A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: Evidence from Uganda

Richard Taylor · Ken Howard

Abstract Deeply weathered crystalline rock forms important aquifers for public water supply throughout low-latitude regions of Africa, South America, and Asia, but these aquifers have considerable heterogeneity and produce low well yields. Aquifers occur in the bedrock and overlying weathered mantle and are the products of geomorphic activity of meteoric water, principally deep weathering and stripping. The fundamental relationship between the hydrogeology and geomorphology of these terrains has, however, remained unresolved. This study demonstrates the ability of a recently developed tectono-geomorphic model of landscape evolution in Uganda to explain the hydrogeological characteristics of two basins, as determined using a combination of textural analysis, slug tests, packer tests, and pumping tests. The geopetal imprint of long-term deep weathering and erosional unloading is identified in the vertical heterogeneity of the fractured-bedrock and weathered-mantle aquifers; horizontal heterogeneity is lithologically controlled. The two units form an integrated aquifer system in which the more transmissive (5–20 m^2/d) and porous weathered mantle provides storage to underlying bedrock fractures (transmissivity, T, ≈ 1 m^2/d). The thickness and extent of the more productive weathered-mantle aquifer are functions of contemporary geomorphic processes. The utility of the tectono-geomorphic model, applicable to deeply weathered environments, is that it coherently describes the basin-scale hydrogeological characteristics of these complex terrains.

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Résumé Les roches cristallines profondément altérées constituent d'importants aquifères captés pour l'eau potable dans les régions de basse latitude d'Afrique australe, d'Amérique du Sud et d'Asie, mais ces aquifères possèdent une hétérogénéité considérable et le rendement des forages y est faible. Ces aquifères se développent dans le substratum et dans sa couverture d'altération; ils résultent des actions géomorphologiques de l'eau météorique, principalement l'altération profonde et le décapage. La relation fondamentale entre l'hydrogéologie et la géomorphologie de ces terrains reste cependant non résolue. Cette étude démontre les possibilités d'un modèle tectono-géomorphologique récemment développé de l'évolution des paysages en Ouganda pour expliquer les caractéristiques hydrogéologiques de deux bassins, définies en utilisant une combinaison de l'analyse texturale, de slug tests, d'essais entre packers et d'essais de pompage. Les marques de l'altération profonde à long terme et du décapage de la couverture sont révélées par l'hétérogénéité verticale des aquifères du substratum fracturé et de sa couverture d'altération; l'hétérogénéité horizontale est contrôlée par la lithologie. Les deux unités forment un système aquifère intégré dans lequel la couverture d'altérites poreuses plus transmissive (5 à 20 m^2/j, soit 6 à 20×10^{-4} m^2/s) constitue la zone de stockage des fractures du substratum sous-jacent ($T = 1$ m^2/j, soit 1×10^{-5} m^2/s). L'épaisseur et l'extension de l'aquifère de la couverture d'altérites plus productive sont fonctions des processus géomorphologiques actuels. L'intérêt du modèle tectono-géomorphologique, applicable à des environnements profondément altérés, réside dans le fait qu'il décrit de manière cohérente à l'échelle du bassin les caractéristiques hydrogéologiques de ces terrains complexes.

Resumen Las formaciones de rocas cristalinas muy meteorizadas constituyen acuíferos notables para el abastecimiento público de agua en todas las regiones meridionales de África, Sudamérica y Asia. Sin embargo, se trata de acuíferos considerablemente heterogéneos, donde se construyen pozos de escaso caudal. Los acuíferos se localizan en la roca sana y en la capa superior meteorizada, y son consecuencia de la actividad modeladora del agua de lluvia, fundamentalmente por meteorización intensa y exfoliación. No obstante, la relación fundamental entre la hidrogeología y la geomorfología de estos terrenos no ha podido ser resuelta. El presente estudio demuestra la capacidad de un modelo tectono-geomorfológico, recientemente desarrollado, sobre la evolución del paisaje en Uganda para explicar las características hidrogeológicas de dos cuencas. El estudio ha combinado diversas técnicas, como el análisis textural, ensayos de cuchareo, ensayos con obturadores y ensayos de bombeo. La huella de la meteorización prolongada y de la descarga erosiva queda registrada en la heterogeneidad vertical de los acuíferos situados en la roca fracturada y en la capa meteorizada. La heterogeneidad horizontal, por su parte, está controlada por la litología. Las dos unidades forman un sistema acuífero en el que la zona más transmisiva (entre 5 y 20 $m^2\ d^{-1}$) y porosa de la capa superior proporciona el almacenamiento a las fracturas de la matriz subyaciente, cuya transmisividad es del orden de 1 $m^2\ d^{-1}$. El espesor y extensión del acuífero más productivo de la capa meteorizada dependen de procesos geomorfológicos contemporáneos. La utilidad del modelo tectono-geomorfológico, aplicable a medios altamente meteorizados, radica en que es capaz de describir de forma coherente las características hidrogeológicas de estas complicadas formaciones en el ámbito de la cuenca.

Key words groundwater development · crystalline rocks · geomorphology · tectonics · Uganda

Introduction

Mantles of weathered crystalline rock are a common feature of landscapes across equatorial Africa, South America, and Asia. Groundwater that is transmitted via coarse weathered debris at the base of weathered mantles and by fractures in the underlying bedrock provides an important source of potable water in many of these regions. Abstraction has occurred historically in rural areas by hand pumps (<10 m^3/d). More recently, groundwater has become the target of intensive abstraction (200–1000 m^3/d) using motorised pumps for low-cost, reticulated water supplies in urban areas. Unfortunately, several studies show that aquifers within the weathered mantle and fractured bedrock possess highly variable but typically low transmissivities (Chilton and Smith-Carington 1984; Houston and Lewis 1988; Howard et al. 1992). These characteristics result in a high incidence of well failure and low well yields (<20 m^3/d).

The hydrogeological characteristics (e.g., hydraulic conductivity and storage) of the weathered mantle and underlying bedrock derive primarily from the geomorphic processes of deep weathering and stripping (colluvial and fluvial erosion). Deep weathering is achieved by the movement of percolating rainfall (i.e., direct groundwater recharge), whereas stripping is effected by the action of water running across the land surface. Prolonged, in situ decomposition of bedrock (deep weathering) produces an unconsolidated weathered mantle (McFarlane 1991; Nahon and Tardy 1992; Thomas 1994; Taylor and Howard 1998). These mantles occur, therefore, in environments where biogeochemical weathering and accumulation of weathered products have been undisturbed by Pleistocene glaciation or by significant aeolian erosion. Their worldwide distribution is shown in *Figure 1*. As shown in *Figure 2*, aquifers tend to occur at the base of the

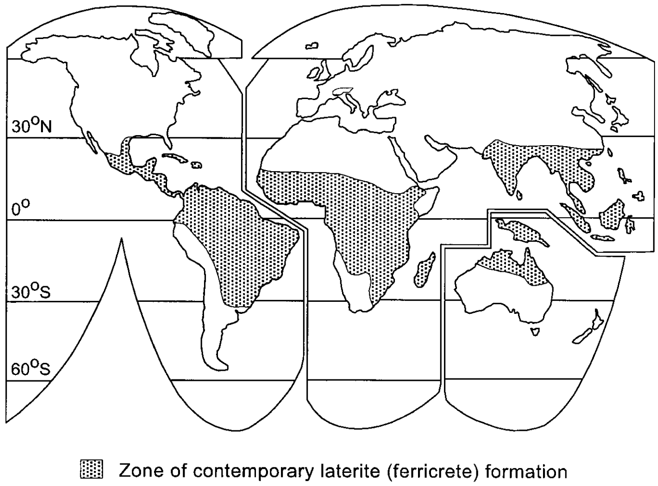


Figure 1 Global distribution of deep weathering environments indicated by laterite (ferricrete) development. (Adapted from Tardy 1992)

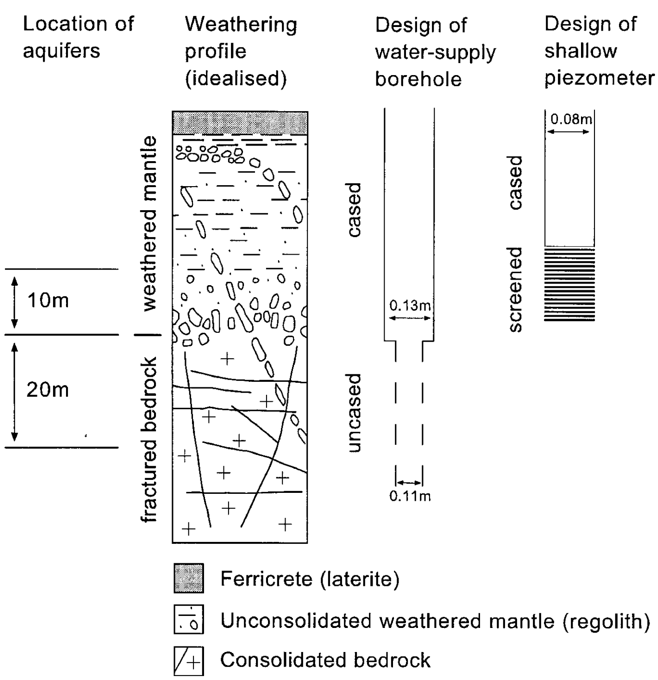


Figure 2 Vertical representation of the weathered crystalline-aquifer system, including locations of aquifers and construction of wells

mantle where less aggressive weathering is associated with saturated conditions and where coarse, partly weathered sand-sized clasts predominate (Eswaran and Bin 1978; McFarlane 1992; Taylor and Howard 1999a). In the crystalline bedrock below the weathered mantle, matrix hydraulic conductivity (K) is exceedingly low (10^{-6} to 10^{-8} m/d), but fractures within the bedrock can form an aquifer. Fracture density tends to increase toward the bedrock surface (Houston and Lewis 1988; Howard et al. 1992). Genesis is attributed to decompression (i.e., isostatic uplift, sheeting) that results from the removal of overlying rock in solution (deep weathering) and by the stripping of pre-weathered, unconsolidated material at the surface (Davis and Turk 1964; Acworth 1987; Wright 1992). Fractures may also derive from historical tectonic activity and be opened through decompression.

Recognising that hydrogeological characteristics result from deep weathering and stripping, a close relationship between the hydrogeology of deeply weathered terrains and the long-term geomorphic evolution of the landscape has been suggested by several authors (Foster 1984; Acworth 1987; McFarlane 1989; Wright 1992; Burke 1995). Attempts to resolve this association have involved random correlations between geographical parameters such as rainfall and relief, and measurements of well performance, either as a well yield or specific capacity (Houston and Lewis 1988; McFarlane et al. 1992). This approach is limited by uncertainty in the measurement of well performance (Chilton and Foster 1995) and the omission of key non-quantifiable parameters (e.g., bedrock lithology). Furthermore, the relevance of contemporary parameters, which represent only a "snapshot" of an otherwise, long-term geomorphic evolution of the landscape, is questionable.

Recent work in Uganda (Taylor and Howard 1998) demonstrates that the long-term evolution of deeply weathered terrains occurs by tectonically controlled cycles of deep weathering and stripping. Tectonic uplift induces episodes of stripping, whereas tectonic quiescence is required for subsequent deep weathering. Climate controls, in part, the rate at which these geomorphic processes operate by determining the input of meteoric water reaching the land surface. This finding is significant in that it provides the basis for a coherent model for landscape evolution. The model has been tested by field studies in Uganda (Taylor and Howard 1999a, 1999b), where distinct lithological and hydrological features are associated with the principal tectonically controlled geomorphic processes (i.e., deep weathering and stripping). The purpose of this study is to examine the hydrogeological characteristics of deeply weathered terrains in Uganda and determine whether they can be usefully explained in terms of a tectono-geomorphic model of landscape evolution. Such an association could provide a basis for developing an effective framework to manage the groundwater resources of these environments.

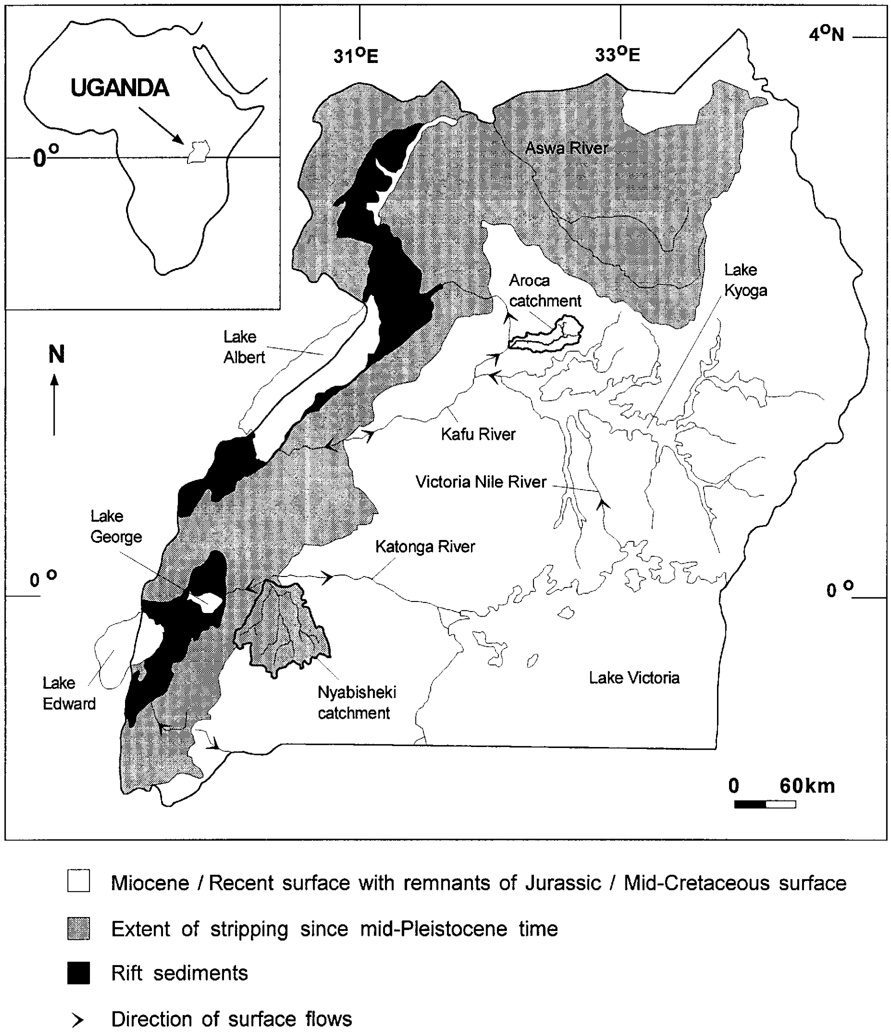
Tectonically Controlled Landscape Evolution in Uganda

A summary of the evolution of the Ugandan landscape since the Permian period is presented here, and a more detailed discussion is given in Taylor and Howard (1998). Following late Palaeozoic glaciation, a trend toward warmer and more humid climates through the Mesozoic Era enabled deep weathering of Precambrian crystalline bedrock formations that produced the Jurassic/mid-Cretaceous surface in Uganda during a period of prolonged tectonic quiescence. This surface is equivalent to the "Gondwana surface" described by King (1962). Uplift associated with the opening of the South Atlantic Ocean terminated this cycle of deep weathering and instigated a cycle of stripping between mid-Cretaceous and early Miocene times. Deep weathering of the succeeding surface (equivalent to King's "African surface") has occurred from Miocene time to the present but was interrupted in the areas adjacent to the western rift, where development of a new drainage base level initiated cycles of stripping during Miocene and Pleistocene times. *Figure 3* shows (1) the extent of stripping in western Uganda since mid-Pleistocene time, and (2) the Miocene/Recent (African) surface in Uganda. According to the proposed tectono-geomorphic model, the Miocene/Recent surface continues to be deeply weathered (i.e., deep weathering is the dominant geomorphic process), whereas the surface in western Uganda continues to be stripped of its weathered mantle.

Study Areas

The Aroca catchment of central Uganda is located on the land surface that is being deeply weathered, whereas the Nyabisheki catchment of southwestern Uganda is situated on the land surface that is being stripped (*Figure 3*). The Aroca catchment, shown in *Figure 4*, covers an area of 840 km^2 and is northeast of the Victoria Nile River. Bedrock geology is unmapped, but Taylor and Howard (1998) present geochemical evidence indicating that the catchment is underlain by biotitic and granulitic acid gneisses of the Precambrian granulite–gneissic complex. Rainfall is about 1500 mm/year and occurs primarily during two rainy seasons (monsoons), in April to May and August to October. The basin has extremely low relief and is drained by a wetland that comprises 7.5 % of the catchment area and slopes 60 m downward from the catchment's eastern boundary to where the wetland meets the Victoria Nile (*Figure 4*). Recharge results from monsoonal rainfall. The annual rate is highly variable but ranges from about 100–200 mm (Taylor and Howard 1996, 1999b). Runoff is <10 mm/year, due in part to exceedingly small surface gradients. Actual evapotranspiration amounts to more than 90 % of rainfall.

Figure 3 Locations of study areas on surfaces of stripping and deep weathering (Miocene/Recent surface) in Uganda. (Taylor and Howard 1998)



The weathered mantle, overlying fractured bedrock, is consistent in thickness (≈30 m) and stratigraphy. A duricrust of iron (i.e., ferricrete) is underlain by reddish-yellow clay and less-weathered, coarser material of primarily gray sandy loam (USDA classification) (Taylor and Howard 1999a). This description closely resembles the "standard" weathered profile (*Figure 2*) that is discussed by several other authors (Jones 1985; Acworth 1987; Barker et al. 1992; Wright 1992; Chilton and Foster 1995).

The Nyabisheki catchment occupies an area of 2914 km^2 and is east of Lake George (*Figure 3*). The catchment, shown in *Figure 5*, is underlain by Precambrian rocks, including the granulite–gneissic complex and metasedimentary cover formations comprising acid gneisses and undifferentiated schists of the Buganda-Toro group (Doornkamp 1970). Quartzites of the Karagwe-Ankolean group, which are resistant to biogeochemical weathering, form a ridge marking the southwestern boundary of the catchment. As in central Uganda, rainfall takes place mainly during two rainy seasons but ranges from 900 mm/year along its eastern boundary to 1100 mm/year to the west. Recharge results from monsoonal precipitation but is restricted to years of very high rainfall (Taylor and Howard 1999b). As in the Aroca catchment, more than 90 % of incoming rainfall is removed from the basin through evapotranspiration. Surface runoff greatly exceeds recharge during most years and is about 30–40 mm/year. The basin is drained by well incised stream channels that slope 200 m downward from the southern boundary to the northern outlet (*Figure 5*). As a result of stripping since mid-Pleistocene time, the weathered mantle is thinner than in central Uganda, and bedrock exposures occur throughout the catchment. Where a weathered mantle overlies bedrock, ferricrete is absent from the top of the profile and the overburden lithology is relatively undifferentiated and coarse-grained (Taylor and Howard 1999a).

Methodology

Hydrogeological characteristics of the weathered mantle and fractured bedrock and the hydraulic inter-

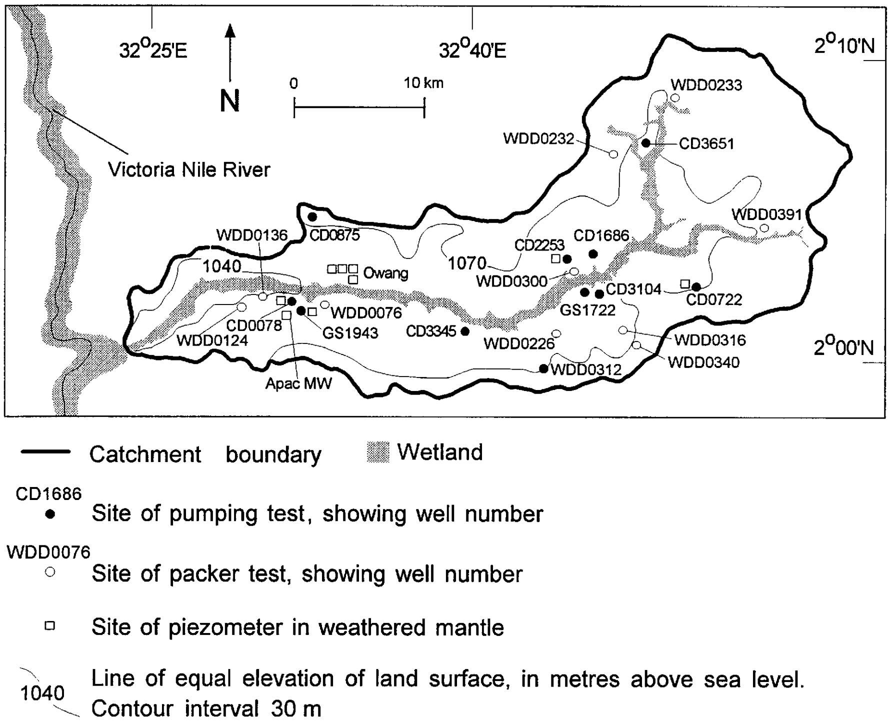


Figure 4 The Aroca catchment in central Uganda, showing topography and locations of tested boreholes and piezometers

action between these aquifer units were investigated by constant-discharge pumping tests, double (outflow) packer tests (Charlesworth et al. 1992), particle-size analysis (Gee and Bauder 1986; Whittig and Allardice 1986), and slug testing (Bouwer and Rice 1976). Throughout the Aroca and Nyabisheki catchments, water-supply boreholes, fitted with handpumps, have been drilled using cable-tool and, more recently, air-rotary methods. These boreholes follow a simple design (*Figure 2*), in which the collapsible weathered mantle is sealed off using a steel (0.15-m diameter) casing, and groundwater is drawn exclusively through open fractures in competent bedrock. Examination of the fractured bedrock aquifer was therefore conducted using these existing boreholes (*Figures 4* and *5*).

Due to the absence of shallow wells within the weathered mantle, investigation of the hydrogeological characteristics of these materials required exploratory drilling. A series of 12 piezometers in both catchments (*Figures 4* and *5*) was drilled by air-rotary methods. Piezometer depths range from 7–27 m. PVC screens (76 mm diameter; 2-mm slots) were placed through the saturated zone and filters of quartz gravel (graded to 4 mm) were installed. Solid PVC casings (76 mm diameter) were set through the unsaturated zone. A cement slurry was grouted above the gravel pack as a seal. Backfilling occurred to a depth of 1 m below ground surface, where a concrete seal and skirting were installed. Well development was achieved using an inertial hand pump. Hydraulic connectivity between the aquifer units was assessed by pumping tests of 1–2 days' duration, withdrawing from bedrock fractures and simultaneously monitoring the water table in the weathered mantle, using piezometers installed beside the pumping borehole.

Vertical Heterogeneity of the Fractured-Bedrock Aquifer

Packer testing of the fractured bedrock was performed at 11 sites in the Aroca catchment (*Figure 4*). The transmissivity (T) of fracture zones over an aquifer thickness (b) of 3.7 m, isolated by packers, was estimated using the relationship between hydraulic conductivity (K) and well discharge developed by Hvorslev (1951). Results of 89 packer tests are shown in *Figures 6* and *7*. The bedrock is highly heterogeneous with depth; the T of test intervals typically ranges over several orders of magnitude at each site. A general decrease in the transmissivity of fracture zones with depth has been noted in other studies of crystalline rock (Davis and Turk 1964; Houston and Lewis 1988) and occurs at six of eleven borehole sites in this study (*Figures 6b,f* and *7b–e*). A significant correlation between the aggregate K (T/b) of fracture zones and their depth below the bedrock surface is not evident from the entire data set, as indicated by *Figure 8*. However, fracture zones with an aggregate K>1 m/d occur only within the first 20 m below the bedrock surface. Results of 233 packer tests at 22 sites in the Nyabisheki catchment (*Figure 5*; Howard et al. 1992) are similar to those observed in the Aroca catchment. The aggregate K of tested zones (b = 3.7 m) within the bedrock varies over several orders of magnitude at each borehole. No significant

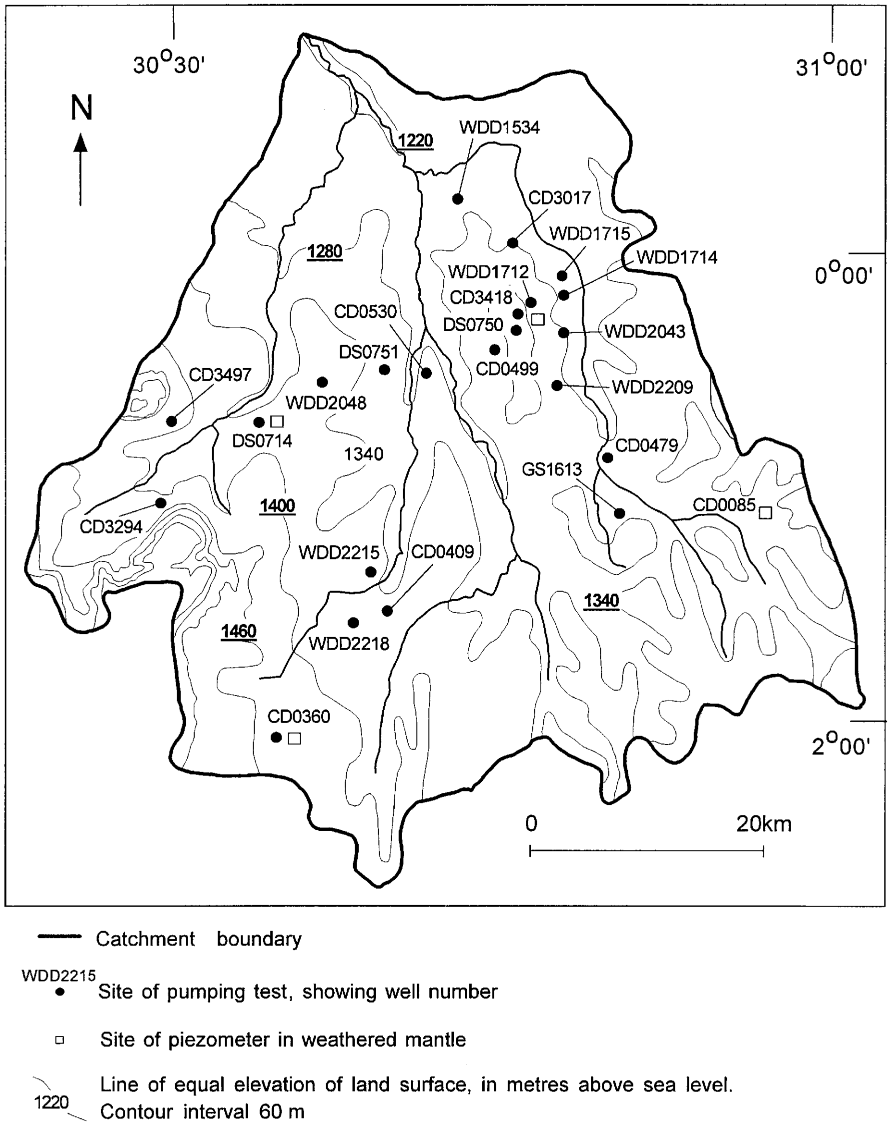


Figure 5 The Nyabisheki catchment in southwestern Uganda, showing topography and locations of tested boreholes and piezometers

correlation between the hydraulic conductivity of fracture zones and their depth below ground surface is apparent. Fracture zones with an aggregate K>1 m/d are restricted to depths of less than 57 m from the ground surface.

Texture and Hydraulic Conductivity of the Weathered-Mantle Aquifer

The in-situ, weathered origin of the overburden is demonstrated by the bimodal particle-size distributions of the profile, as shown in *Figure 9*. The mass fraction of fine-to-medium sand increases with depth, whereas the mass fraction of medium clay decreases. This pattern is typical in the Aroca catchment, where less weathered (coarser) materials occur with depth. The water table occurs at a similar depth (8–13 m) in all eight piezometers. In the Nyabisheki catchment, truncated profiles commonly occur in which shallow, fine-grained horizons are absent. The water table in the Nyabisheki catchment is also commonly below the bedrock surface. A summary of the textural analysis of weathered mantle below the water table is given in *Table 1*, which shows that the weathered-mantle aquifer in the Aroca catchment is a sandy loam (USDA classification).

Enhanced weathering in the unsaturated zone (Taylor and Howard 1999a) produces a clay-rich material of lower permeability and is responsible for apparent, semi-confined conditions in the weathered-mantle aquifer, as observed during drilling. As shown in *Table 2*, static water levels occur at slightly shallower depths than the depth at which water was first encountered during drilling. Semi-confined conditions in the weathered mantle have also been observed in Malawi and Zimbabwe (Chilton and Smith-Carington 1984; Houston and Lewis 1988; McFarlane 1992).

Slug tests were performed on the saturated weathered mantle to provide a measure of K. Results in

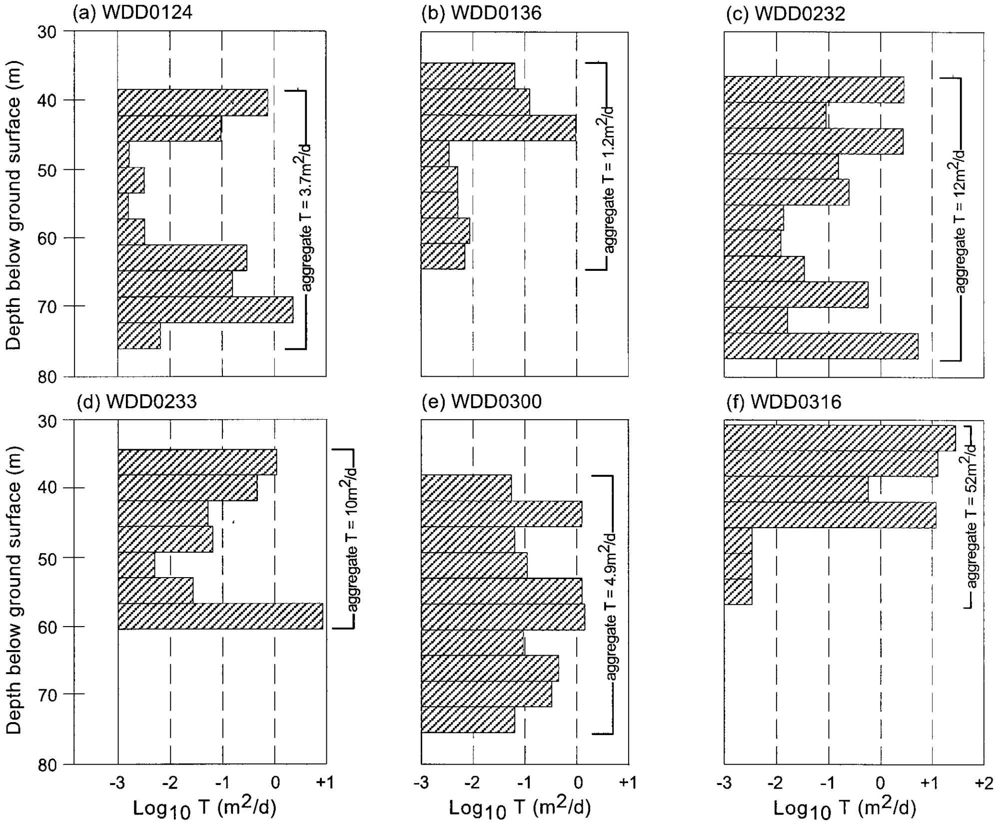


Figure 6 Relation between $\log_{10}$ transmissivity (T) of tested fracture zones and depth for six sites in the Aroca catchment: **a** WDD0124; **b** WDD0136; **c** WDD0232; **d** WDD0233; **e** WDD0300; **f** WDD0316

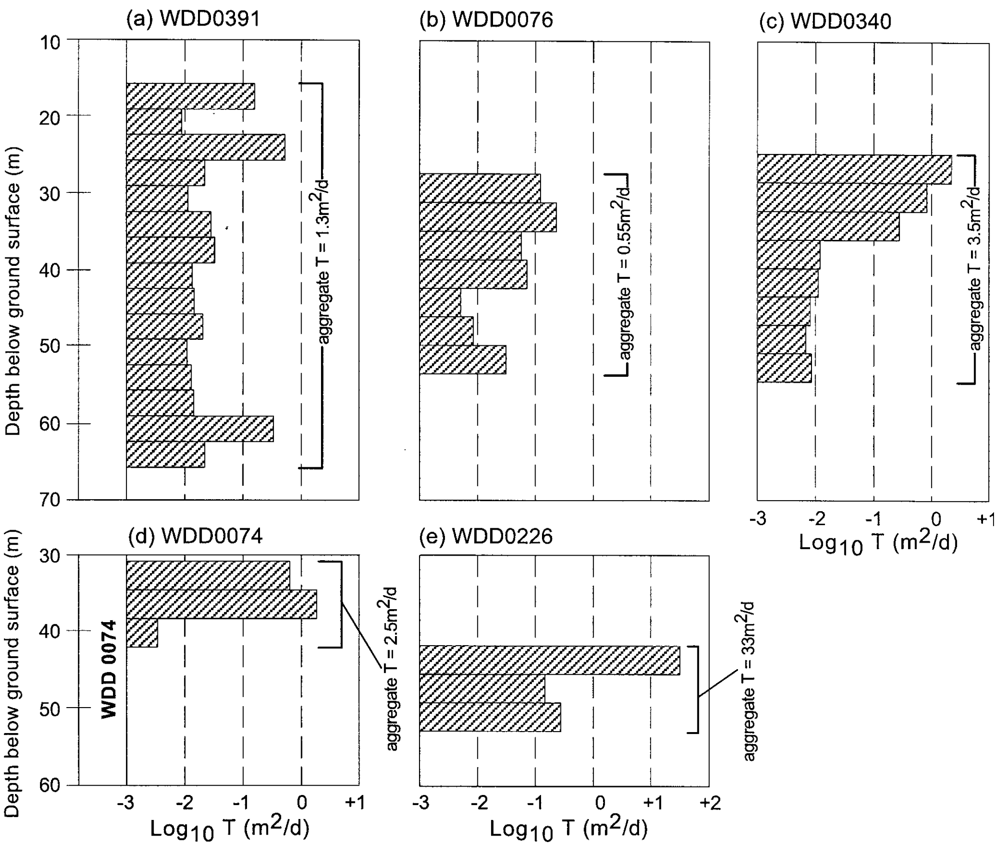


Figure 7 Relation between $\log_{10}$ transmissivity (T) of tested fracture zones and depth for five sites in the Aroca catchment: **a** WDD0391; **b** WDD0076; **c** WDD0340; **d** WDD0074; **e** WDD0226

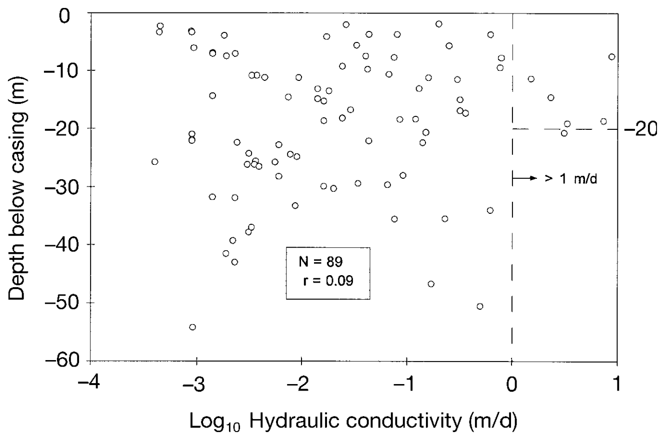


Figure 8 Relation between depth below well casing (i.e., below bedrock surface) and $\log_{10}$ of hydraulic conductivity for packer-tested zones in the fractured-bedrock aquifer of the Aroca catchment

Table 2 show that K ranges from 0.04–0.7 m/d with a median value of 0.4 m/d. Recognising that the weathered mantle becomes coarser with depth and that only the most shallow fraction (30 %) of the aquifer thickness was tested (*Table 2*), bulk K of the weathered-mantle aquifer is expected to exceed 0.4 m/d and is estimated to be approximately 1 m/d. These data are comparable with results in Malawi, where the hydraulic conductivity ranges from 0.2–1.8 m/d (Chilton and Smith-Carington 1984). Thus, with a saturated thickness of 15–20 m in the Aroca catchment (*Table 2*), the T of the weathered mantle is about 5–20 m^2/d, a result that is consistent with work in Malawi, Zimbabwe, and other areas of Uganda, as shown in *Table 3*.

Hydraulic Response of the Fractured-Bedrock Aquifer to Pumping

Drawdown responses during pumping tests in the fractured-bedrock aquifer in Uganda often deviate from the classical confined-aquifer response (Theis 1935), exhibiting a significant reduction in the rate of drawdown with time; examples are shown in *Figure 10*. Stabilisation of drawdown suggests the effects of one or a combination of (1) a constant-head boundary (e.g., surface-water body), (2) microfissures from within the fractured bedrock, or (3) an adjacent water-bearing formation. The absence of surface-water bodies in the vicinity (within 250 m) of any of the tested boreholes precludes the first possibility. Resolution of the principal source of storage from the remaining two possibilities was achieved by determining the best theoretical approximation (i.e., pumping-test solution) of the drawdown response. Solutions for a leaky aquifer (Moench 1985), fractured aquifer (Moench 1984), and a confined aquifer (Papadopulos and Cooper 1967) were considered. The method of Papadopulos and

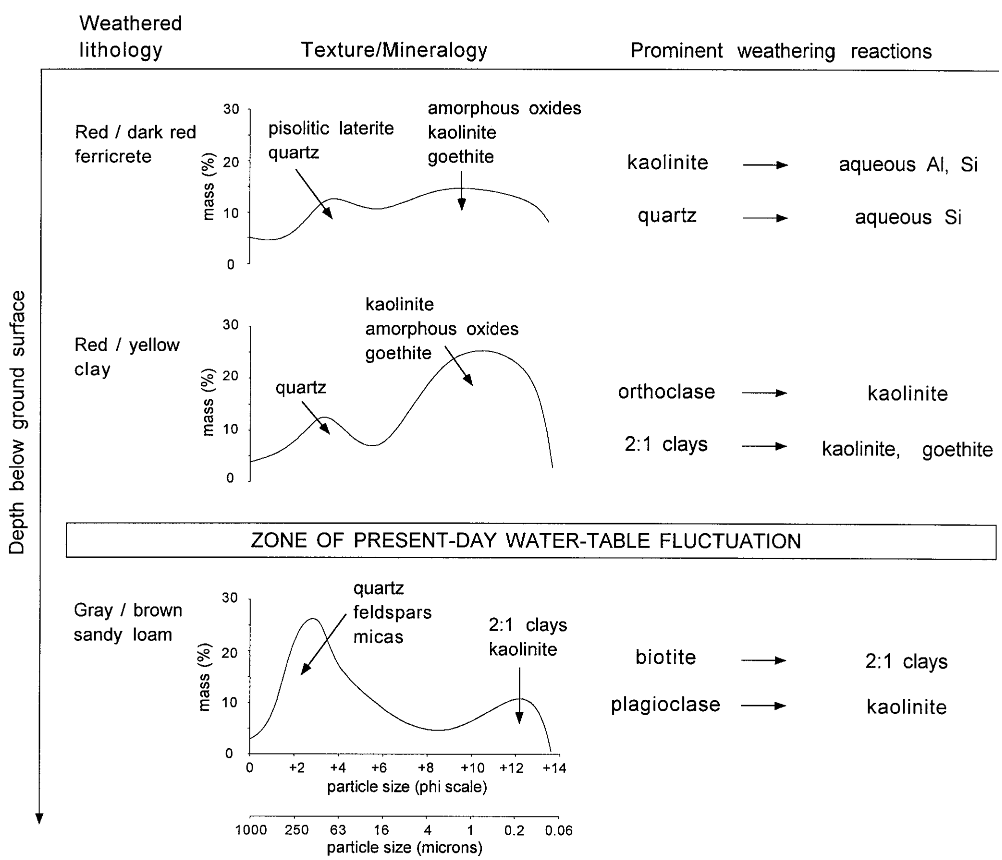


Figure 9 Stratigraphy, texture, and geochemistry of the weathered mantle derived from acid rocks in Uganda. (Modified from Taylor and Howard 1999a)

Table 1 Textural analysis of weathered-mantle aquifer, Aroca catchment. *mbgs* Metres below ground surface

Piezometer	Static water level (mbgs)	Analysed interval (mbgs)	Particle-size distribution[a] (%)			USDA texture
			Sand	Silt	Clay	
Apac MW	9.8	11.0–15.0	76.4 ± 0.1	12.9 ± 0.7	10.7 ± 0.4	Sandy loam
CD0078	7.8	8.8–11.8	67.9 ± 0.1	16.3 ± 0.7	15.7 ± 0.4	Sandy loam
GS1943	9.3	11.0–15.0	77.6 ± 0.1	10.5 ± 0.7	12.0 ± 0.4	Sandy loam
Owang #1	8.0	15.0–18.0	69.5 ± 0.1	19.2 ± 0.7	11.3 ± 0.4	Sandy loam
Owang #3	12.3	17.5–20.0	73.7 ± 0.1	17.1 ± 0.7	9.2 ± 0.4	Sandy loam
Owang #6	10.3	11.0–15.0	63.7 ± 0.1	21.8 ± 0.7	14.5 ± 0.4	Sandy loam

[a] Sand ≥ 62.5 μm; silt > μm; clay ≥ 2 μm (ASTM 1985)

Table 2 Water levels and hydraulic conductivity of the weathered-mantle aquifer, based on slug-test results. *mbgs* Metres below ground surface

Piezometer	Catchment	Depth water struck (mbgs)	Static water level (mbgs)	Δh[a] (m)	Screen interval (m)	Saturated thickness (m)	Fraction screened (%)[d]	K (m/d)[e]
Apac MW	Aroca	10	9.8	+0.2	10.0–15.0	14.0[b]	35	0.04
CD0078	Aroca	8.8	7.8	+1.0	8.8–11.8	12.4[b]	24	-
CD2253	Aroca	14.6	13.2	+1.4	14.6–19.0	22.9[b]	19	0.3
GS1943	Aroca	10	9.3	+0.7	10.0–11.4	14.4[b]	10	-
Owang #1	Aroca	9.2	8.0	+1.2	9.0–17	≈21[c]	≈31	-
Owang #2	Aroca	15	10.9	+4.1	13.0–19.0	≈17[c]	≈35	0.5
Owang #3	Aroca	12	12.3	-0.3	13.0–17.0	≈17[c]	≈24	-
Owang #6	Aroca	11	10.3	+0.7	10.5–13.1	≈20[c]	≈13	0.7
Median (Aroca)		11.5	10.1	+0.9	-	≈17	≈24	0.4
CD0360	Nyabisheki	21	19.2	+1.8	21–27.4	≈11[c]	≈60	0.05
DS0714	Nyabisheki	-	13.0	-	12–21	15.7[b]	51	-

[a] Δh=depth of water struck – depth of static water level
[b] Saturated thickness = (adjacent) borehole casing depth – depth of static water level
[c] Saturated thickness = depth to bedrock (from EM soundings) – depth of static water level
[d] Upper fraction of aquifer in weathered mantle
[e] Hydraulic conductivity derived from slug/bail tests using the solution of Bouwer and Rice (1976)

Table 3 Transmissivity (*T*) of weathered mantle (regolith) in parts of Africa, based on pumping-test results

T range (m^2/d)	T mean[a] (m^2/d)	No. of sites	Location	Reference[b]
1–20	5.5	134	Livulezi, Malawi	Chilton and Foster (1995)
0.2–5	2.1	81	Dowa, Malawi	Chilton and Foster (1995)
1–60	5.2	64	Masvingo, Zimbabwe	Chilton and Foster (1995)
2–10	3.4	27	Masvingo, Zimbabwe	Chilton and Foster (1995)
0.2–40	4.6	6	Malawi/Zimbabwe	Chilton and Foster (1995)
0.4–170	4.8	40	Mukono, Uganda	Taylor (unpublished data)

[a] Geometric mean
[b] Also references therein

Cooper (1967), which takes into account well-storage effects, was adopted to represent the response of a confined aquifer, because it matches field data more closely than does the Theis (1935) curve.

Results of pumping-test interpretations from both study areas are presented in *Tables 4* and 5. Although pumping rates and the durations of tests varied, matching solutions were obtained in a number of instances. In the Aroca catchment (*Table 4*), leaky-aquifer conditions (*Figure 10b*) were resolved at 10 of 11 sites tested. The response of the fractured bedrock to pumping was significantly more variable in the Nyabisheki catchment (*Table 5*). A leaky-aquifer solution satisfactorily represents the drawdown response at 5 of 21 sites. Confined and leaky aquifer solutions are both able to represent the drawdown response (i.e., the aquifer type could not be resolved) at 11 sites. At 5 sites, the response was best matched by the fractured-aquifer solution of Moench (1984). A summary of the results from both catchments is given in *Table 6*.

Median values of bulk T and specific capacity, C_s, from each catchment area are very similar. The principal difference between the study areas is the response

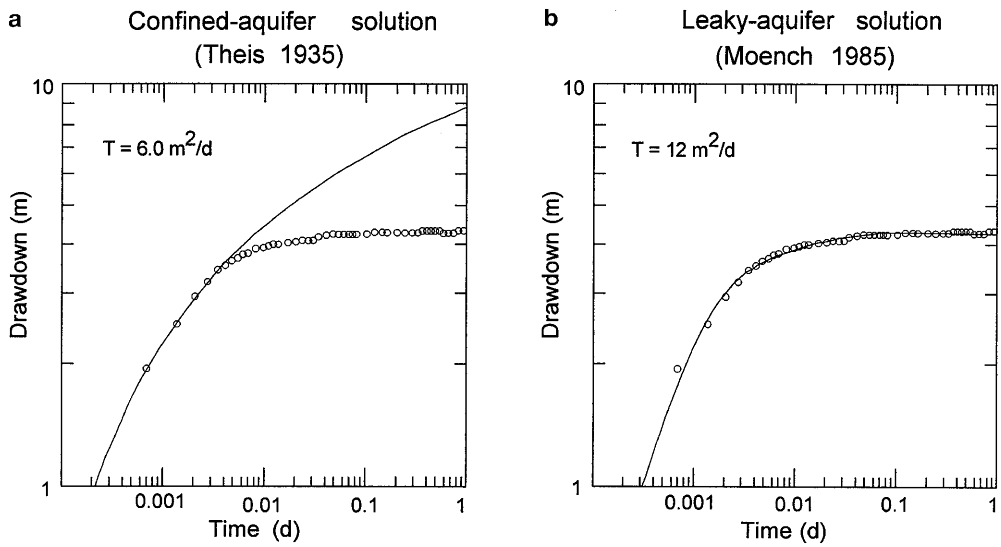


Figure 10 Pumping-test solutions to drawdown response in the fractured-bedrock aquifer with time for borehole CD0078 in the Aroca catchment. **a** Theis (1935); **b** Moench (1985)

Table 4 Results of pumping tests conducted in the fractured-bedrock aquifer of the Aroca catchment. *T* Transmissivity; *K* matrix hydraulic conductivity; C_s specific capacity

			Matching pumping-test solution			
Borehole number	Pumping rate (m^3/d)	Duration (h)	Leaky[a] T (m^2/d)	Confined[b] T (m^2/d)	Fractured[c] K (m/d)	C_s (actual) (m^3/d/m)
CD0078	72	24	14	-	-	17
CD0722	60	24	1.2	-	-	2.3
CD0875	22	3	0.47	0.44	-	1.0
CD1686	58	5	1.0	-	-	3.0
CD2253	38	3	0.62	-	-	2.6
CD3104	66	5	1.2	-	-	3.8
CD3345	35	3	0.33	-	-	1.1
CD3651	72	5	8.4	-	-	15
GS1722	54	4	8.0	-	-	9.0
GS1943	72	24	5.9	-	-	6.6
WDD0312	58	5	10	-	-	14

[a] Moench (1985)
[b] Papadopulos and Cooper (1967)
[c] Moench (1984)

of the fractured bedrock to pumping. In the Aroca catchment, leaky-aquifer conditions are consistently observed. In the Nyabisheki catchment, the response varies to include fractured and leaky aquifer conditions as well as that which is unresolved between a confined and leaky aquifer. Median bulk T of the fractured-bedrock aquifer in Uganda ($\approx$1 m^2/d) is less than the estimated T for the weathered-mantle aquifer (5–20 m^2/d). This finding differs from previous suggestions that the unconsolidated aquifer has a relatively low transmissivity, whereas the fractured bedrock has a relatively high transmissivity (Rushton and Weller 1985; Acworth 1987; Houston and Lewis 1988; Barker et al. 1992).

Horizontal Heterogeneity of the Fractured-Bedrock Aquifer

Bulk transmissivities of the fractured bedrock determined by pumping tests vary over three orders of magnitude (*Tables 4* and *5*) and are comparable with the results of packer testing, as shown in *Figure 11*. Results of previous studies of fractured crystalline rock are shown in *Table 7*. In all studies, bulk T varies similarly, over three orders of magnitude. The fractured-bedrock aquifer demonstrates, therefore, not only vertical heterogeneity, as determined by packer testing, but also significant horizontal heterogeneity. Horizontal heterogeneity is attributed to local variations in lithology. Pronounced lithological control is consistent with geochemical evidence from Kenya (Pye 1986) and Uganda (Taylor and Howard 1998), which suggests that a higher ratio of orthoclase to plagioclase in parts of the bedrock is responsible for the development of inselbergs ("island hills") on account of the greater resistance of orthoclase to weathering.

The ability to predict transmissive (productive) fracture zones in the bedrock has been central to efforts to improve the success of borehole drilling programmes in deeply weathered terrains. To this end, surface-geophysical methods such as electrical resist-

Table 5 Results of pumping tests conducted in the fractured-bedrock aquifer of the Nyabisheki catchment. *T* Transmissivity; *K* matrix hydraulic conductivity; C_s specific capacity

Borehole number	Pumping rate (m^3/d)	Duration (h)	Matching pumping-test solutions			C_s (actual) ($m^3/d/m$)
			Leaky[a] T (m^2/d)	Confined[b] T (m^2/d)	Fractured[c] K (m/d)	
CD0360	30	42	2.3	-	-	7.9
CD0409	12	4	0.64	0.75	-	2.1
CD0479	15	4	-	-	0.27	19
CD0499	22	4	4.7	6.0	-	6.2
CD0530	51	21	11	12	-	32
CD3294	22	4	7.3	-	-	6.8
CD3418	10	22	1.0	1.2	-	0.93
CD3497	4.3	16	0.24	-	-	0.51
DS0714	34	3.5	0.81	0.98	-	1.5
DS0750	30	3	-	-	0.83	34
DS0751	14	3.5	-	-	0.044	12
GS1613	13	4	1.0	1.0	-	2.6
WDD1534	17	9	-	-	0.34	2.4
WDD1712	50	9	0.67	2.2	-	2.1
WDD1714	10	3.5	3.9	-	0.0045	1.2
WDD1715	6	3	0.12	0.40	-	0.43
WDD2043	10	3	0.43	0.85	-	1.1
WDD2048	31	12	5.2	-	-	3.9
WDD2209	10	3.5	0.22	0.20	-	0.58
WDD2215	7.8	4.5	0.13	-	-	0.51
WDD2218	14	4	0.37	0.34	-	1.2

[a] Moench (1985)
[b] Papadopulos and Cooper (1967)
[c] Moench (1984)

Table 6 Summary of pumping-test results from the fractured-bedrock aquifer in the Aroca and Nyabisheki catchments. *T* Transmissivity; C_s specific capacity

Catchment	Total no.	No. leaky[a]	No. fractured[b]	No. undefined[c]	Median T[d] (m^2/d)	Median C_s ($m^3/d/m$)
Aroca	11	10	0	1	1.2	3.8
Nyabisheki	21	5	5	11	1.0	2.1

[a] Moench (1985) leaky-aquifer solution
[b] Moench (1984) fractured-aquifer solution
[c] Confined solution (Papadopulos and Cooper 1967) or leaky-aquifer solution (Moench 1985)
[d] For fractured aquifers, T = K· (length of borehole below well casing)

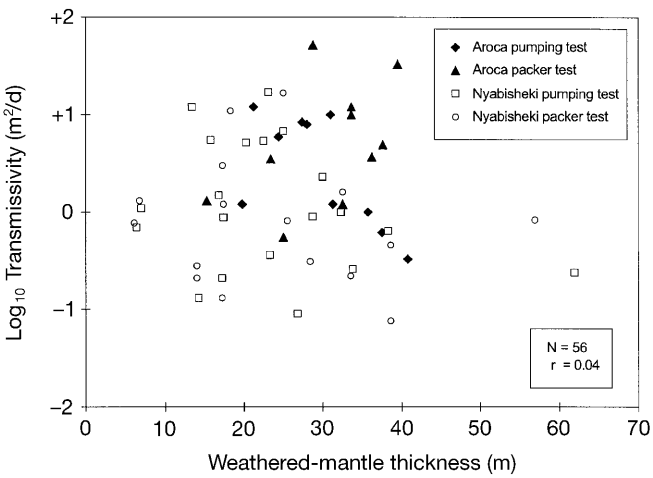


Figure 11 Relation between (1) $\log_{10}$ bulk transmissivity of the fractured-bedrock aquifer, determined by packer testing and pumping tests in both study areas, and (2) thickness of weathered mantle, indicated by depth of borehole casing

ivity and electromagnetics have commonly been employed. Although electrical-resistivity methods have been shown to indicate the thickness of the weathered mantle (i.e., depth to the top of bedrock) (White et al. 1988), correlations between geophysical data and borehole yields in fractured crystalline rock have not been realised (Olayinka 1992; Olorunfemi et al. 1995). Barker et al. (1992) assert, nevertheless, that maximum regolith development (i.e., thickness of the weathered mantle) occurs where the degree of fracturing within the bedrock is greatest. Results of packer tests and pumping tests in both catchments of Uganda challenge this assertion. A plot of bedrock transmissivity versus weathered-mantle thickness (*Figure 11*) shows no correlation between these two parameters at 56 sites.

Two assumptions that are central to the assertion of Barker et al. are that (1) fractures in the bedrock arise primarily from decompression associated with the weathering of overlying rock (i.e., sheeting), and (2) the observed thickness of the weathered mantle

Table 7 Transmissivity (T) for fractured crystalline rock, as reported for previous studies in Africa. *n.a.* Data not available

T range (m^2/d)	T mean[a] (m^2/d)	No. of sites	Method	Location	Reference
5–60	n.a.	25	Pumping tests	Botswana	Buckley and Zeil (1984)
0.8–80	5.5	60	Pumping tests	Zimbabwe	Houston and Lewis (1988)
0.9–90	7.3	69	Pumping tests	Zimbabwe	Houston and Lewis (1988)
0.07–250	1.1	22	Packer tests	Uganda	Howard et al. (1992)

[a] Geometric mean

(regolith) is a measure of the amount to which the overlying stress has been reduced to induce fracturing. The first assumption appears to be valid, based on the general observation that the most productive fractures occur just below (<20 m) the bedrock surface (Houston and Lewis 1988; Howard et al. 1992; this work). Genesis of these productive fractures is best explained by sheeting. The second assumption depends upon a notion of unicyclic weathered-mantle development, which is at odds with the polycyclic evolution of weathered mantles (i.e., regoliths) in Africa (Ollier 1959; Thomas 1965; Partridge and Maud 1987; Taylor and Howard 1998) and other Gondwana continents, including Australia (Hill et al. 1995), India (Demangeot 1975), and South America (Schaeffer et al. 1995). From the Jurassic to early Miocene times, the Aroca and Nyabisheki catchments underwent a parallel geomorphic evolution of prolonged deep weathering followed by stripping. Since early Miocene time, the land surface in the Aroca catchment has been deeply weathered, whereas the Nyabisheki catchment has been subjected to cycles of stripping during mid-Miocene time and from mid-Pleistocene time. In this light, similar hydrogeological characteristics of the fractured bedrock observed in both catchments can be explained by decompression that was induced by comparable erosional unloading from the Jurassic Period to the Miocene Epoch. This could explain, furthermore, why present-day weathered-mantle thickness is not necessarily related to the transmissivity of bedrock fractures. Relative to this geomorphic influence, slight differences in the petrology of Precambrian micaceous rocks between the Aroca and Nyabisheki catchments are not considered significant.

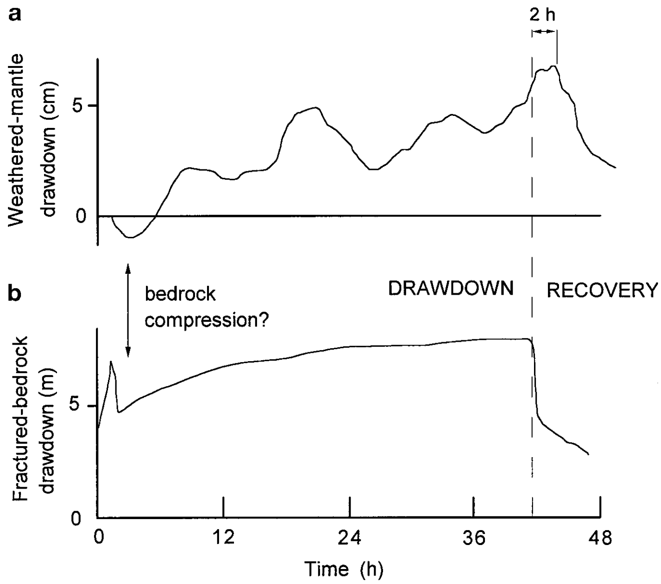


Figure 12 Relation between drawdown and time (linear plot) in **a** weathered mantle and **b** fractured bedrock, for a 2-day pumping test at borehole CD0360 in the Nyabisheki catchment

Hydraulic Connectivity of the Fractured-Bedrock and Weathered-Mantle Aquifers

Leakage from the weathered mantle, which is inferred from "leaky aquifer" responses to pumping of the fractured-bedrock aquifer, is supported by measurements of hydraulic head (h) in the weathered mantle during prolonged pumping tests of the fractured-bedrock aquifer; data and results are shown in *Table 8*. Drawdown in the weathered-mantle aquifer was

Table 8 Comparison of water levels in the weathered mantle and fractured bedrock under static (non-pumping) conditions and conditions of pumping from the fractured-bedrock aquifer

		Static water levels			Pumping water levels		
Borehole number	Piezometer distance (m)	Fractured bedrock (mbgs)[a]	Weathered mantle (mbgs)[a]	Δh^b (m)	Fractured bedrock (mbgs)[a]	Weathered mantle (mbgs)[a]	Δh^b (m)
CD0078	4.7	8.46	6.83	1.63	12.78	6.86	5.92
CD0722	4.0	2.23	2.08	0.15	30.75	2.20	28.55
CD2253	4.6	13.28	12.58	0.70	36.37	12.68	23.69
GS1943	5.9	9.93	9.33	0.60	20.98	9.36	11.62
CD0360	3.8	19.00	18.63	0.37	26.91	18.70	8.21

[a] mbgs: metres below ground surface
[b] magnitude of the difference in hydraulic head (h) between the weathered mantle and fractured bedrock

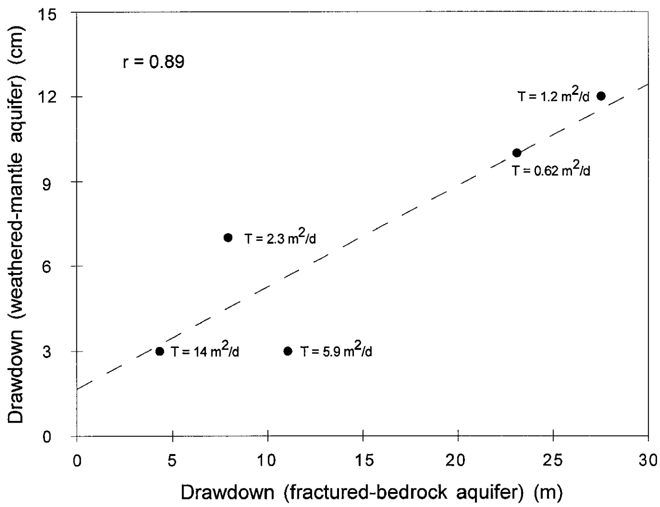


Figure 13 Relation between drawdown in weathered mantle and drawdown in fractured bedrock during pumping tests of 1–2 days' duration at five sites in both study areas

observed during each pumping test. *Figure 12* is a linear plot of drawdowns for site CD0360 in the Nyabisheki catchment. Drawdown in the weathered mantle occurred several hours after the commencement of pumping and continued for 1–2 h after pumping ceased. Recovery was then relatively rapid and confirms hydraulic interaction between aquifer units. The influence of barometric pressure on water levels in the weathered mantle could not be resolved because of an absence of measurements, both historically and at the time of pumping. Although this influence is often significant, the observed trend in drawdown in the weathered mantle (*Figure 12*) suggests that barometric pressure played a secondary role to the hydraulic stress imposed through drawdown in the fractured bedrock. This is supported by the fact that the magnitude of drawdown in the fractured bedrock correlates well with the magnitude of drawdown in the weathered mantle, as shown in *Figure 13*. These data show that the boreholes tapping the less transmissive bedrock had greater drawdown within the fractured-bedrock aquifer and induced increased drawdown in the weathered mantle.

Leakage from the weathered mantle to bedrock fractures is also indicated by stable isotope tracers (^{2}H, ^{18}O), which show that aquifers in the weathered mantle and fractured bedrock receive recharge from the same source, monsoonal rainfall (Taylor and Howard 1996, 1999b). Because the fractured bedrock is entirely concealed by the weathered mantle in the Aroca catchment, monsoonal rainfall necessarily provides recharge to the fractured-bedrock aquifer through leakage from the overlying weathered mantle. Confirmation of the link between the two aquifers, which is indicated by pumping-test and isotopic data, is of practical significance. Leaky-aquifer conditions in the fractured bedrock during test pumping of boreholes necessarily indicate the contribution of groundwater storage from the weathered mantle. Because fractured crystalline rock has a low storativity, the presence of a hydraulic connection to the more porous overburden is critical to the long-term productivity of boreholes drawing from bedrock fractures.

Tectono-Geomorphic Model of the Hydrogeology of Deeply Weathered Crystalline Rock

The hydrogeology of weathered crystalline rock in the two study areas differs primarily by the extent of the aquifer in the weathered mantle. These areas feature contrasting post-Miocene geomorphic histories that have been described by Taylor and Howard (1998, 1999a, 1999b). Cross-sectional models of the regional hydrogeological characteristics for each surface and their relationship to present-day movement of meteoric water, and, hence, geomorphic process, are depicted in *Figure 14*. The models, summarised below, demonstrate the interrelationships among the geomorphology, hydrology, and hydrogeology of weathered crystalline rock on a regional scale. The extent of the Miocene/Recent surface and of the surface of stripping following mid-Pleistocene uplift in Uganda, which are represented by the Aroca and Nyabisheki catchments, respectively, is shown in *Figure 3*.

On the surface of deep weathering in Uganda (the Miocene/Recent surface), very gently sloping convex interfluves (Ollier et al. 1969) of low relief include a thick (≈30-m) mantle developed by in-situ weathering of crystalline rock since the Miocene Epoch (Taylor and Howard 1998, 1999a). Contemporary deep weathering results from a large ratio of annual recharge to runoff (25–40:1) with recharge events during bimodal pulses of monsoonal rainfall (Taylor and Howard 1996, 1999b). Transmission of the recharge flux in the subsurface occurs by way of a regional aquifer in the weathered mantle and a less transmissive aquifer in the fractured bedrock. Due to very small surface gradients and a corresponding lack of incision, groundwater discharge occurs primarily by evapotranspiration within extensive wetlands (dambos) that form a significant fraction (5–10%) of the basin area. Basin discharge is buffered by the high storage capacity of the thick weathered mantle.

On the surface of stripping in Uganda (i.e., the extent of mid-Pleistocene stripping), broadly concave interfluves (Ollier et al. 1969) of variable relief feature a thinner weathered mantle that has been subjected to cycles of stripping in mid-Miocene time and since mid-Pleistocene time (Taylor and Howard 1998, 1999a). Continued stripping is effected by a low ratio of annual recharge to runoff (0.17–0.33:1) (Taylor and Howard 1999b). The significantly reduced recharge flux, relative to that of the surface of deep weathering, is transmitted to well incised drainage channels by the

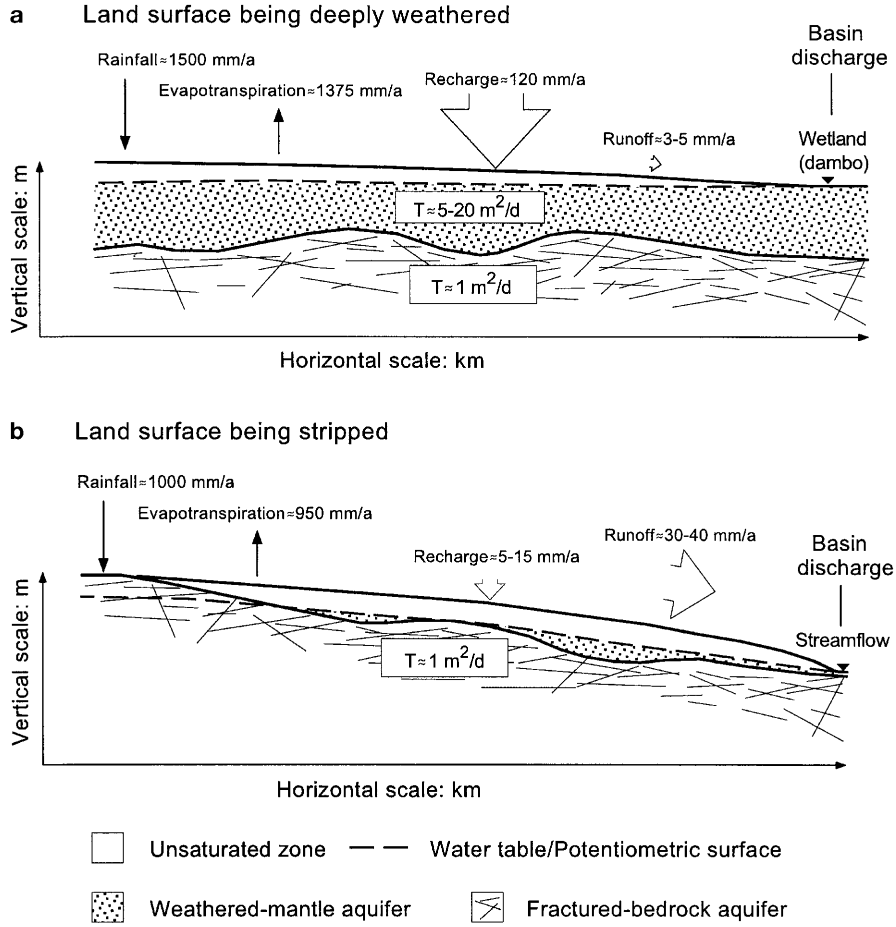


Figure 14 Conceptual cross-sectional models of regional hydrogeology for **a** surface of deep weathering and **b** surface of stripping. Hydrological fluxes and aquifer transmissivities derived from study of two catchments (Aroca and Nyabisheki) in Uganda. (From Taylor and Howard 1999b; this work)

fractured bedrock and, in places, by localised aquifers in the weathered mantle. Discharge is in the form of highly variable streamflow that results from the high runoff component and the fact that the thinner weathered mantle reduces buffering of the basin inputs (runoff, recharge).

Evidence in Uganda shows that weathered land surfaces evolve by tectonically controlled cycles of deep weathering and stripping (Taylor and Howard 1998, 1999a, 1999b). Tracing the geomorphic evolution of weathered land surfaces and identifying the dominant geomorphic process operating on those land surfaces (i.e., deep weathering or stripping) provide an understanding of the hydrogeological and hydrological characteristics of each surface. This tectono-geomorphic model for comprehending weathered-aquifer systems embodies the "holistic" approach recommended by other authors (Foster 1984; Acworth 1987; Wright 1992). Furthermore, it is of practical use to planners, because it enables definition of suitable areas for the development of the weathered-mantle aquifer and intensive groundwater abstraction (200–1000 m^3/d) from the weathered mantle and fractured bedrock.

Summary and Conclusions

This study demonstrates that the hydrogeological characteristics of deeply weathered crystalline rock derive from and, hence, are related to long-term, tectonically controlled geomorphic processes. Permeability in the bedrock arises from fractures, which are attributed to decompression resulting from the removal of overlying rock in solution (deep weathering) and by colluvial and fluvial erosion (stripping). The overlying unconsolidated mantle is the product of deep, in-situ weathering. Sand-sized clasts predominate at the base of the mantle and form an aquifer that is an order of magnitude more transmissive (5–20 m^2/d) than underlying bedrock fractures ($\approx$1 m^2/d). This conclusion, noted previously (Chilton and Smith-Carington 1984; Howard and Karundu 1992), highlights the practical importance of investigating the extent of the more productive, weathered-mantle aquifer rather than the common and expensive pursuit of often illusory fractures deep within the bedrock. Vertical heterogeneity in both aquifers is due to the geopetal influence of deep weathering and stripping (i.e., in-situ vertical differentiation and isostatic uplift). The weathered mantle provides storage for the fractured-bedrock aquifer, and thus the two units form an integrated aquifer system, albeit of highly variable and relatively low transmissivity.

The hydrogeological characteristics of deeply weathered crystalline rock are, on a regional scale, well explained by the tectono-geomorphic model. In the areas of tectonic quiescence, where the land surface is being deeply weathered, the aquifer in the weathered mantle is regionally extensive. In contrast, aquifer occurrence in the weathered mantle is localised in areas of (recent) tectonic uplift, where the land surface is being actively stripped. Similar vertical heterogeneity and median bulk transmissivity of the fractured bedrock arise from long-term, parallel histories of erosional unloading from the Mesozoic Era to the Miocene Epoch, causing comparable decompressive stresses within the bedrock. Recognition of how meteoric water has affected and continues to drive the geomorphic processes (deep weathering and stripping) acting on deeply weathered land surfaces is the key to understanding the hydrogeological characteristics of these complex environments.

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