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Evidence for extreme variations in the permeability of laterite from a detailed analysis of well behaviour in Nigeria

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Abstract:

Laterite soils are widespread in tropical Africa and have a large impact on the hydrology of the areas they cover. The permeability of laterite helps determine the partitioning of runoff and interflow and regulates groundwater recharge to underlying bedrock. Groundwater within laterite also forms a widespread source of drinking water, typically from unimproved hang-dug-wells. Despite its importance, there is little published information on laterite aquifer properties. In this study, data from a 6 m deep well in Nigeria have been analysed to characterise the hydraulic conductivity of the laterite from repeated pumping tests. Transmissivity measurements from 40 tests spread out across a hydrological year varied from 0.1 to 1000 m^2/d. Further interpretation of the data demonstrate a strong non-linear decrease in horizontal hydraulic conductivity with depth, characterised by an upper horizon of extreme permeability (400 m/d), and a much lower permeability profile beneath (<0.1 m/d). These data are substantiated with observations from other wells throughout the area. This non-linear permeability structure has several implications: the upper laterite can facilitate rapid lateral throughflow in the wet season, enabling contaminants to be transported significant distances (up to 1 km); natural groundwater levels are restricted to a narrow range for much of the year; and, in the dry season, the lower permeability of the deeper laterite restricts the amount of water which can be abstracted from shallow wells, leading to well failure. The work highlights the need for a wider study to better understand laterite soils and the role they play in regional hydrology. © 2013 Natural Environment Research Council. *Hydrological Processes* published by John Wiley & Sons Ltd.

KEY WORDS laterite; permeability; groundwater

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BACKGROUND

Laterite soils have widespread occurrence in tropical Africa (Figure 1) (Areola 1996; Fookes 1997). The soils are important to both the hydrology and hydrogeology of these areas: controlling the partitioning of rainfall between runoff and slower moving shallow groundwater; regulating recharge to underlying bedrock aquifers; and also providing an important thin aquifer in their own right (Lawrence *et al.*, 2001; Skinner 2003; Pritchard *et al.*, 2008; Taylor *et al.*, 2010). Despite the importance of laterite soils, little is published on their aquifer properties or the extent to which they impact surface water and groundwater resources. Improving our understanding of the hydrogeology of laterite soils is increasingly important in helping to determine how runoff, groundwater recharge and groundwater supply will respond to climate change (Taylor *et al.*, 2010; Bonsor *et al.*, 2010; Cuthbert M.O. and Tindimugaya C. 2010).

The term laterite is used broadly to describe the deeply weathered, red or yellow soils which are widespread within the tropics worldwide (Driesson *et al.*, 2001). Laterite soils form as the result of intense weathering of old (Pleistocene or older) stable geomorphic surfaces in humid climates and are characterised by high concentrations of residual, primary minerals alongside sesquioxides and kaolinite in the upper soil profile, which is what gives the yellowish (goethite) or reddish (haematite) soil colour (McFarlane 1970; Ollier and Galloway 1990; Areola 1996; Fookes 1997; Driesson *et al.*, 2001).

Distinct horizons are developed in laterite from the long-term weathering process, with a general translocation of clays towards the base of the laterite and retention of iron and/or aluminium-minerals in the upper horizons (Langsholt 1992; Thomas 1995; Dalhous *et al.*, 2000; McFarlane and Bowden, 2006). Overall, the permeability of the laterite is known to decrease with depth (e.g. Sharma *et al.*, 1987; Fookes 1997), but the rate and magnitude of change in permeability with depth are poorly understood with only a few quantitative studies (Ruprecht and Schofield 1993). Within the most intensely weathered laterite soils, hard concretionary ferricrete layers with

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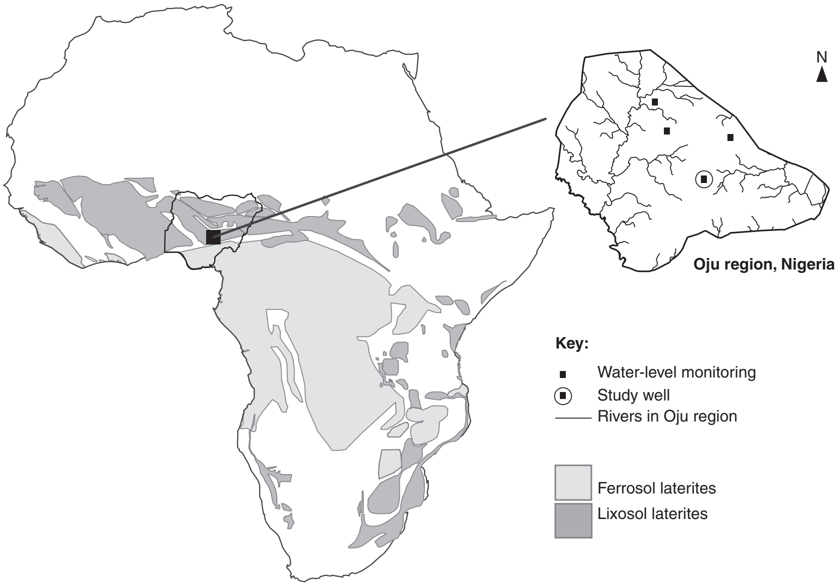

Figure 1. The extent of the main types of laterite soils in Africa, with inset showing the Oju study area and well locations, southeast Nigeria. Adapted from FAO 2001 Soils of the World

tubular void spaces can develop in the uppermost horizons, whilst a pronounced clay layer can develop at the base (McFarlane 1970; Langsholt 1992; Dalhaus *et al*., 2000; Driesson *et al*., 2001). These laterite soils are termed Lixosols, and the clay-rich horizon is usually developed within 5 m from the ground surface (Driesson *et al*., 2001). This leads to shallow zones of high permeability in the upper laterite (Taylor *et al*., 2010) that can facilitate rapid throughflow of groundwater analogous to that within high permeability, low storage karstic aquifers (Langsholt 1992; White 2002; Grasso *et al*., 2003), above a low permeability clay base (Ollier and Galloway 1990). Such properties of laterite are important to the movement and quality of shallow groundwater, both within the laterite and to underlying bedrock (Lawrence *et al*., 2001; Skinner 2003; Pritchard *et al*., 2008; Taylor *et al*., 2010).

The objective of this paper is to provide detailed quantitative data on the aquifer properties of laterite soils in an area of Nigeria to give better insight into how these soils can impact the hydrology and hydrogeology of the areas they cover. The study applies an analysis of water-level and pumping test data collected during a wider hydrogeological investigation in the Oju region of southeast Nigeria in 1996–2000 (Davies and MacDonald 1999; MacDonald *et al*., 2005).

STUDY AREA

The Oju region in southeast Nigeria (Figure 1) has a seasonally wet climate with 1600 mm annual rainfall falling within intense rainfall events over a 6 month wet season (Davies and MacDonald 1999). Oju is situated in the lower section of the Benue Trough, a major geological rift structure infilled with Cretaceous-age fine-grained, low permeability sediments (Ofoegbu 1985; MacDonald *et al*., 2005). A complex laterite soil has developed across the area as the result of prolonged exposure of the Cretaceous sediments to a tropical climate. Due to the low permeability of the bedrock aquifers, many people are reliant on shallow wells within the laterite; however, these are characterised by seasonal deterioration in yield during the dry season leading to the failure of 95% of shallow wells by the end of the dry season (MacDonald and Davies 1997). Seasonal deterioration in water quality within the wet season often further compromises the sustainability of unimproved shallow wells within the laterite in the region.

The stratigraphy of the laterite at the study site was determined from drill core-sections and cuttings collected during well construction and clay analyses. The laterite displays a strong weathering profile and is classified as a *lixosol* according to the FAO (2001) pedogenetic classification (Driesson *et al*., 2001). Below topsoil, reddish-brown ferrallitic material, rich in iron oxide extends to 2.5 m below ground level (mbgl) (Figure 2). This is underlain to 3 mbgl, by a concretionary horizon containing pisoliths and concentric and linear void spaces. Below 3 mbgl, clayey horizons interlayered with thin weathered bands of siltstone comprise an increasing proportion of the laterite (Figure 2). The base of the weathered laterite profile is marked by a highly weathered pallid clay layer, which extends to the weathered bedrock surface at 4.75 mbgl (Figure 2).

The study well, from which the pumping test data were analysed, is a large-diameter (1.4 m) shallow hand-dug

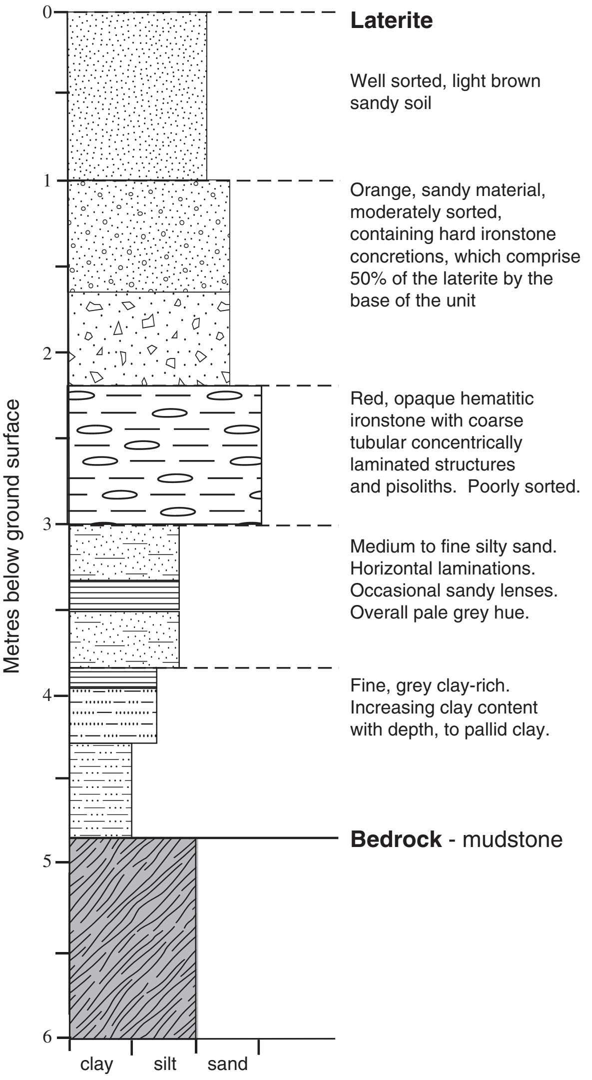

Figure 2. Laterite lithology, Oju

well 6 m deep. The base of the well partially penetrates (by 0.5 m) the mudstone bedrock which underlies the laterite in Oju. Water-level data were also analysed from a 165 mm diameter observation borehole cored to 12 m, situated 5 m from the pumped well. This observation borehole was left open across its full length and stabilised with screen (127 mm diameter). An unpumped, unlined traditional well, 5 m deep, situated 20 m from the pumped well was also monitored for part of the year. The data are augmented by regional water-level data from 11 pumped wells in the Oju region (approx. 1600 km^2).

METHODS

The data series used for analysis covered the hydrological year 1998–1999 and are shown in Figure 3. The study well was at the disposal of the research team for 1998–1999, and over 115 pumping cycles are recorded in the data series, from controlled conditions. A constant rate submersible pump, set at 1.1 l/s was used throughout the pumping test series. Continuous water-level data are available from the pumped well from a munro-record; whilst daily manual dip data are available for the two observation wells, 5 and 20 m from the pumped well. Daily rainfall data were collected on site.

Sixty pumping tests were selected from 13 different time intervals within the 1998–1999 dataset for analysis. The tests were selected on the basis of the time of year and the saturated thickness of the laterite immediately adjacent to the well when the pumping tests were conducted. By selecting 60 tests at chronological intervals in 1998–1999 dataset, it was possible to generate a subset of the pumping test data which related to different saturated thicknesses of the laterite surrounding the study

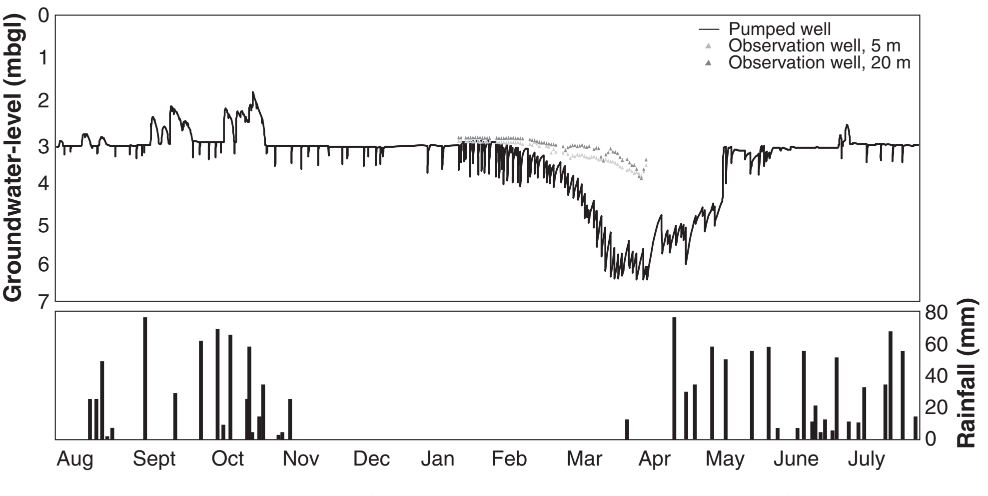

Figure 3. Water-level data from the three study wells in Oju and daily rainfall data

well – enabling the aquifer properties of different laterite horizons to be examined. All the tests within the 1998–1999 dataset were conducted using a set pumping rate of 1.1 l/s, and a fixed volume of water was extracted from the well each time. Half the selected pumping test series are distributed throughout the dry season and half within the wet season.

The pumping test data were analysed using BGSPT (Barker 1988; Barker and Macdonald 2000). BGSPT is a freely available computer programme which numerically solves the generalised well function developed by Barker (1988) for large-diameter wells in fractured aquifers and incorporates many other well functions as special cases (e.g. that of Papadopulos and Cooper (1967)). It evaluates the solution using the numerical Laplace transform inversion and achieves a fit to data by least squares through a series of iterations. The BGSPT model has been used successfully for analysing pumping test data from wells with storage in a variety of aquifers worldwide (e.g. Mace 1999, Kulkarni *et al*., 2000; MacDonald *et al*., 2008). Where several pumping cycles were recorded in rapid successive, these were analysed together to determine an average transmissivity. This reduced the chance of deriving anomalous transmissivity values from incomplete recovery of the well.

RESULTS

Water-level data. The continuous water-level record from the pumped well (Figure 3) indicates marked differences in the laterite source behaviour at different times of the year. From May to February, an almost constant groundwater level of 3.0 m below ground level (bgl) is maintained in the well (Figure 3). In response to rainfall, the water table rises rapidly from this base level over a period of hours in the wet season and returns to the base level over a period of days. This gives rise to asymmetric peaks in the water-level record from the base water level in the wet season (Figure 3). On cessation of pumping, there is a rapid recovery during the wet season, with water levels returning to the base groundwater level at 3 mbgl within minutes, but the response becomes markedly slower through the dry season (Figure 4). By the mid dry season (February), the response to cessation of pumping is slow (days), and there is incomplete recovery of water levels between successive pumping tests, and the water level in the pumped well begins to decline (Figures 3 and 4). By the end of the dry season (April), the water level is shown to drop by 3 m (from 3 to 6 mbgl) and the well effectively fails (Figure 3). Water levels in the well recover to the original base level of 3 mbgl over a period of 2 months following onset of the wet season (Figure 3). The marked differences in the source behaviour indicate the aquifer properties of the laterite to be different across its saturated thickness.

Monthly water-level records from 11 other pumped shallow wells across the Oju region show similar trends to the pumped study well (see some examples in Figure 5). In each, an almost constant base groundwater level is maintained at 2–3 mbgl until the mid dry season. As in the study well, water levels then decline through the dry season (on average by 6 m within a 4–8 m range), and by the end of the dry season, most of the wells fail.

Data from the observation wells adjacent to the study well show a different seasonal trend to the pumped well. Both observation wells show the same base groundwater level at 3 mbgl in the early dry season as observed in the study well, but by the end of the dry season, groundwater levels drop by only 0.5 m from this base groundwater level in the observation wells, compared to 3 m in the study well (Figure 3). The observations wells have a comparable construction to the study well – all three wells being effectively open for their entire length. Water-level data recorded for all the wells are, therefore, comparable, and there was no vertical head distribution present between the wells to cause the difference observed in groundwater levels in the dry season. Collectively, the data indicate the deeper water levels observed in the pumped well at the end of the dry season do not reflect a regional groundwater level decline, and instead they more

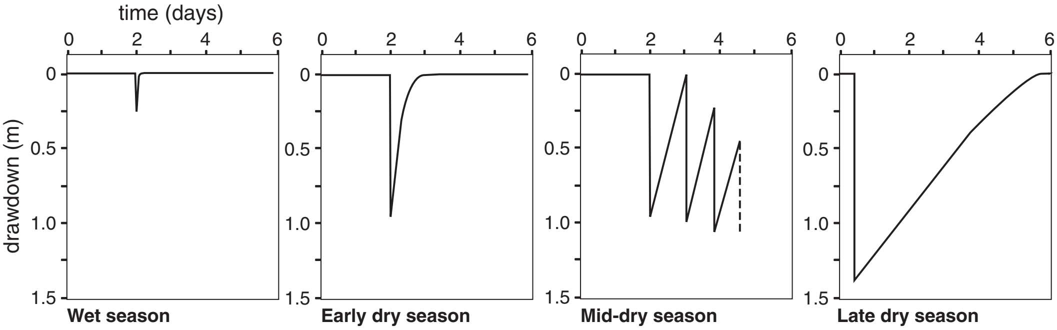

Figure 4. Seasonal recovery response of water levels in the pumped study well

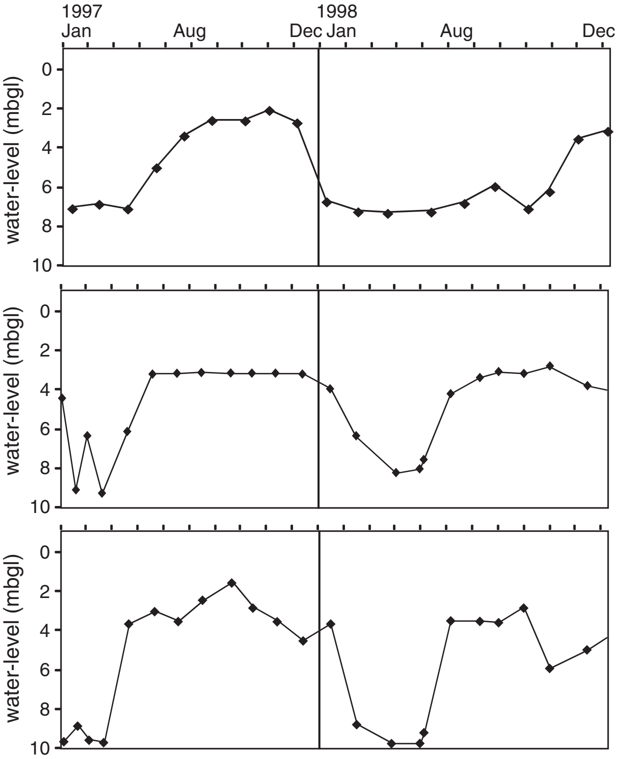

Figure 5. Monthly water-level data from pumped shallow wells constructed within laterite, around the Oju region

likely reflect a local cone of depression of the water table caused by pumping. Similar observations were made by Calow *et al.* (1997, 2010) when considering how wells and boreholes fail during drought.

Laterite permeability. Analysis of the pumping test data reveal the laterite soil to be characterised by extreme variations in permeability over small changes in saturated thickness. Transmissivity of the laterite soil in Oju ranges from 0.1 to 1000 m^2/d (Figures 6 and 7). Highest transmissivity (100–1000 m^2/d) were measured when the uppermost horizon of the laterite was saturated; lowest transmissivity values (0.1–5 m^2/d) were determined when only the pallid clay at the base of the laterite was saturated (Figure 7). As shown by Figure 6, the very high and low values of transmissivity are observed for limited time periods in the year: the extreme transmissivity estimates are only estimated from pumping tests conducted in the wet season following intense rainfall events, when the upper parts of the laterite soil become saturated (between 2 and 3 mbgl; Figure 8); and the very low transmissivity values are only determined at the end of the dry season, when only the

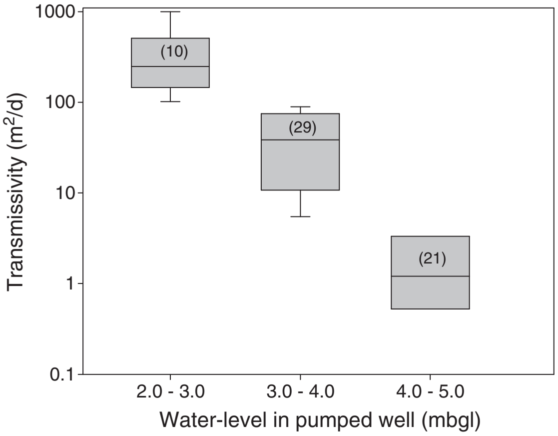

Figure 7. Transmissivity of laterite determined from analysis of pumping test data at different times across wet and dry season when water levels in the pumped well were at different levels. The bracketed numbers indicate the number of pumping tests represented in each water-level depth range

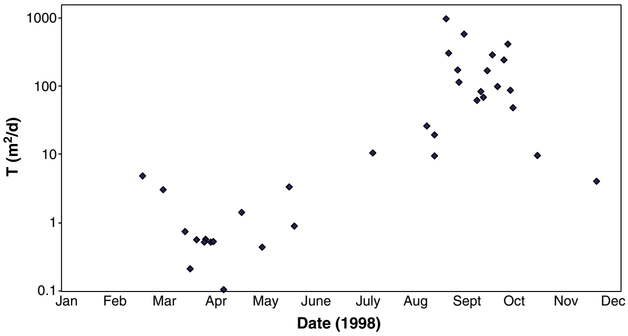

Figure 6. Seasonal variation in measured transmissivity of laterite soil

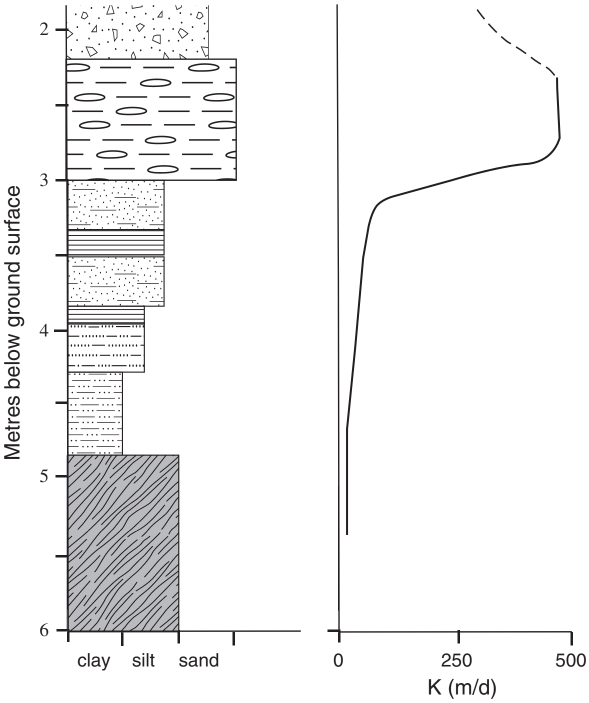

Figure 8. Schematic lithological log of laterite soil and measured permeability

clay-rich base of the laterite is saturated immediately adjacent to the well. For most of the year, when the saturated thickness of the laterite adjacent to the study well is approximately 2 m (corresponding to a groundwater level of approx. 3 mbgl), the transmissivity of the laterite is shown to be generally 10–100 m^2/d (Figure 7).

The hydraulic conductivity (K) profile of the laterite was calculated from the transmissivity (T) and saturated thickness (b) according to $T = Kb$ (Figure 8). The uppermost horizon of the laterite soil, which is only saturated for short periods (days) within the wet season, following very intense rainfall events, is calculated to have the highest hydraulic conductivity (100–400 m/d). Below this horizon, hydraulic conductivity is shown to decrease by an order of magnitude (to 3–50 m/d) in the underlying soil profile over a saturated thickness of 0.5 m, and to decrease by a further order of magnitude (to 0.5–3 m/d) towards the base of the laterite soil (Figure 8). The lowest clay layer of the laterite has negligible hydraulic conductivity (0.03–0.1 m/d).

The medium to low hydraulic conductivity values measured are comparable to those determined by other case studies in laterites around the world (e.g. McFarlane 1970; Sharma *et al.*, 1987; Ogunsanwo 1989; Ruprecht and Schofield 1993; Taylor and Howard 1997; Eilers *et al.*, 2007; Osazuwa and Chinedu 2008). For example, Ruprecht and Schofield (1993) determined the upper horizons of a laterite soil in Western Australia to have hydraulic conductivity of around the order of 10 m/d, and underlying soil horizons approximately an order of magnitude less. None of the previous work, however, identifies hydraulic conductivity as high as those determined within the uppermost saturated laterite horizon in Oju, which is saturated for only limited periods following intense rainfall in the wet season.

DISCUSSION

The data from this study indicate an extreme range of permeability to exist in laterite soils, and there to be a non-linear decrease in permeability with depth. The similarity of the data and source behaviour between the study well and the 11 other pumped wells monitoring in the Oju area (approx 1600 km^2) indicates this stratification of permeability in the laterite soil to occur across the Oju area. The results highlight the importance of characterising laterite permeability to understand shallow drinking source behaviour, and potential recharge to underlying bedrock aquifers, and there is a need for similar research across a much wider area in the tropics to better characterise laterite soils.

Laterite permeability

Causes for such an extreme range of hydraulic conductivity (<0.01 to 400 m/d) measured in the laterite over only 3.5 m saturated thickness relate to changes in the physical properties of the laterite soil with depth.

Highest values (400 m/d) are measured within the uppermost horizon of the saturated laterite soil, which has a concretionary soil structure containing pisoliths (Figure 8). This soil structure is the result of advanced hydrolysis in the weathering process which formed the laterite soil (McFarlane 1970; Fookes 1997). Pisoliths are typically found to develop in the zone of regional water-table fluctuation in the weathering profile – as observed in Oju – where there is repeated aeration and saturation of the soil (McFarlane 1970). Petrography work shows the residual soil structure in this upper horizon in the laterite in Oju to contain large tubular concentrically laminated structures and voids between the pisoliths (Lott 1998). These voids within the soils structure will act as preferential flowpaths, facilitating rapid throughflow of groundwater through the high permeability conduits (Langsholt 1992; Ruprecht and Schofield 1993; Driesson *et al.*, 2001). The extreme permeability horizon is likely to act as a horizontal conduit, through which rainfall infiltrating the laterite is transported laterally through the soil. Such rapid lateral throughflow of shallow groundwater would explain the constant base groundwater level maintained just below the high permeability horizon throughout the wet season at 3.0 mbgl. In intense rainfall events, the water table rises above this laterite horizon, when the infiltration rate exceeds the capacity of high permeability horizon to transport rainfall recharge laterally away. With cessation of rainfall, groundwater levels quickly return to the base groundwater level at 3.0 mbgl. The importance of rapid throughflow of shallow groundwater through these preferential pathways in the shallow laterite soil is also highlighted by work in Uganda by Taylor *et al.* (2010), who found that the average groundwater flow velocities in shallow laterite horizons often exceeded that of the inert solute tracer, chloride.

Beneath the high permeability horizon, the laterite soil becomes more homogeneous, and as a result hydraulic conductivity of the soil is measured to decrease to 3–50 m/d, over a saturated thickness of only 0.5 m. With increasing clay content in the laterite with depth, the hydraulic conductivity is measured to further decrease to 0.5–3 m/d over a saturated thickness of 1.5 m in the underlying soil profile. The base of the laterite, which is pallid clay, has negligible permeability (0.03–0.1 m/d). The lower permeability of the laterite soil beneath the upper horizons is insufficient to recharge the well to replace pumped groundwater; therefore, with frequent pumping in the dry season, the water levels decline rapidly and the well effectively fails.

The changes in laterite permeability with depth are shown schematically alongside a lithological log of the laterite in Figure 8. It is known from the drill core sections the pisoliths do not extend to ground surface in the laterite, and the overlying top soil of the laterite is of a more homogenous structure (Ollier and Galloway 1990; Taylor *et al*., 2010). The permeability of the laterite is, therefore, likely to decrease above the high permeability pisolith horizon as indicated in Figure 8. A non-linear decrease in permeability is indicated with depth in the laterite. The abrupt change in permeability in the laterite below the high permeability concretionary horizon at 3.0 mbgl is likely to be a principal factor to the difference in source behaviour between the wet and season.

Implications of laterite permeability

The extreme range in permeability identified across the saturated thickness of laterite soil by this work highlights the need to take the non-linear nature of soil permeability into account when characterising catchment conditions and the response of wells in laterite.

Recharge and runoff. The permeability profile of the shallow laterite soil in Oju will have significant implications to the hydrology and hydrogeology of the region: the laterite soil restricts recharge to the underlying bedrock aquifers (Cretaceous mudstone units), as well as influencing runoff and surface water resources. Shallow groundwater stored within bedrock units beneath the laterite in Oju is the main source of drinking water for the rural population as across many parts of rural Africa (MacDonald *et al*. 2012), and as a result understanding the recharge to these aquifers is essential to assess the long-term sustainability of the groundwater supplies (Cuthbert M.O. and Tindimugaya C. 2010; Edmunds 2012; Lapworth *et al*., 2012)

Data presented by this study show laterite soils are likely to limit recharge to underlying bedrock aquifers, principally due to the very low permeability of the pallid clay layer at the base of the laterite soil, which will significantly limit vertical infiltration of any water stored in the laterite to the underlying bedrock (Figure 9). Actual recharge to the underlying bedrock is, therefore, likely to

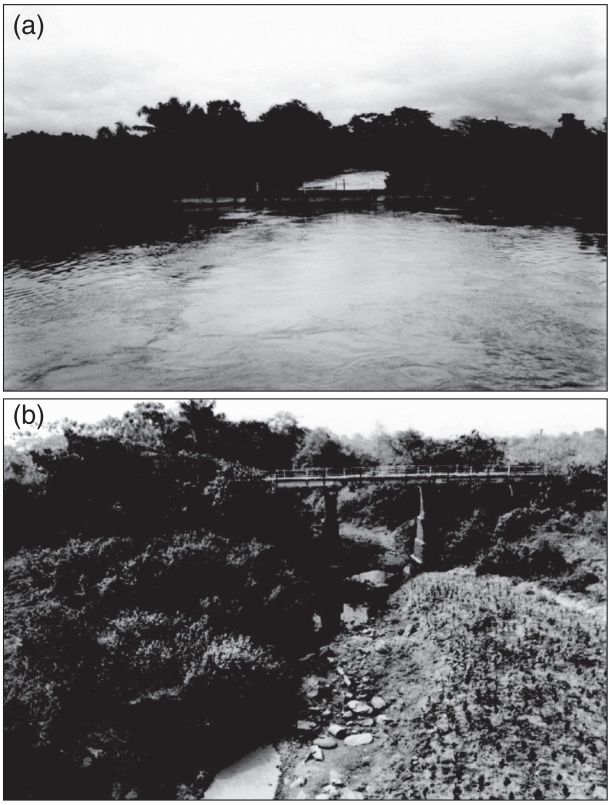

Figure 10. Surface water resources show a flashy seasonal response in Oju. Photographs (a) and (b) are taken from the same place along the River Oju; photograph (a) was taken in the wet season; (b) in the early dry season

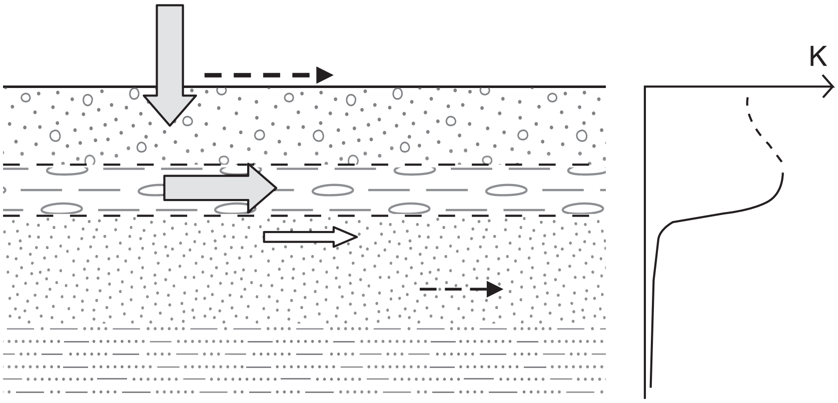

Figure 9. Runoff and recharge within laterite soil. The high permeability horizon within the upper laterite soil facilitates rapid infiltration and lateral throughflow of shallow groundwater, limiting recharge to the underlying bedrock. The lower permeability of the underlying laterite soil limits both lateral movement of groundwater, and recharge to the bedrock

be much lower than the high potential recharge presented by rainfall in the wet season (Eilers *et al.*, 2007).

Laterite soils will also influence runoff and the hydrology of regions they cover. The high permeability horizons in the upper laterite are likely to facilitate rapid lateral throughflow of rainfall in the soil (Figure 9) leading to a highly flashy catchment response to rainfall. This is observed in Oju with strong seasonality of surface water resources. In the wet season, the River Oju responds rapidly to rainfall – the time lag between peak rainfall and river discharge being significantly less than 24 h. The rapid lateral throughflow of water in the laterite within the wet season is likely to limit the amount of water stored by the laterite itself; water being rapidly transported to local discharges, rather than being stored in the laterite. Within the dry season, the river dries up entirely with almost no component of base flow from shallow groundwater at all (Figure 10).

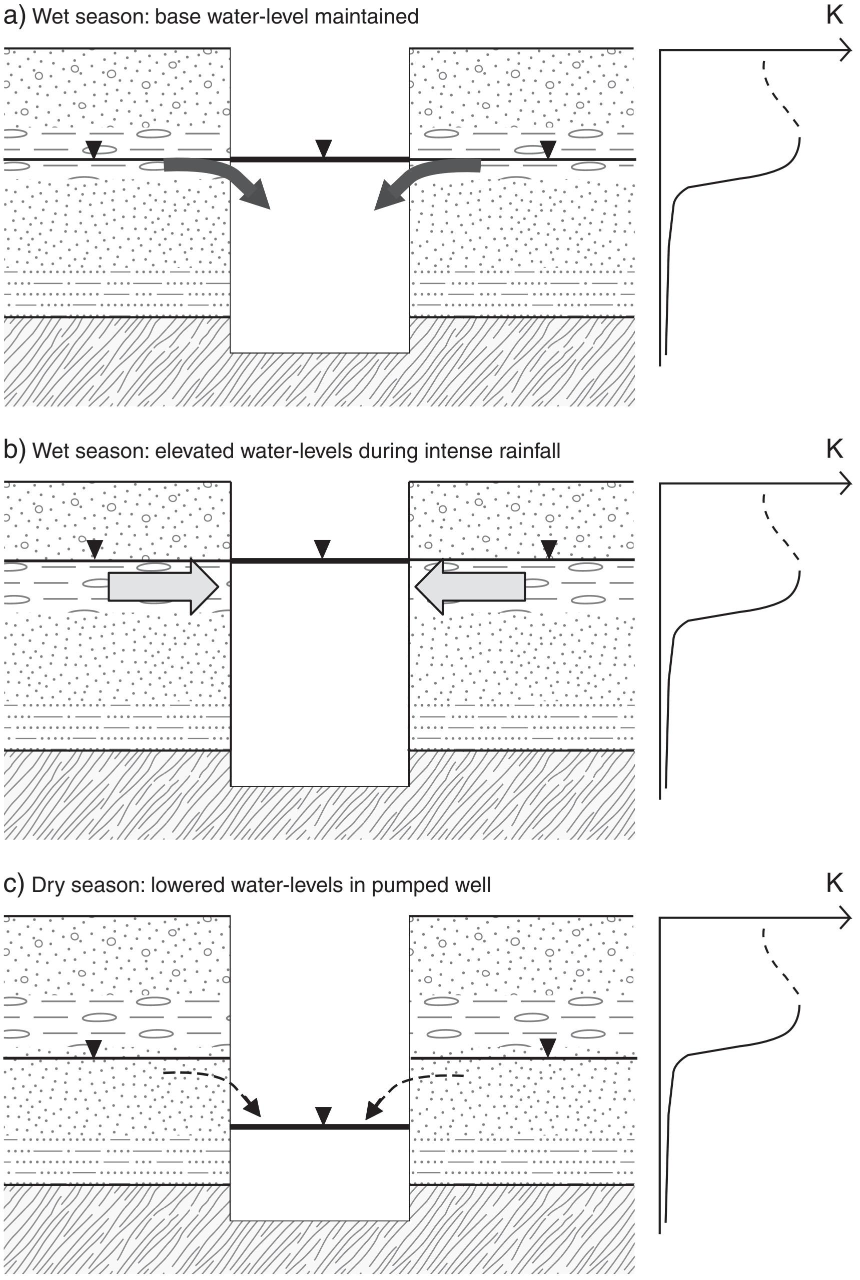

Figure 11. Impact of laterite permeability to shallow well behaviour. During the wet season, the higher permeability horizons of the laterite are saturated, enabling rapid recovery of water levels; within the dry season, the well is recharged from ‘top-down’ recharge through a seepage face. The lower permeability of the lower laterite means well recovery is slower

Reliability of shallow wells in laterite soils. Many shallow wells are constructed in laterite throughout Africa, a large number of which fail seasonally (MacDonald and Calow, 2009; MacDonald et al. 2009). Despite their limited functionality, these wells are an important source of drinking water in large parts of sub-Saharan Africa. The data presented in this study offer some insight into the nature of laterite aquifers and the factors leading to the seasonal failure of shallow wells in laterite.

The rapid recovery (hours) of water levels in the pumped study well in response to cessation of pumping in the wet season indicates the permeability of the very shallow laterite soil to be sufficient to transport enough water to meet demand, and there to be sufficient recharge from rainfall in the wet season (Figures 3 and 5). Once rainfall stops in the dry season, recovery of water levels within the well is slower between successive pumping tests (Figures 3 and 5). The decline in water levels in the pumped well accelerates as the dry season progresses as the higher permeability horizons of the upper laterite dewater (Figures 3 and 11). Eventually, shallow wells that penetrate only the laterite are likely to fail, and it is only deeper wells that intersect groundwater in the underlying weathered bedrock that are likely to be sustainable throughout the dry season (Chilton and Foster 1995).

Shallow groundwater quality in laterite soils. The quality of shallow groundwater is widely reported to vary seasonally within shallow wells across Africa, despite a relatively constant source of contamination from sanitation (Taylor *et al*., 2004; Sutton, 2004; Dzwairo *et al*., 2006; Migele *et al*., 2007; JMP 2008; Pritchard *et al*., 2008). This deterioration in water quality in the wet season is an important consideration to the sustainability of shallow groundwater supplies in laterite, as well as the year-round functionality of the shallow wells.

The seasonal deterioration observed in shallow groundwater quality is likely to be at least in part attributable to the permeability structure of the laterite soils. The high permeability of shallow laterite horizons means shallow groundwater is highly vulnerable to contamination from the ground surface in the wet season. The very permeable upper horizons of laterite will enable high infiltration rates of rainfall and rapid lateral throughflow of water within the shallow laterite soil during intense rainfall events. As a result, a significant deterioration of water quality can be observed within hours of rainfall in laterite soils, with inflow of suspended solids and other contaminants (Taylor *et al*., 2004; Godfrey *et al*., 2005). The existence of preferential pathways in the upper horizon of the Oju laterite will also mean contaminants can be transported significant distances in the soil (over 1 km) whilst still virulent. Unfeasible separation distances are, therefore, likely to be required in some soils to ensure sufficient travel time (25 days) between water supplies and contamination sources, so that the pathogenic contaminant load is no longer virulent by the time it reaches a water supply (Lawrence *et al*., 2001).

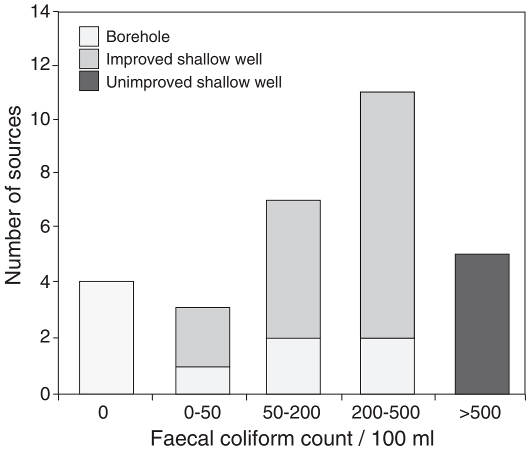

Figure 12. Association of water groundwater quality and sources in the Oju area, based on faecal coliform count. Thirty-five different supplies from disparate villages and households were tested

The shallow water table maintained within the laterite throughout the wet season in Oju also means there is very limited attenuation of contaminations within the thin unsaturated zone in the laterite soil. Moreover, within periods of very intense rainfall events when the water table is elevated, data from Oju show contamination may enter the groundwater directly from the base of latrines with little, if any, attenuation. In Oju, shallow groundwater in Oju typically contained 200–500 faecal coliforms per 100 ml in the wet season (Davies and MacDonald 1999). Whilst no systematic survey of water-borne disease was undertaken in Oju, it is well known that high coliform concentrations increase the risk of water-borne disease in regions where populations are dependent on contaminated drinking water (Hunter *et al*., 2010). Data from a survey of faecal coliform concentrations from different groundwater sources in Oju demonstrated that sources which took water from the laterite had the highest coliform contamination (Figure 12). Highest coliform counts were found within shallow unimproved wells. Slightly lower coliform counts were measured from shallow improved wells (i.e. had a semi permeable cement lining). Borehole supplies which cased out the laterite entirely, and abstracted shallow groundwater from the underlying Cretaceous mudstone bedrock, contained very few coliforms (Figure 12).

CONCLUSIONS

Analysis of pumping test data from a shallow well constructed in laterite soil in southeast Nigeria reveals extreme variations in permeability within the laterite.

Transmissivity of the laterite soil ranges from 0.1 to $1000\,\mathrm{m^2/d}$ depending on the saturated thickness. Highest transmissivity values ($100–1000\,\mathrm{m^2/d}$) were measured in the uppermost horizons of the laterite soil, which are saturated for only limited periods in the wet season (days) during the most intense rainfall events. Beneath this horizon, the laterite soil is characterised by much lower transmissivity ($5–50\,\mathrm{m^2/d}$) and a non-linear decrease in permeability with depth overall. The base of the laterite soil has negligible transmissivity ($<0.05\,\mathrm{m^2/d}$). The permeability structure of laterite soils has significant implications to the hydrology and hydrogeology of the region: laterite soils are likely to limit recharge to underlying bedrock aquifers, due to the very low permeability of the base of the laterite soil; within the wet season, the very high permeability of the upper laterite will facilitate rapid lateral throughflow of shallow groundwater in the laterite, enabling contaminants to be transported significant distances (up to 1 km) whilst still virulent; the high permeability layer makes it more likely to constrain natural groundwater level variations to a narrow range; and in the dry season, the lower permeability of the underlying laterite restricts the amount of water which can be abstracted from shallow supplies constructed in the laterite source, leading to well failure.

This study provides evidence for the extreme range of permeabilities possible within the shallow horizons of laterite soils, and the data provides a useful input to large-scale permeability assessments (e.g. Gleeson *et al*., 2010; MacDonald *et al*., 2012), which often have to interpolate the permeability of soils, sub-soils and rocks in Africa from data elsewhere (e.g. North America or Europe). The work highlights the need for a much wider study across tropical areas to better understand laterite aquifers and the role they play in regional hydrology and hydrogeology.

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REFERENCES

Areola O. 1996. Soils. In *The Physical Geography of Africa*, Adams W, Goudie AS, Orme AR (eds). Oxford University Press: New York; 134–147.

Barker JA. 1988. A generalised radial flow model for hydraulic tests in fractured rock. *Water Resources Research* **24**: 1796–1804.

Barker JA, MacDonald DMJ. 2000. Programs to simulate and analyse pumping tests in large-diameter wells, *British Geological Survey Technical Report*, WD/00/17.

Bonsor HC, MacDonald AM, Calow RC. 2010. Potential impact of climate change on improved and unimproved water supplies in Africa. In *Sustainable water*, Hester RE, Harrison RM (eds). Royal Society of Chemistry, Issues in Environmental Science and Technology: 31 Cambridge, UK; 25–50, 25 pp.

Calow RC, Robins NS, MacDonald AM, Macdonald DMJ, Gibbs, BR, Orpen WRG, Mtembezeka P, Andrews AJ, Appiah SO. 1997. Groundwater management in drought prone areas of Africa. *International Journal of Water Resources Development* **13**: 241–261.

Calow RC, MacDonald AM, Nicol AL, Robins N. 2010. Ground water security and drought in Africa: linking availability, access and demand. *Ground Water* **48**(2): 246–256. DOI: 10.1111/j.1745-6584.2009.00558.x

Chilton PJ, Foster SSD. 1995. Hydrogeological Characterisation And Water-Supply Potential Of Basement Aquifers In Tropical Africa. *Hydrogeology Journal* **3**(1): 36–49.

Cuthbert M.O. and Tindimugaya C. 2010. The importance of preferential flow in controlling recharge in tropical Africa and implications for modelling the impact of climate change on groundwater resources, *Journal of Water and Climate Change*, **1**(4): 234–245.

Dalhaus PG, MacEwan RJ, Nathan EL, Morand VJ. 2000. Salinity on the southeastern Dundas Tableland, Victoria. *Australian Journal of Earth Sciences* **47**: 3–11.

Davies J, MacDonald AM. 1999. Final report: the groundwater potential of the Oju/Obi area, eastern Nigeria, *British Geological Survey Technical Report*, WC/99/32.

Driesson P, Deckers J, Spaargaren O, Nachtergaele F. 2001. Lecture notes on the major soils of the world, World Soil Resources Reports, Food and Agricultural Organization of the United Nations (DRIESSEN *ET AL*., 2001), Rome, pp 307.

Dzwairo B, Hoko Z, Love D, Guzha E. 2006. Assessment of the impacts of pit latrinesnon groundwater quality in rural areas: A case study from Marondera district, Zimbabwe, *Physics and Chemistry of the Earth, Parts A/B/C*, **31**(15-16): 779–788.

Edmunds MW. 2012. Limits to the availability of groundwater in Africa. *Environmental Research Letters* **7**: 021003. DOI: 10.1088/1748-9326/7/2/021003.

Eilers VHM, Carter RC, Rushton KR. 2007. A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North-east Nigeria. *Geoderma* **140**(1-2): 119–131.

Fookes PG (ed). 1997. Tropical Residual Soils, A Geological Society Engineering Group Working Party Revised Report, Published by The Geological Society, pp 15-40, 121-147.

Gleeson T, Smith L, Moosdorf N, Hartmann J, Durr HH, Manning AH, van Beek LPH, Jellinek AM. 2010. Mapping permeability over the surface of the Earth. *Geophysical Research Letters* **38**: LO2401.

Godfrey S, Timo F, Smith M. 2005. Relationship between rainfall and microbiological contamination of shallow groundwater in Northern Mozambique. *Water SA* **31**(4): 609.

Grasso DA, Jeanninb PY, Zwahlen F. 2003. A deterministic approach to the coupled analysis of karst springs' hydrographs and chemographs. *Journal of Hydrology* **271**: 65–76.

Hunter PR, MacDonald AM, Carter RC. 2010. Water supply and health. *PLoS Medicine* **7**(11): 9. DOI: 10.1371/journal.pmed.1000361.

JMP. 2008. Global water supply and sanitation 2008 report. Joint monitoring programme WHO/UNICEF,World Health Organisation, Geneva. Accessed at: http://www.who.int/water_sanitation_health/monitoring/jmpfinal.pdf.

Kulkarni H, Deolankar SB, Lalwani A, Joseph B, Pawar S. 2000. Hydrogeological framework of the Deccan basalt groundwater systems, wet-central India. *Hydrogeology Journal* **8**: 368–378.

Langsholt E. 1992. A water balance study in lateritic terrain. *Hydrological Processes* **6**: 11–27.

Lapworth DJ, MacDonald AM, Tijani MN, Darling WG, Gooddy DC, Bonsor HC, Araguás-Araguás LJ. 2012. Residence times of shallow groundwater in West Africa: implications for hydrogeology and resilience to future changes in climate. *Hydrogeology Journal*. DOI: 10.1007/s10040-012-0925-4

Lawrence AR, MacDonald DM, Howard AG, Barret MH, Pedley S, Ahmed KM, Nalubega M. 2001. Guidelines for Assessing the Risk to Groundwater from On-Site Sanitation, British Geological Survey Commissioned Report, CR/01/142.

Lott GK. 1998. Thin section petrography of thirty-five samples from boreholes in the Cretaceous succession of the Benue Trough, Nigeria, *British Geological Survey Technical Report*, WH/98/174C, 33 pp.

MacDonald AM, Barker JA, Davies J. 2008. The bailer test: a short effect pumping test to assess borehole success. *Hydrogeology Journal* **16**: 1065–1075.

MacDonald AM, Bonsor HC, O'Dochartaigh BE, Taylor RG. 2012. Quantitative maps of groundwater resources in Africa. *Environmental Research Letters* **7**: 024009.

MacDonald AM, Calow RC. 2009. Developing groundwater for secure rural water supplies in Africa. *Desalination* **248**(1-3): 546–556.

MacDonald AM, Calow RC, MacDonald DMJ, Darling GW, Ó Dochartaigh BÉ. 2009. What impact will climate change have on rural water supplies on Africa?. *Hydrological Sciences Journal* **54**: 690–703.

MacDonald AM, Davies J. 1997. The hydrogeology of the Oju area, Eastern Nigeria: an initial assessment, *British Geological Survey Technical Report*, WC/97/54, 62 pp.

MacDonald AM, Kemp SJ, Davies J. 2005. Transmissivity variations in Mudstones. *Ground Water* **43**: 259–269.

Mace RE. 1999. Estimation of hydraulic conductivity in a large-diameter, hand-dug wells using slug-tests methods. *Journal of Hydrology* **219**: 34–45.

McFarlane MJ, Bowden DJ. 2006. Mobilization of aluminium in the weathering profiles of the African surface in Malawi. *Earth Surface Processes and Landforms* **17**(8): 789–805.

McFarlane MJ. 1970. Lateritization and landscape development in Kyagwe, Uganda. *Quarterly Journal of the Geological Society of London* **126**: 501–534.

Migele J, Ombeki S, Ayalo M, Biggerstaff M, Quick R. 2007. Short report: Diarrhoea prevention in a Kenyan school through the use of a simple safe water and hygiene intervention. *The American Journal of Tropical Medicine and Hygiene* **76**(2): 351–353.

Ogunsanwo O. 1989. CBR and shear strengths of compacted laterite soils from southwestern Nigeria. *Quarterly Journal of Engineering Geology, London* **22**: 317–328.

Ofoegbu CO. 1985. A review of the geology of the Benue Trough, Nigeria. *Journal of African Earth Sciences* **3**: 283–291.

Ollier CD, Galloway RW. 1990. The Laterite Profile, Ferricrete and Unconformity. *Catena* **17**: 97–109.

Osazuwa IB, Chinedu AD. 2008. Seismic refraction tomography imaging of high-permeability zones beneath an earthen dam, in Zaria area Nigeria. *Journal of Applied Geophysics* **66**: 44–58.

Papadopulos IS, Cooper HH. 1967. Drawdown in a well of large diameter, *Water Resources Research* **3**(1): 241–244.

Pritchard M, Mkandawire T, O'Neill JG. 2008. Assessment of groundwater quality in shallow wells within the southern districts of Malawi, *Physics and Chemistry of the Earth*. DOI: 10.1016/j.pce.2008.06.036

Ruprecht JK, Schofield NJ. 1993. Infiltration characteristics of a complex lateritic soil profile. *Hydrological Processes* **7**: 87–97.

Sharma ML, Barron RJW, Fernie MS. 1987. Areal distribution of infiltration parameters and some soil physical properties in lateritic catchments. *Journal of Hydrology* **94**: 109–127.

Skinner, B 2003. *Small-scale water supply: a review of technologies*. ITDG Publishing: London; 100–114.

Sutton S. 2004. Preliminary desk-top study of potential for self-supply in sub-Saharan Africa, *Report for WATERAID and the Rural Water Supply Network*, pp 1-15.

Taylor RG, Howard KWF. 1997. The dynamics of groundwater flow in the regolith of Uganda. In *Shallow groundwater systems*, IAH-ICH Special Volume **18**, Simmers I, Dillon PJ (eds). Heise-Verlag Hannover, Germany; 37–52.

Taylor R, Cronin A, Pedley S, Barker J, Atkinson T. 2004. The implications of groundwater velocity variations in microbial transport and wellhead protection – review of field evidence. *FEMS Microbiology Ecology* **49**: 17–26.

Taylor R, Tindimugaya C, Barker J, Macdonald D, Kulabako R. 2010. Convergent Radial Tracing of Viral and Solute Transport in Gneiss Saprolite. *Ground Water* **48**(2): 284–294.

Thomas MF. 1995. *Geomorphology in the Tropics: A study of weathering and denudation in low latitudes*. Wiley and Sons: New York; 52–165.

White WB. 2002. Karst hydrology: recent developments and open questions. *Engineering Geology* **65**: 85–105.