger water supplies requires a much greater investment to locate restricted zones of higher transmissivity and/or to construct wells of large effective radius.

7. Uncertainty remains about the processes and rates of aquifer recharge, especially in the more arid areas. Nevertheless, the location of sufficiently permeable zones to permit economic abstraction usually remains a greater constraint than resource availability.

8. Groundwater quality often exhibits substantial variation, both with depth in the aquifer and spatially over short distances. This variability is a reflection of the locally complex and very sluggish groundwater flow regime, and is an additional constraint on aquifer exploitation.

ACKNOWLEDGMENTS

This paper is published with the permission of Dr Peter Cook, Director of the British Geological Survey (BGS), a component institute of the Natural Environment Research Council. The paper is based mainly on published British work and draws primarily on the results of major groundwater research and drought relief programmes funded by the (British) Overseas Development Administration (ODA) and the European Economic Community during 1985-90.

An attempt has been made to produce a succinct review and thereby disseminate further the efforts of numerous British hydrogeologists in advancing our understanding of the water-supply potential of the African basement aquifers. Amongst these, we wish to highlight the leading role of Dr Edmund Wright, who retired as BGS-Head of Overseas Hydrogeology/ODA-Groundwater Adviser in 1988. The important contributions made by other British hydrogeologists are indicated from the references cited in the text. The support of collaborating organisations, particularly the Ministry of Water Development in Zimbabwe and the Ministry of Works-Water Department in Malawi, is acknowledged.

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