Characteristics of the weathered basement aquifer in Malawi in relation to rural water supplies

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ABSTRACT Prolonged weathering of crystalline Basement Complex rocks in Central Africa has produced a layer of unconsolidated material which forms an extensive but relatively thin aquifer of low permeability. This is an important source of rural water supplies in Malawi. Potential yields are low, but the 0.25-0.5 l s\(^{-1}\) required for handpumps can be widely obtained where the saturated thickness is more than 10 m. Although the aquifer is relatively extensive, on a local scale, differences in bedrock mineralogy and structure produce significant variations in its physical and chemical characteristics. The distribution of permeability within the aquifer and its relationship to the fluctuating water table are important in determining the drought reliability of the aquifer. Occurrences of poor quality groundwater affect the acceptability of the water supplies and the costs of rural water supply projects. There are difficulties in estimating recharge to the weathered basement aquifer, but even at complete water supply coverage for the rural population the abstraction is only a small proportion of the annual recharge.

Caractéristiques de l'aquifère dans le socle altéré au Malawi concernant l'alimentation des collectivités rurales

RESUME L'altération prolongée des roches cristallines du complexe de base en Afrique Centrale a produit une couche de matériaux non consolidés qui constitue un aquifère étendu mais relativement mince et d'une faible perméabilité. Il constitue une source importante d'approvisionnement en eau dans les campagnes au Malawi. Les productions potentielles sont faibles, mais le débit de 0.25 à 0.5 l s\(^{-1}\) requis pour les pompes à main peut être largement obtenu là où la couche saturée est épaissie de 10 m. Bien que la nappe aquifère soit relativement étendue, à l'échelle locale, les différences dans la structure et la minéralogie du substratum rocheux produisent des variations importantes dans les caractéristiques chimiques et physiques. La répartition

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de la perméabilité à l'intérieur de la nappe et ses relations avec les fluctuations du niveau d'eau sont importantes pour déterminer si elle peut donner satisfaction en temps de sécheresse. L'apparition d'eaux souterraines de qualité médiocre a une incidence sur l'acceptation de projets d'amélioration d'alimentation en eau et sur les coûts de projets d'approvisionnement ruraux. Il est difficile d'estimer la recharge annuelle de l'aquifère de cette roche de base altérée, mais le prélèvement que représente l'utilisation domestique des eaux souterraines n'est qu'une faible partie des réserves en eau reconstituées à chaque saison des pluies.

INTRODUCTION

The UN International Drinking Water Supply and Sanitation Decade has focussed the attention of governments on the problems of providing safe water and adequate sanitation facilities for all by 1990. Along with many other countries, Malawi has adopted the goals of the Decade. Malawi has an international reputation for gravity-fed piped-water projects; however, the available protected catchments giving reliable yields of surface water can only serve part of the estimated 1990 rural population of 7.2 million. Thus, by 1990 more than 5 million people must depend either on groundwater or on very expensive surface supplies involving the construction of storage dams and treatment works.

Crystalline igneous and metamorphic rocks make up a large proportion of the continent of Africa, and underlie much of Malawi. The groundwater potential of these areas has, in the past, generally been considered low, partly because the occurrence of groundwater in this terrain and the importance of the weathered basement as an aquifer have been misunderstood. As a result, the weathered zone was often partially or completely lined-out in water supply boreholes, and much of the large body of existing borehole data is therefore poorly representative of the overall groundwater conditions. The description of the characteristics of the weathered basement aquifer in this paper is based on the results of drilling programmes undertaken during the last four years, to investigate and to exploit this aquifer.

GEOLOGY AND GEOMORPHOLOGY

A summary of the geology of Malawi has been given by Carter & Bennett (1973). Much of the country is underlain by crystalline metamorphic and igneous rocks of Pre-Cambrian to Lower Palaeozoic age referred to as the Basement Complex (Fig.1). They are high grade metamorphic rocks, mainly gneisses, which suffered intense folding and granitization and have since remained as a tectonically-stable shield area for many millions of years. Epeirogenic events have uplifted these rocks in large blocks. Prolonged weathering under tropical conditions has produced a characteristic topography of peneplain and inselberg hills. Several erosion surfaces can be recognized (Lister, 1965), the most important and extensive of which
Weathered basement aquifer in Malawi

is the late Cretaceous to Miocene African surface, which in Malawi takes the form of a plateau at a general elevation of 1000-1250 m a.s.l. From this surface rise inselberg remnants of the earlier Gondwana and post-Gondwana surfaces. The formation of the Rift Valley has interrupted and modified this surface, particularly in the southern part of Malawi (Fig.2). The occurrence of groundwater is thus controlled by a combination of topography and geology.

OCCURRENCE OF GROUNDWATER

The plateau surface is characterized by a layer of unconsolidated material produced by the prolonged in situ weathering of the bedrock. The degree of alteration decreases progressively downwards until fresh, unweathered rock is reached. In detail, the character of the weathered zone varies with the parent rock type and texture, but a generalized profile can be given (Fig.3). Towards the edge of the escarpment, the uplift associated with the development of the Rift
Valley has resulted in rejuvenation of the rivers and increased erosion, and much of the unconsolidated, weathered material has been removed. The weathered zone also thins towards the bedrock outcrops in inselberg hills. However, in the plateau areas of Malawi, the weathering products of the Basement rocks provide a thin, but extensive and more or less continuous aquifer, of great importance as a source of rural domestic water. In contrast, the underlying unweathered bedrock is rarely a significant aquifer. Even where fracturing may produce somewhat higher localized permeability the available storage in the fresh rock is negligible, and a borehole drilled into fresh bedrock will draw on the storage of the overlying weathered zone aquifer.

The weathering profile is generally 15–30 m thick, and may be thicker where faults or fracture zones have permitted the weathering processes to penetrate more freely. The relatively impermeable surface layers of clay (Fig.3) produce semi-confined aquifer conditions; during drilling, water is commonly struck around the base of the clays and the rest water level usually stands several
metres above this depth. Table 1 summarizes the results of recent drilling programmes in which the boreholes were completed in the weathered zone aquifer; drilling was halted when fresh, hard bedrock was reached, as determined from the markedly decreasing rate of penetration and from lithological samples.

AQUIFER PROPERTIES

Yields

The weathered basement aquifer produces generally low borehole yields. Yields of greater than 2 l s⁻¹ are relatively uncommon and the potential for motorized pumping for irrigation or small reticulated supplies is therefore limited. On the other hand, yields of 0.25-0.5 l s⁻¹, sufficient for handpumps, can usually be obtained (Table 1). The results of these recent drilling programmes have shown that, with the use of proper borehole design and construction techniques (Chilton et al., 1982), adequate yields for handpumps can be obtained widely from the weathered basement aquifer without the use of geophysical siting techniques. In both the Livulezi and Dowa West projects, boreholes were sited primarily by the villagers themselves, under the supervision of a hydrogeologist to avoid clearly unpromising sites with shallow bedrock or potential pollution hazards (Lewis & Chilton, 1984).

Borehole yields are generally highest where the saturated thickness of the weathered zone is greatest and the parent bedrock coarsest. Good yields are often obtained where major fractures,
TABLE 1  Summary of drilling results for the weathered basement aquifer

<table>
<thead>
<tr>
<th>Location*</th>
<th>Number of boreholes:</th>
<th>Depth (m):</th>
<th>Water struck (m):</th>
<th>Water level (m):</th>
<th>Yield (l s⁻¹):</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Successful†</td>
<td>X</td>
<td>σ</td>
<td>X</td>
</tr>
<tr>
<td>Livulezi project</td>
<td>145</td>
<td>134</td>
<td>24.1 ± 6.1</td>
<td>11.3 ± 5.1</td>
<td>7.0 ± 3.8</td>
</tr>
<tr>
<td>Dowa West project</td>
<td>81</td>
<td>67</td>
<td>26.7 ± 5.8</td>
<td>15.2 ± 6.9</td>
<td>10.6 ± 6.9</td>
</tr>
<tr>
<td>Lilongwe</td>
<td>18</td>
<td>17</td>
<td>30.0 ± 5.4</td>
<td>10.2 ± 2.2</td>
<td>7.8 ± 1.8</td>
</tr>
</tbody>
</table>

*See Fig.1 for locations
†Successful boreholes defined in relation to handpump requirement of 0.25 l s⁻¹ minimum.

TABLE 2  Test pumping results from high yielding boreholes in the Lilongwe areas

<table>
<thead>
<tr>
<th>Borehole number</th>
<th>Discharge rate (l s⁻¹)</th>
<th>Length of test (h)</th>
<th>Drawdown (m)</th>
<th>Specific capacity (l s⁻¹ m⁻¹)</th>
<th>Transmissivity (m² day⁻¹)</th>
<th>Average kₕ (m day⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4E 80 CC137</td>
<td>1.5</td>
<td>24</td>
<td>22.2</td>
<td>0.07</td>
<td>2-10</td>
<td>-</td>
</tr>
<tr>
<td>4F 39 CC111</td>
<td>2.2</td>
<td>72</td>
<td>14.5</td>
<td>0.15</td>
<td>?</td>
<td>-</td>
</tr>
<tr>
<td>4F 35 CC112</td>
<td>1.4</td>
<td>72</td>
<td>14.4</td>
<td>0.10</td>
<td>20-35</td>
<td>1.0-1.8</td>
</tr>
<tr>
<td>4F 31 CC113A</td>
<td>5.0</td>
<td>75</td>
<td>24.5</td>
<td>0.20</td>
<td>10-35</td>
<td>0.4-1.2</td>
</tr>
<tr>
<td>4D 272 GP 7</td>
<td>2.0</td>
<td>72</td>
<td>11.7</td>
<td>0.17</td>
<td>12</td>
<td>0.5</td>
</tr>
<tr>
<td>4D 274 GP 8</td>
<td>1.5</td>
<td>49</td>
<td>10.4</td>
<td>0.14</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>4D 273 GP 4</td>
<td>0.5</td>
<td>60</td>
<td>4.7</td>
<td>0.11</td>
<td>7</td>
<td>0.2</td>
</tr>
</tbody>
</table>
faults, or shear zones in the bedrock have allowed the weathering processes to penetrate deeply. The test yield of 51 \text{s}^{-1} from borehole CC113A (Table 2) is exceptionally high for the weathered basement; here the saturated aquifer thickness is 29 m and the maximum available drawdown is 30 m. The application of a fuller range of exploration techniques is justified where higher yields are required and a much greater capital investment is to be made in boreholes, pumps and surface works (for example small urban water supplies with motor pumps and reticulation works). Exploration for promising sites where the weathered zone aquifer has maximum saturated thickness at present includes the use of aerial photographs to locate structural features, resistivity geophysics and in some cases test drilling.

Specific capacity

Specific capacity data give a better indication of borehole and aquifer performance than records of yield alone as they reflect aquifer permeability and thickness. The specific capacities of the recently constructed, higher-yielding boreholes in the Lilongwe area (Table 2) are relatively high, especially so for CC113A. For the boreholes in the Dowa West and Livulezi projects, specific capacities range downwards to 0.01-0.02 \text{s}^{-1}\text{m}^{-1} below which a borehole will not even sustain a village handpump supply.

Transmissivity

Test pumping of boreholes in the Livulezi and Dowa West projects was for short periods (generally 4 or 5 h) and water levels in some cases were quickly drawn down to pump suction, with a consequent reduction in discharge rate for the remainder of the test. The response to pumping is frequently complex suggesting heterogeneous aquifer conditions. The interpretation of the data is also complicated by gravity drainage as the aquifer passes from a semi-confined to an unconfined condition and by the decrease in saturated thickness which causes a fall in transmissivity as the aquifer is dewatered. Analysis of the early parts of both drawdown and recovery phases indicated local transmissivities of 1-20 m\text{day}^{-1} in the Livulezi project and 0.2-5 m\text{day}^{-1} in the Dowa West project.

The great complexity and heterogeneity of the weathered basement aquifer on a very local scale is illustrated by detailed test pumping of two boreholes at the new Lilongwe International Airport. Water levels were measured in the pumping borehole and two observation boreholes in each case; the form of the response to pumping is unusual and similar in all boreholes except pumping well CC113A (Figs 4 and 5). There is a steep "shoulder", which is probably a barrier boundary effect suggesting that the cone of depression is extending into a zone of lower permeability material, and this is followed by a decline in the rate of drawdown indicating a recharge boundary. The latter effect may reflect vertical leakage through the less permeable upper layers of the aquifer and surface clays. An alternative explanation might be gravity drainage during dewatering as the water level falls below the semi-confining clays, but although this is feasible in the case of CC112 it is unlikely to
explain the response in the observation boreholes to CC113A in which the water level remains within the surface clays. It should be noted that the above interpretations are not definitive since several different configurations of aquifer characteristics could result in a similar response to pumping.

The small drawdown and delayed response in the nearer observation borehole (OW 1) during pumping of CC113A, are thought to reflect the fact that it only partially penetrates the weathered zone. It is suspected that the lower part of the aquifer contributes most of the yield and that there is poor hydraulic connection between the upper and lower layers. This was confirmed by conductivity logging and chemical sampling in the boreholes. The delayed response is probably largely due to very low permeability in the most weathered upper layers which could be compounded by lateral anisotropy as there is also strong vertical banding (relict foliations or mineralogical layering). Another possibility is that the pumping borehole and OW 2 (but not OW 1 at right angles to them) both intersect a more substantial fracture trace preserved in the weathered material.

It is clear that the weathered basement aquifer behaves in a very complex manner. The heterogeneity of the material both vertically and laterally results in highly variable flow from different horizons. The early data have been used to estimate local transmissivity before the response to pumping is dominated by complex boundary effects, and the late data have been used to indicate regional transmissivity.
(Table 3). If the long tails of late data are interpreted as the effects of leakage rather than some other recharge boundary, the true regional transmissivity will be about half of the apparent transmissivity indicated. The late data are also important for supply boreholes such as those at Lilongwe International Airport, to

TABLE 3 Transmissivity estimates for Lilongwe International Airport site

<table>
<thead>
<tr>
<th>Borehole number</th>
<th>Transmissivity $(m^2\cdot day^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type curve method†† (early data):</td>
</tr>
<tr>
<td></td>
<td>Drawdown</td>
</tr>
<tr>
<td>CC113A OW1</td>
<td>22</td>
</tr>
<tr>
<td>CC113A OW 2</td>
<td>39</td>
</tr>
<tr>
<td>CC113A</td>
<td>19</td>
</tr>
<tr>
<td>CC113A OW 2</td>
<td>11</td>
</tr>
<tr>
<td>CC113A OW 2</td>
<td>37</td>
</tr>
</tbody>
</table>

†† is too large for straight line relationship (Cooper & Jacob, 1946) to hold for early data.
††Type curve cannot be fitted accurately for late data which fall on very flat section of curve.
estimate long term pumping water levels for the setting of pump suction, discharge rates and pumping regime. The estimates of transmissivity based on recovery data are not consistent with those based on drawdown data because of the effects of aquifer heterogeneity, and the former are, therefore, considered to be less reliable, especially when using early recovery data.

Permeability

The nature of the aquifer, with relict mineralogical or structural banding persisting in the weathered material, will ensure that aquifer properties are highly anisotropic. Vertical permeability is likely to be much lower than horizontal permeability, and there may also be great variation laterally. On the basis of the transmissivity determinations and aquifer thicknesses, average permeabilities are likely to be in the range 0.05-1.5 m day\(^{-1}\). The most permeable horizons are unlikely to exceed 5 m day\(^{-1}\).

WATER LEVEL FLUCTUATIONS

Measurements of groundwater levels taken over the last 10 years by borehole maintenance units indicate a range of seasonal fluctuations in water level of 1-5 m. However, these measurements are relatively infrequent (when a handpump is removed for repairs) and can only be used as a general guide. Groundwater levels are now being monitored with autographic recorders at several sites; on the plateau area north of Lilongwe, seasonal fluctuations of 2-3.5 m have been recorded in 1980-1981 and 1981-1982, and only 1-2 m in 1983.

Significant changes in water level clearly have important implications for this relatively thin and shallow aquifer, especially when drawdowns during pumping are large. Where the aquifer is only 15-20 m thick, a fall in water level of 5 m could result in a loss of aquifer transmissivity and a decline in borehole performance. This has been observed in the Livulezi project, where a retesting programme was carried out in July and August 1983 to evaluate the performance of boreholes drilled in 1981 and early 1982. The two rainfall years 1981-1982 and 1982-1983 have produced less than average recharge, although they have not been such extreme drought years as elsewhere in southern Africa. Of the 134 new boreholes in the project, seven were practically dry by the end of the 1983 dry season. A further 15 were experiencing difficulty sustaining the handpump yield; a mixture of air and water being produced as the pumping water level drew down to the pump intake. The retesting programme indicated an average decline in water level of 2.8 m in the 19 boreholes tested, with over 6 m in two of the boreholes. A detailed evaluation of the retesting results, however, shows that there is not always a correlation between falling water levels and declining yield; there may also be changes in borehole performance caused by the borehole infilling and by clogging of screen or gravel pack. In addition if the decline remains largely within the semi-confining clays, and the transmissivity of the aquifer is concentrated in the middle and lower parts of the
weathered profile, then even substantial declines in water level could have a less dramatic effect on borehole performance than might be expected.

Seasonal or longer term fluctuations in water level have even greater implications for the dug wells which draw from this shallow aquifer. Of the 60 dug wells in the Livulezi project, 19 were experiencing supply difficulties by the end of the 1983 dry season. Thus, even concentrating construction in the later part of the dry season, and using dewatering pumps to permit excavation to several metres below water level, may not be sufficient to ensure reliable supply through two or more successive dry years. This could produce problems for rural water supply programmes based only on dug wells. A combination of dug wells and boreholes, with their greater aquifer penetration, is desirable.

RECHARGE

In preparing a major report on the groundwater resources of the country (Smith-Carington & Chilton, 1983), detailed consideration has been given to the seasonal recharge to the weathered basement aquifer. Estimates of recharge by analysis of hydrographs, groundwater level fluctuations, flowmets and catchment water balances show a broad range (Table 4) and have highlighted some of the complexities of the behaviour of the weathered basement aquifer.

<table>
<thead>
<tr>
<th>Method</th>
<th>Recharge to weathered basement aquifer (mm)</th>
<th>Sources of major uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseflow separation</td>
<td>15-80</td>
<td>&quot;dambo&quot; hydrology</td>
</tr>
<tr>
<td>Groundwater flow</td>
<td>4-36</td>
<td>transmissivity</td>
</tr>
<tr>
<td>Catchment water balance</td>
<td>18-96</td>
<td>actual evapotranspiration</td>
</tr>
<tr>
<td>Groundwater level fluctuations</td>
<td>10-35</td>
<td>&quot;dambo&quot; behaviour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>storage coefficient</td>
</tr>
</tbody>
</table>

Conventional hydrograph analysis by separation of the baseflow component (Hall, 1968) provides at first sight an excellent approach; there is a large body of good quality riverflow data in Malawi. However, the plateau areas of Malawi are characterized by "dambo", broad, grass-covered, swampy valleys which may be seasonally flooded and have no well defined channel. Such valleys occupy up to 25% of the land area and have a distinctive hydrological regime. The hydrograph form is rather flattened, without the marked peaks that would be expected from high intensity, tropical rainstorms. The dambo acts as a storage reservoir which buffers the peaks by slow overland flow through the dambo grasses. Baseflow separation may
give an accurate indication of the groundwater component of flow at the gauging station but it may underestimate the total recharge to the weathered basement aquifer above the gauge. A significant amount of groundwater could be moving from the interfluves, discharging to the drainage system and being evaporated or transpired from the dambo before reaching the gauge. The dambo vegetation remains relatively green and appears to be losing water by evapotranspiration throughout the dry season. If this water were derived entirely from groundwater flow to the dambo, the implied volume of recharge in the catchment could be several times greater than that registered at the gauge.

The regional flow pattern in the plateau areas is one of very low hydraulic gradients, often less than 0.005, and flow towards the major rivers. In detail, the flow pattern is more complex, with groundwater movement from the interfluves towards the dambo on a much more local scale. In the Dowa West project, the large number of new wells and boreholes in close proximity has permitted the construction of more detailed local piezometric contours. Even though these show that hydraulic gradients in the weathered basement aquifer may be locally steeper, ranging from 0.015 to 0.04, the very low estimated aquifer transmissivities mean that the volume of groundwater flow to the dambo is relatively low. The figures for recharge implied from this detailed study (Table 4) suggest that the volume of groundwater flow to the dambo is not sufficient to maintain the apparent high level of evapotranspiration from the dambo vegetation throughout the dry season. The water transpired must therefore come at least partly from storage within the dambo clays, with the consequent build up of soil moisture deficits.

Good rainfall and runoff data are available for carrying out catchment water balances, but the estimation of actual evapotranspiration ($E_A$) for a catchment is made difficult by the uncertainties over dambo behaviour. No field measurements of $E_A$ have been made, but observations of the dambo during the dry season suggest that the losses by evapotranspiration are likely to be higher than those suggested by Balek (1977) for wooded catchments with dambo in Zambia.

Estimation of recharge from seasonal fluctuations in groundwater levels is hampered by inadequate knowledge of the storage coefficient of the aquifer and the need to allow for changes in storage coefficient if the water level falls below the semi-confining clays. The method can only be relied on to give a broad comparative check on the other methods.

The wide range in recharge estimates given above is not yet critical with respect to domestic supplies since current groundwater abstraction from wells and boreholes with handpumps is estimated to be equivalent to less than 1 mm year$^{-1}$ when expressed over a whole catchment, which is small in relation to any of the recharge estimates. Even for total supply coverage of the densely populated rural areas of Malawi to meet design targets to 27 l day$^{-1}$ per person, the required annual abstraction rises to the equivalent of only 2-3 mm. Thus estimating recharge to the weathered basement aquifer in Malawi would only become critical if increasing domestic, agricultural and perhaps small scale commercial demands for water lead to greater groundwater abstraction.
GROUNDWATER QUALITY

The chemical quality of groundwater in the plateau areas is generally good, indicating that the weathered zone is highly leached of soluble minerals, and groundwater is likely to be derived from relatively recent recharge. The electrical conductivity (EC), which is indicative of the general level of mineralization, is usually less than 1500 μS cm\(^{-1}\) and most commonly even below 750 μS cm\(^{-1}\). The chemical quality is widely suitable for domestic use. The water can be classified as predominantly calcium-bicarbonate type, although in some cases cation exchange may have occurred and magnesium or sodium may be dominant.

There are, however, localized areas of much poorer quality groundwater which can present problems for domestic supply. The EC may be locally greater than 3000 μS cm\(^{-1}\) and in extreme cases up to 7000 μS cm\(^{-1}\). The quality is variable over short distances; in the Dowa West project, boreholes producing groundwater with ECs approaching 4000 μS cm\(^{-1}\) and less than 1000 μS cm\(^{-1}\) occur only a few hundred metres apart. This extreme spatial variation is evidence of slow movement of groundwater and incomplete mixing, and confirms the typically low permeability of the aquifer suggested by test pumping.

High sulphate concentrations have been found to be a cause of poor water quality. Of the 67 successful boreholes (Table 1) in the Dowa West project, only 40 had sulphate levels of less than the WHO recommended limit of 400 mg l\(^{-1}\). Eight were between 400 and 800 mg l\(^{-1}\) and 19 were above 800 mg l\(^{-1}\); of these nine were above 2000 mg l\(^{-1}\). Waters with high sulphate content, especially when in combination with high magnesium are unsuitable for human consumption because of their laxative effect. Thus, in addition to the 14 boreholes with inadequate yields, a further four have been abandoned because of the adverse groundwater quality. The local inhabitants may have become accustomed to high sulphate levels and eight of the boreholes with marginal water quality have been equipped with hand-pumps at the request of the villagers so that they can judge for themselves whether the water from the new boreholes is acceptable in relation to alternative sources of supply.

The occurrence of such high sulphate levels in Dowa West cannot easily be related to differences in bedrock composition. There may be a link with the upward leakage of mineralized waters along fracture zones; conductivity logging and chemical depth sampling indicate the sulphate concentration often increases with depth. It might appear, therefore, that the problem could easily be overcome by installing shallow hand-dug wells instead of boreholes. However, epsom salts (Mg SO\(_4\)) and gypsum crystals (Ca SO\(_4\)) have been found in significant amounts in some dried up surface water courses, evaporating spring discharges and in pits dug in the dambo clays at the end of the dry season; these indicate poor quality groundwater in the surrounding catchments. While there is little bedrock exposure within the Dowa West project (because of the thick weathered zone), there is some evidence from the relevant published geological map and memoir (Bellingham & Bromley, 1973) that pyrite and pyrrhotite occur in the Basement Complex gneisses. The high sulphate levels may thus be the result of progressive oxidation of sulphide-rich parent material, with one of the products being sulphuric acid.
which subsequently reacts with minerals containing magnesium and calcium.

For the provision of rural water supplies, investigations of the distribution (both vertically and laterally) and possible origins of high mineralization are required at two levels. Firstly, a better knowledge of the broad scale of variations in groundwater quality over a project area is required at the planning stage, so that water quality problems can be anticipated and adequate financial provision made to cover the estimated extra cost of abandoning any boreholes or wells. In preparation for each project, a comprehensive water quality survey should be carried out. At the end of the dry season, riverflow will be largely baseflow and sampling at this time will be generally indicative of some facets of the regional groundwater quality. This should be augmented by pumped samples from boreholes and protected dug wells, samples from open wells and springs and an examination of "dambo" for evidence of sulphate deposition. Secondly, a better knowledge of the local variations in groundwater quality is required during implementation. The additional costs from unsuccessful water points can then be reduced, as poor quality groundwater may be avoided by an appropriate choice between shallow dug well and deeper borehole and/or by careful siting of the water point. These investigations require water quality logging and depth sampling in boreholes and sampling as drilling progresses. In response to the problems encountered in Dowa West, a simple field method for determining sulphate concentration has been developed. This enables unsuitable boreholes or wells to be abandoned at an early stage of construction, with minimal cost to the project.

Another chemical characteristic of the groundwater, which may possibly restrict its use for rural water supply, is the common occurrence of high iron concentrations which, while not in themselves damaging to health, can lead to unacceptability because of the bitter taste and discolouration of food and laundry. There is a danger that people will dislike the improved water supply and will continue to use unprotected sources which are frequently polluted (Lewis & Chilton, 1984). In some cases the iron is associated with the high sulphates resulting from sulphide oxidation, and in others it is thought to be derived from ferro-magnesian minerals during weathering. The presence of organic fulvic acids may result in complexing and hence increased mobilization of the iron. Iron deposits are often observed on the downhole components of handpumps when they are removed for maintenance; these precipitates have formed because of aeration during pumping. The pH of groundwater is usually in the range of 6.3-6.8 and corrosion of borehole lining and handpump components by this slightly acidic groundwater may also add to the iron problem. The routine use of PVC borehole linings is helping to reduce this problem, and it is hoped that the eventual adoption of plastic pump components will lessen it further.

CONCLUSIONS

The importance of the weathered zone aquifer has largely been ignored in the past, both in Malawi and elsewhere in Africa where similar terrain occurs. Recent experience in Malawi has shown that, by the
careful application of standard borehole design and construction techniques, the weathered basement aquifer will usually support borehole yields of 0.25-0.5 l s\(^{-1}\) where its saturated thickness is more than 10 m. In most of the plateau areas of Malawi, yields sufficient for a handpump can therefore be obtained without the need for sophisticated siting techniques, and an intensive programme to provide rural supplies from groundwater is underway.

The weathered basement aquifer is relatively extensive, but on a local scale its characteristics are very variable. The original bedrock mineralogy and structure determine both the rate and the products of the weathering process; these produce major variations, sometimes over very short distances, in the physical and chemical characteristics of the aquifer. In relation to the provision of rural water supplies from this aquifer, two characteristics are of particular importance. Firstly, the permeability distribution within the aquifer and its relationship to seasonal and longer term water level fluctuations, since this determines drought reliability. Secondly, significant occurrences of poor quality groundwater affects the acceptability of improved water supplies and the costs of rural water supply projects. An improved knowledge of the permeability distribution, magnitude of water level fluctuations and distribution and origins of poorer quality groundwater is required so that the best use can be made of this important aquifer in the efforts to meet the targets of the UN Decade.

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