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Review Article

Termite Mounds as Bio-Indicators of Groundwater: Prospects and Constraints

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ABSTRACT

Reliance on modern sophisticated equipment for making 'discoveries' has limited the human power of observing subtle clues in the environment that are capable of saving cost and labour that come with researching new resources and methods to improve life for all. Due to the growing scarcity of potable water, especially in African and Asian countries, newer, cheaper and reliable methods of investigating groundwater resources are becoming critical. One such potentially promising method is mapping the distribution of termite mounds in the environment. Termite mounds are conspicuous landscape features in tropical and sub-tropical regions of the world. Built from surrounding soils by several species of termite, the properties of mound soil are relatively different from the surrounding soil in most cases, indicating improved hydraulic properties. In this paper, the aim is to review the possibility of employing termite mounds as prospecting tools for groundwater search from three spatial scales of observation. From assessing the smallest to the highest scale of observation, it can be concluded that termite mounds' prospect as surface indicators of groundwater is apparent. Review findings indicate increased surface water infiltration, presence of riparian tree vegetation and other trees with tap-root system around termite mounds, linear assemblage of termite mounds along aquiferous dykes and seep-lines as well as the dependence of termites on water but avoidance of places with risk of inundation. Whether they indicate permanent groundwater reserves in all cases or whether all species depend largely on water for their metabolism is a subject for further research.

Keywords: Bio-indicator, bioturbation, groundwater, spatial scale, termite mounds

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INTRODUCTION

Access to water is recognised as a key limiting factor to socioeconomic development of any nation (United Nations, 1997). Management of water resources has been a major issue for stakeholders in recent years (Adelana et al., 2008; Tijani et al., 2016) as competition for economic development, associated with rapid growth in population, agricultural mechanisation and urbanisation has brought in significant land use changes and increased demand of water (Pradhan, 2009; Akankpo & Igboekwe, 2012; Fashae et al., 2013). This is especially true for developing countries like those in Africa where water scarcity has brought untold hardship, including poverty and civil unrest among the population (Ferriz & Bizuneh, 2002; El-baz, 2008). Water is plentiful on our mother Earth (Plummer et al., 2010), but it is usually not available where and when needed nor is the quality always suitable for all purposes, especially human use (Al-Abadi & Al-Shamma, 2014). Of all the accessible freshwater available on Earth, groundwater accounts for about 60% (Manap et al., 2011), which is about 35 times the water in all rivers and lakes (Plummer et al., 2010). In addition, groundwater has the advantages of low development cost, excellent natural quality, limited vulnerability, drought reliability and availability in vast geological formations. In addition, it is a dependable water supply source across all climatic zones (Jha et al., 2007). Notwithstanding the advantages, one constraint with groundwater exploration is actually locating the favourable spot or water-bearing fissure for its development as there is no one-hundred-percent chance of success in locating the resource anywhere. Thus, the search for groundwater, especially in difficult or complex geological terrains, is not only expensive but time consuming, labourious (Fenta et al., 2014) and often associated with a high rate of failure (Edet et al., 1998; Bala et al., 1999). As most communities in both developed and developing parts of the world are increasingly depending on groundwater for various uses (Oh et al., 2011; Kura et al., 2014; Park et al., 2014), it is necessary to identify natural features in the environment that can aid narrowing down our groundwater search to places that hold promise.

Places with good promise could be indicated by the prevalence of conspicuous soil mounds constructed by termites, also referred to as “ecosystem engineers” or “soil engineers” (Dangerfield et al., 1998; Bottinelli et al., 2014; Jouquet et al., 2016a). Termites are one of the most successful groups of social insects whose engineering resourcefulness include selection of soil particles (sorting) from depths for the construction of their below and/or above ground nest (Arhin et al., 2015), construction of galleries, tunnels and foraging holes below ground level (Mando et al., 1996) and burrowing of large quantities of soil underground to bring to the surface for litter harvesting (Bottinelli et al., 2014; Jouquet et al., 2015a) among others. The result is that they successfully modify the physical (change soil porosity and bulk density), hydraulic (increase soil water retention, induce higher infiltration rate), chemical (change soil pH, C, N and CEC) and biological (change soil organic matter, nutrient cycling) characteristics of their nests soil compared to the adjacent soil (e.g. Choosai et al., 2009; Jouquet et al., 2015a; Moura et al., 2014). The concentration of termite activities in a location increases ecological heterogeneity, and the nest environments serve as fertility islands or hotspots for plant and tree growth (Jouquet et al., 2005; Bonachela et al., 2015), reflecting improvement in soil characteristics including water content. Consequently, the engineering activities of termites have been an interesting subject area for research by soil scientists, plant scientists, entomologists, agronomists, veterinarians, ecosystem managers, civil engineers, architects and mineral explorationists. The hydrogeologist whose concern is to locate groundwater in appreciable quantity and quality should also be featured in this interest list.

It has been observed in various parts of Africa that termite mound locations are locally exploited for locating groundwater sources. For example, in the North-central part of Nigeria, largely covered by basement complex rocks of Eburnean-Pan African age, some villagers rely on epigeal termite mounds for locating groundwater sources (personal observation). A similar observation has been made in Cameroon (Van Ranst, personal communication) and Ghana (Dowuona et al., 2012). This paper, therefore, aimed to review the possibility of utilising termite mounds as prospecting tools for locating suitable groundwater sources from three different spatial scales of observation viz. mound soil aggregate scale, mound profile scale and landscape scale. Jouquet et al. (2016a) reviewed the impact of termites on soil structure and water dynamics on four scales of observation, where they focussed on soil water content (shallow depth) as it affected plant species heterogeneity as opposed to groundwater storage for community supply.

BASIC FEATURES OF TERMITES

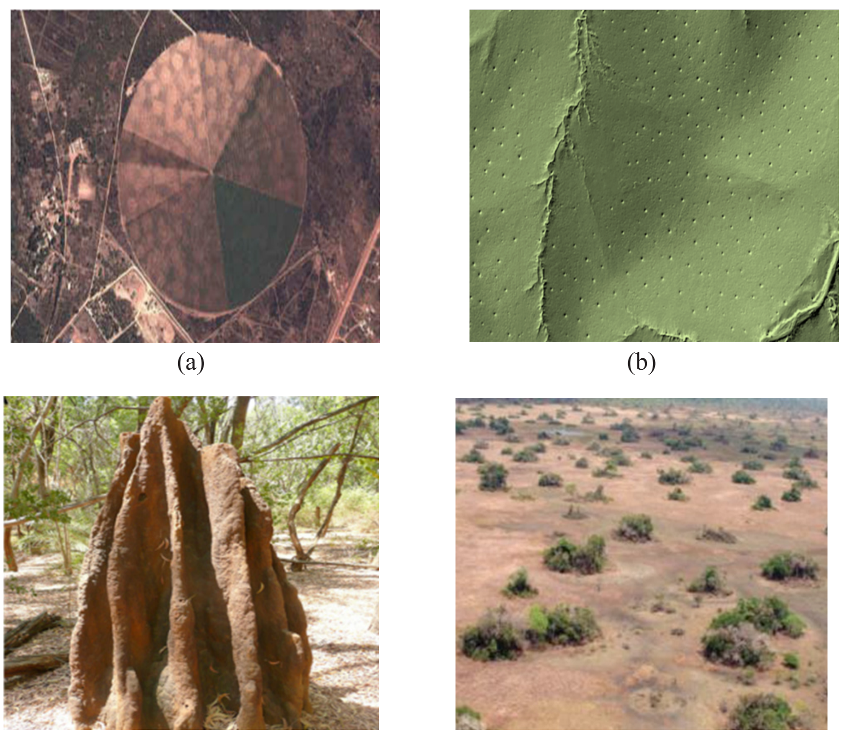
Termites are eusocial insects that are mainly divided into lower (paraphyletic) and higher (monophyletic) species (Jouquet et al., 2016a). The higher species (infraorder Isoptera) is most important in this regard, with over 3000 known species (Rajeev & Sanjeev, 2011; Sarcinelli et al., 2009). They are said to comprise about 75% of modern termite species (Krishna et al., 2013 from Jouquet et al., 2016a) that feed on various food types ranging from wood, leaf litter, crop residue and soils to animal dung (Bottinelli et al., 2014; Jouquet et al., 2016a). Although termites are found worldwide with the exception of Antarctica, they are particularly important in the tropical and subtropical savannahs of Africa, Australia, Asia, and South America (Bonachela et al., 2015) as they account for higher diversities in these continents and build high-rising and long-lasting above-ground nests (Jouquet et al., 2005; Sarcinelli et al., 2009; Mujinya et al., 2013; Nauer et al., 2015). Termite nests, preferably referred to as 'mounds' are built from soil material (mostly clay), saliva and excreta (Denovan et al., 2001; Rajeev & Sanjeev, 2011; Jouquet et al., 2016a). Mound shapes vary in terms of their architecture from conical, dome, cathedral and mushroom to lenticular in shape (Arhin & Nude, 2010; Arhin et al., 2015) which according to Korb and Linsenmair (1998a, 1998b) are dependent on environmental temperature conditions. The height of mounds could be a function of species type, clay availability and level of disturbance in the environment, but generally range from almost a few centimetres above ground level to as high as 2 m as recorded in Southern India (Jouquet et al., 2015a), 4.4 m in Namibia (Grohmann et al., 2010), and up to about 8 m in D. R. Congo (Mujinya et al., 2013, 2014).

Table 1
Termite diversity by bontinent (order isoptera)

Continent	Africa	Asia	S. America	Australia	N. America	Europe
No. of species	1,000	435	400	360	50	10

Source: UNEP (2000)

Termite mounds, especially those built by the fungus-growing species (Termitidae, Macrotermitinae subfamily) present only in Africa and Southeast Asia, are conspicuous features of many landscapes of tropical and sub-tropical regions of the continents (Levick et al., 2010; Jamali et al., 2013). Termites build these mounds to protect themselves against predators and sunlight (Korb & Linsenmair, 2000; Jouquet et al., 2016a) and for the maintenance of high humidity, temperature and food (Jouquet et al., 2016a). These mounds can be viewed from remotely sensed images when their density is high and the patterning is regularly spaced (Francis et al., 2012; Mujinya et al., 2014; Adhikary et al., 2016). They are, however, mostly mapped by field measurements (Roose-Amsaleg et al., 2005; Ackerman et al., 2007; Sako et al., 2009). This is because field mapping avails the opportunity to take measurements such as height and diameter of mounds as well as record activity status, all of which is not achievable with satellite images. However, the use of airborne surveys carrying a Light Detection and Ranging (LIDAR) sensor was successfully used to map termite mounds in Kruger National Park, South Africa (Levick et al., 2010; Davies et al., 2014a, 2014b, 2016). The surveys were successful in recording mound heights and diameters but for mostly heights >1 m. However, this survey type may not be applicable if activity status and species identification are required.



(a) (b) (c) (d)

Figure 1. Termite mounds as viewed from remotely sensed images and field mapping. **(a)**: Patches left behind by termite mounds after two years of clearing as seen from Google Earth (Adhikary et al., 2016), **(b)**: Over-dispersed termite mounds at Kruger National Park, South Africa viewed from LIDAR image (Davies et al., 2014b), **(c)**: Single cathedral termite mound devoid of vegetation (source: Jouquet et al., 2016b), **(d)**: Termite mounds covered by trees in Sofala, Mozambique, image taken from helicopter (Source: Bonachela et al., 2015)

Various studies have underscored the benefits of termite mounds to the environment. These include growth of certain species of vegetation as a result of improved physical, chemical and biological conditions of mound soil (e.g. Mando et al., 1996; Choosai et al., 2009; Bonachela et al., 2015), accumulation of minerals such as Ag, U, Cu, Cd, Ni, Co, Mn, Pb and Zn in mounds as a result of termites' burrowing activities below ground (Kebede, 2004; Arhin et al., 2015), human exploitation of mound soil for erection of structural buildings because of their sesquioxide content (Yamashina, 2010) and consumption of mound soil for their geophagic effects (Kalumanga et al., 2016). Although unstudied, it is likely, therefore, that termite mounds can serve as pointers to local groundwater distribution in the environment because of the improved physical and hydraulic conditions of the mound soil (Ackerman et al., 2007; Moura et al., 2014) as well as the strategic positioning of the mounds themselves (Mege and Rango, 2009; Davies et al., 2014b; Kalumanga et al., 2016).

Improved hydraulic conditions of mound soil may significantly increase surface water infiltration and reduce runoff, thereby increasing the chances of groundwater recharge (Bargués-Tobella et al., 2014). This phenomenon is somewhat understood by some rural Africans who site their water wells around high-rise termite mounds. Also, trees springing out from termite mounds have their leaves ever fresh even during extended dry periods, an indication of a water source below. On the basis of positioning, places prone to surface water submergence are avoided by termites but because water is essential for livelihood, they may line their nests along seepage lines through which groundwater is recharged (Mege & Rango, 2009) and in other cases along groundwater outcrop areas (spring) (Davies et al., 2014b).

DISCUSSION OF THE THREE SCALES OF OBSERVATION

Analysing termite mounds' prospects as groundwater indicators from different spatial scales could serve the purpose of discerning subtle clues from the small scale (often considered trivial) to more significant evidence at intermediate and larger scales.

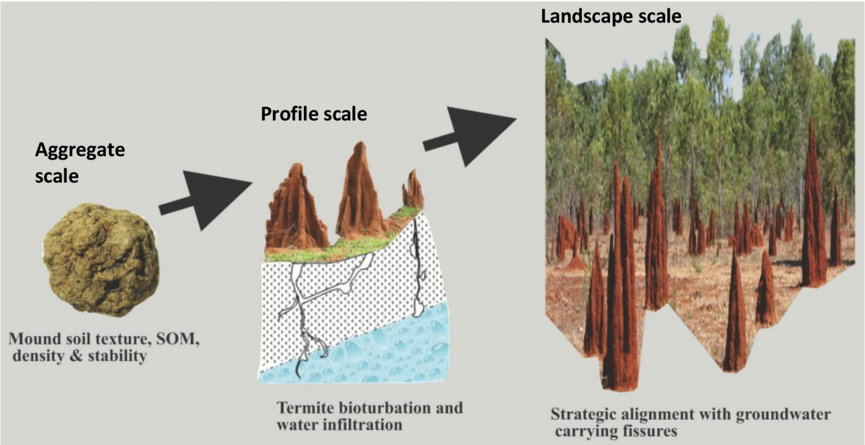


Figure 2. Termite mounds at three scales of observation. At aggregate scale, changes in soil texture, organic matter and bulk density have implication on water hydraulics. At profile scale, termite burrowing activities can influence surface water infiltration, while at landscape scale it can indicate water-bearing fractures and suitable places for groundwater exploration

Aggregate Scale

At the smallest scale of observation, the important factors to be considered are soil texture, organic matter and bulk density. Numerous studies have investigated mound soil texture in comparison with off-mound soil, and the results have shown some variability. For example, clay content has been reported to be higher (Roose-Amsaleg et al., 2005; Mujinya et al., 2010; Dowuona et al., 2012; Jouquet et al., 2015b; Adhikary et al., 2016), proportionately (Levick et al., 2010) and slightly lower (Ackerman et al., 2007) than surrounding off-mound soils. Clay enrichment on mound soil is mostly attributed to fungus-growing termite species that have the ability to select certain size fractions of soils in mound construction (Mujinya et al., 2010; Jouquet et al., 2016a). Soils generally are weathering products of rocks and their textures have varying implications to water drainage and storage. Depending on the mineral constituents present, some rocks weather to produce more clay than others. It will then be expected that termite mounds will thrive more in such clay abundant areas because of the availability of construction material, but instead, such areas tend to be avoided. For example, Levick et al. (2010) and Davies et al. (2014b) observed the abundance of termite mounds on sandy granitic soils than on clayey basaltic soils in Kruger National Park, South Africa. If termites depend on soil properties of the environment as pointed out by Jouquet et al. (2015b), the reason as to why they neglect clay-rich environments has largely not been given. Clay on the surface store large quantities of water and at the same time serve as an impediment to subsurface infiltration. Accordingly, it can be viewed that termites require clay fractions for stability of their mounds because clay has more binding and cementing capability than the remaining soil fractions but at the same time, requires good drainage conditions that might not be offered in clay-rich environments. As a result, an appreciable percentage of silt and sand is mixed with enriched clay content in moderate clay environments for mound construction (Seymour et al., 2016). The higher the percentage of clay used for mound construction, the more the increase in soil porosity and water-holding capacity at mound sites, but these translate to reduced soil drainage; hence, the soil exhibits low hydraulic conductivity. However, termites are reported to avoid soils with high water holding capacity (Schuurman & Dangerfield, 1997) and a decrease in clay content with depth beneath termite mounds has been reported in the Upper Katanga, D. R. Congo (Mujinya et al., 2010). Alternatively, the mounds are restricted to drier climatic zones or where prolonged episodes of rainfall are not experienced (Kandasami et al., 2016). Hence, it can be summarised that although termite mounds are constructed from clay, which may serve as impediment to vertical drainage, finer particles contribute to capillary action that allows water to be transported from the ground to the upper reaches of the mounds (Dangerfield et al., 1998; Turner, 2000).

Soil organic matter (SOM) is another factor that determines the stability of mound soil aggregates (Jouquet et al., 2016a) as well as the physical properties of mound soil. SOM is directly related to soil texture as it tends to increase as the clay content increases and results in aggregate formation by binding the soil particles together with their micropores and macropores (Food and Agriculture Organisation [FAO], 2005). This makes termite mounds relatively resistant to degradation by rain and other agents, decreasing runoff and erosion. The literature discloses higher SOM content in termite mounds compared with off-mound soil, especially for mounds constructed by soil-feeding termite species because they add their faeces and other biogenic structures as binding materials to the construction medium (Moura et al., 2014; Jouquet et al., 2004; 2011; 2016a). The effect of higher SOM content in soil indirectly impacts positively on soil porosity as a consequence of increased micro-organism activity in the soil, promoting continuity of pore space; hence, soil water storage is increased and probably continues its infiltration into the saturation zone. However, SOM decreases with increase in depth (Brauman, 2000; Jouquet et al., 2015b) and because investigations at this scale have rarely exceeded the foot zone (ground level) of termite mounds (Muyinya et al., 2010; Dowuona et al., 2012), it is difficult to suggest if modification in physical and hydraulic conditions of soil below mound structures extend to greater depths in reflection of SOM content. If not, surface water infiltration will be limited to mound soil and might not exceed a few metres beneath the mound as demonstrated by Choosai et al. (2009), where a flooded paddy field was found to be unsaturated at depth 0-30 cm. Furthermore, an increase in porosity following enrichment in SOM content on termite mounds might be insignificant compared with adjacent soil that is porous and sandy.

Bulk density is dependent on soil organic matter, soil texture and their packing arrangement. Generally, loose, well aggregated, porous soil and soil rich in organic matter have lower bulk density (USDA, 1998). The engineering dexterity of termites separates them into two groups as regards density of their mounds. While some species such as Cubitermes, Trinervitermes and Macrotermes can compact their mound soils raising bulk density high to frustrate plant colonisation, others such as Amitermes do not compact their mound soils (Malaka, 1977). Ekundayo and Aghatise (1997) obtained slightly higher bulk densities on mound surfaces constructed by Macrotermes sp. compared to surrounding soils in fallow and cropped lands of Mid-Western Nigeria. Similarly, Dowuona et al. (2012) obtained higher bulk density on mounds sited on rhodic acrisol soil of coastal savannah of Ghana and also showed the bulk density increasing with depth. On the other hand, Ackermann et al. (2007) and Tilahun et al. (2012) found no significant difference between the mean bulk density of mounds and control soil in Amazonia, Brazil and Southern Ethiopia, respectively. Bulk density has direct impact on soil porosity (Haghnazari et al., 2015) and its severity is dependent on soil texture (Abdel-Magid et al., 1987).

Increased bulk density of mound soil can be attributed to its higher clay and silt fractions, which increase its water-holding capacity, making it much easier for termites to work on its compaction. Needless to say, the activities of predators, especially browsing animals like elephants, reported to feed on mound soil (Kalumanga et al., 2016), can contribute to this compaction as does the thumping effect of rain especially on mounds without canopy protection. Although compaction increases the aggregation and stability of mound soils, it leads to closing up of pore space and reduced hydraulic conductivity. This can be aggravated when mound soils are composed of carbonate minerals such as $CaCO_3$, which causes crust formation thereby, further reducing infiltration rate (Mujinya et al., 2010; Adhikary et al., 2016). Conversely, plants and trees are observed to flourish on other mounds, a manifestation of enhanced physical and hydraulic characteristics that provide a local source of water to sustain vegetation all through the year (Turner, 2006; Pardeshi & Prusty, 2010). Tree species such as Combretum imberbe and Phalaenopsis violacea described as lowland and riparian habitat species were found with increased density around termite mounds on hill crests in Kruger National Park, South Africa

(Davies et al., 2016). The soil conditions of these mounds, even though on hill crests several meters above the surrounding plains, mimic that of lowland areas, where the soil properties such as texture, bulk density and organic matter content favour nutrient and water availability. Although with reduced density, high water demanding tree species such as Combretum apiculatum and Colophospermum mopane were also found around termite mounds (Davies et al., 2016).

The pros and cons at this scale abound, making it difficult to deduce whether or not modification in mound soil properties will result to any significant increase in runoff collection and storage underground, especially when considering the limited area covered by individual mounds, density coverage of mounds per hectare and the volume of soil material used for mound construction. The almost generalised conclusion of clay enrichment on termite mound soils further heighten the constraints of large groundwater storage below the mounds as the clay soil will not only wick in water into the mound but will also hold it tightly (Turner, 2006), thus restricting storage below ground.

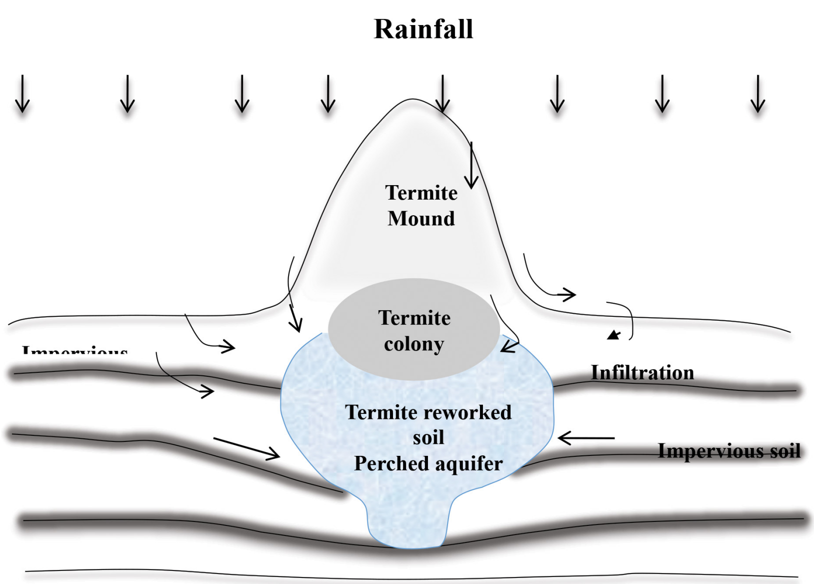


Figure 3. Schematic sketch of rainwater infiltration around termite mound due to improved soil physical properties and storage in perched aquifer below colony chamber. Modified from Turner (2006)

Mound Profile Scale

Perhaps a larger scale of observation might clear some ambiguity and present a better understanding of this topic. At the profile scale, the construction of the network of foraging galleries, tunnels and shafts of varying inclination from the mound surface to depths below the mound in a process known as bioturbation is among the reckoned engineering skills of termites (Arhin et al., 2015). Termites burrow large quantities of soil below ground for the construction of surface mounds and other features within the interior of mounds such as the queen's chamber, fungus garden, vertical chimney and networked tunnels and galleries (Turner, 2000; Kandasami et al., 2016) for maintaining efficient exchange of respiratory gasses and regulation of humidity and temperature (Jouquet et al., 2006; Nauer et al., 2015). Termite excavating activities create macropores on mound soil as well as destruction of the crust below the mounds, increasing the rate of surface water infiltration, which can continue long after termite activity has ended (Léonard & Rajot, 2001) conducted infiltration tests using both simulated rainfall and ponding methods on termite mounds in Niger and found the infiltration capacity of mounds built by *Macroterme Subhyalinus* to be as high as 9 cm^3/s. However, they stressed the possibility of this to the large number of foraging holes exceeding 30 per square metre and located on positions topographically too low to be able to intercept surface water. In Amazonia, Brazil, Ackerman et al., (2007) used the constant head single ring method to obtain infiltration rates six times greater on mounds than in the surrounding control soils. However, other instances have recorded lower infiltration rates on termite mounds than in the surrounding soils. This is mostly attributed to the low permeability of the clay that makes up the mound and the near absence of surface conduits or foraging holes on some mounds (Dowuona et al., 2012; Bargués Tobella et al., 2014). Again, studies at this scale have been limited by depth of investigation, thereby constraining our appreciation of how deeply the soil profile is affected by termite tunnelling and burrowing activities. At a soil depth of about 3 m below the termite mound foot, Mujinya et al. (2013) observed evidence of groundwater from the mottling of Mn-Fe oxides and attributed it to reducing and oxidising conditions in the mound as a result of water table fluctuation in the perched aquifer below. Other studies with clearly different objectives discovered by chance a high groundwater table during both wet and dry seasons in places with high densities of termite mounds (Mujinya et al., 2011; Dowuona et al., 2012; Kandasami et al., 2016). However, a high groundwater table in the dry season is not known with perched aquifers as they lack surface water replenishment during this season, thereby drying up. This can be catastrophic to the termite colonies that depend so much on water for their metabolism (Dangerfield et al., 1998). It can, therefore, be suggested that the aquifers are more inclined to being permanent than perched.

Investigations into deeper soil depths have greatly contributed to the understanding of why termites create burrows in soil profiles. It appears that their dependence on permanent water supply and avoidance of periodic inundation (Mege & Rango, 2009; Levick et al., 2010; Davies et al., 2014b) are the primary reasons. In Rhodesia (present-day Zimbabwe), underground mining of gold availed a number of researchers the opportunity to study the relationship between termites and gold anomalies recorded on termite mounds. At a depth of about 200 ft, termites were observed to have created burrows from soil surface through rock fissures below to access groundwater in permanent underground reservoirs (West, 1965). Watson (1972) identified Odontotermes latericius as tunnelling through Kalahari sand to locate fractured sections of the underlying basement complex rock and continue down through a gold mine shaft to access groundwater-bearing fissures at a depth of about 27 m. On their return to the surface, they picked gold samples that were deposited on mounds. For this reason, termite mounds have become valuable prospecting sites for mineral exploration (e.g. West, 1965; 1970; Arhin et al., 2015) but ironically, not for groundwater search. Fluctuations in water level in the fissure occur seasonally, rising during the wet season and lowering in dry season. To keep up with the lowering water table in dry season, the termites excavate deeper into the fissures and deposit the material in the mound (West, 1970). This could be the explanation why Amitermes, Cubitermes and Trinervitermes termite species are acknowledged to enlarge or reconstruct their mounds after the rainy season (Skaife, 1955; Sands, 1961a as cited in Bouillon, 1970).

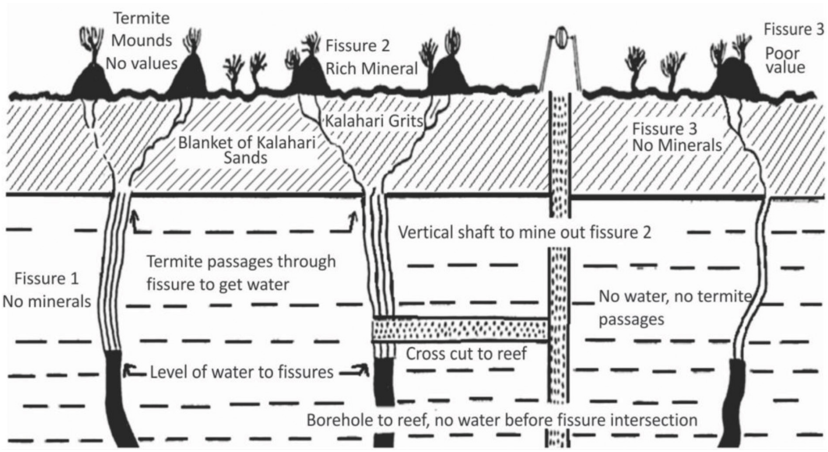


Figure 4. Schematic section through Leopard Mines in present-day Zimbabwe. Termite mounds built at surface from where the termite colony burrow through Kalahari sands to access basement fractures leading to water- bearing fissures below with water table at 27 m depth. On their way back, they pick gold grains from fissure 2 where a horizontal reef lies at 23 m depth to deposit in their mound. Figure based on West (1970)

Landscape Scale

Investigation at this scale of observation is sparse and is mainly limited to mound density estimation, evaluation of relationships between mounds and woody tree or plant vegetation distribution, mound distribution across mean annual precipitation changes and across broad geology. Termites strategically site their mounds where nutrients such as food and water are readily available. It has been observed of termites to avoid lowland environments and erect their structures on hill crests where building material is limited but where water and perhaps woody food can easily be sourced without risk of inundation. Levick et al. (2010) and Davies et al. (2014b) described mounds in Kruger National Park of South Africa as lining above seep-lines on hill crests, offering better drainage obviously because of the sandy nature of the soil. The seep-line could be the colony’s source of permanent groundwater (groundwater outcrop) and because woody vegetation is higher on the hill crest, making it an idle habitat. The dependence of termites on groundwater was also stressed following their relationship with aquiferous dykes in North-western Ethiopian lowlands (Mege & Rango, 2009). Termite mounds were strategically constructed in linear pattern on outcropped, fracture dense aquiferous sections of the dykes with a remarkable regular spacing between mounds and were completely absent on surrounding basaltic flow country rock, which has similar mineralogy as the dyke. Although the termite species was not identified, it is clear evidence that mound locations serve as pointers to identifying water-bearing sections of the dykes and that groundwater is chiefly among the factors governing termite mound distribution. A similar observation has been made in central Nigeria, where termite mounds are assembled in a linear fashion though without immediate evidence of a dyke or any linear structure (Ahmed II pers. obs.), but their strong relationship with Mangifera indica and Azadirachta indica tree species with large trunks known to have tap-root systems might just be an indication of what lies beneath. On the land surface, termite mounds associated with trees also influence the preferential flow of runoff towards their course (Bargues-Tobella et al., 2014), but what remains poorly understood is the preference of termites for regions of lower annual rainfall as demonstrated by Davies et al. (2014b). Higher annual rainfall would translate to more water available for underground storage but probably for security of their nests from degradation by rain, termites would prefer lower rainfall regions.

Table 2
Direct and indirect evidence of termite mound impact on groundwater

Author(s)	**Country**	**Scale of observation**	**Method(s)**	**Comments**
Ackerman et al., 2007	Brazil	Aggregate and profile	Field survey and experiment, laboratory tests	Improve infiltration, low soil water retention on termite mounds show promise for groundwater recharge
Bargués-Tobella et al., 2014	Burkina Faso	Landscape	Field experiment	Surface water flow preferentially around trees associated with termite mounds, increasing chances of infiltration
Davies et al., 2014b	South Africa	Landscape	Airborne LIDAR survey	Geology, drainage, wood cover accounted for termite mound patterning and distribution, which is a reflection of soil texture and permeability.
Davies et al., 2016	South Africa	Landscape	Airborne LIDAR survey	Tree species associated with lowlands had increased density near termite mounds at hill crest. Lowlands and valleys are suitable sites for groundwater exploration.
Dowuona et al., 2012	Ghana	Aggregate and profile	Field sampling and laboratory analysis	Physical and hydraulic properties to support runoff interception are poor but wells in the study area are known to be very productive.
Jouquet et al., 2015a	India	Aggregate	Field sampling and laboratory analysis	Cracks on termite mounds developed due to shrinking in the dry season can allow rainwater to directly penetrate into the mound.

Table 2 (*continue*)

Author(s)	**Country**	**Scale of observation**	**Method(s)**	**Comments**
Kalumanga et al., 2016	Tanzania	Aggregate and profile	Field survey and sampling	Termite mound distribution is controlled by surface and groundwater availability and not by clay or woody vegetation.
Leonard & Rajot, 2001	Niger	Profile	Field experiment and simulation	Macropores formed by termites increased infiltration rates in both ponding and rainfall simulation experiments.
Levick et al., 2010	South Africa	Landscape	Airborne LIDAR survey and clay content analysis	Termite mounds are built above seep-lines on well-drained sites where clay content is average.
Mege & Rango, 2009	Ethiopia	Landscape	Field survey	Groundwater storage in dolerite dyke controls the distribution of termite mounds.
Moura et al., 2014	Brazil	Aggregate and profile	Field and laboratory experiments	Enhanced mound soil porosity and infiltration as well as reduced bulk density hold promise for groundwater recharge.
Mujinya et al., 2013	D. R. Congo	Profile	Field investigation	There is evidence of a seasonally high groundwater table from the mottling of Mn-Fe oxides below the termite mounds.
Yamashina, 2010	Namibia	Landscape	Field survey	Termite mounds are distributed along seasonal streams, lowlands and areas with sharp changes in inclination (probably discontinuities) on mountainous regions.
Watson, 1972	Zimbabwe	Profile	Field and underground mines survey	Termite species *O. latericus* builds mounds directly above basement fissures where the termites burrow to access water at 27 m depth.
West, 1965	Zimbabwe	Profile	Field and underground mines survey	Reconstruction of mounds during dry season is evidence of termites' burrowing further into the ground, trying to reach the groundwater table that has dropped in response to the season.

CONCLUDING REMARKS AND SUGGESTIONS FOR FURTHER STUDY

As surface water is becoming scarce due to climate change causing unusual drying up of rivers and streams on which most of the rural populace rely for their supply, groundwater development becomes a favourable alternative. It is known that groundwater is drought reliable and available in almost all geologic formations. However, there is less than 1% chance of hitting water-bearing formations should wells be sited without adequate prospecting (West, 1965). Our quest for employing only sophisticated equipment such as geophysical tools in groundwater prospecting with enormous cost and labour attached has limited our power of observation. Identifying termite mound locations could mean that the arduous part of the prospecting job has been done at zero cost. Termites' reliance on water for their metabolism and avoidance of inundation from surface water somewhat constrain their habitation to areas with groundwater reserves that can last through the long dry season. Whether these reserves are permanent in all cases is a subject of further research. Furthermore, the current practices in groundwater prospecting entail the analysis of lineaments from remotely sensed images. Lineaments are linear to curvilinear lines of weaknesses on the earth surface through which runoff are thought to recharge aquifers. Many studies have employed this method to zone prospective groundwater-potential areas with impressive success rates (Solomon & Quiel, 2006; Jasrotia et al., 2013; Rahmati et al., 2014; Pinto et al., 2015). A major limitation with this method lies in its inability to distinguish between open lineaments (or water-bearing lineaments) from closed ones; hence, only zones with high lineament densities are assigned greater prospects. This limitation can be addressed when termite mound locations are integrated into such data to show only those fractures that harbour groundwater. Likewise, high topographic areas are usually characterised as poor in terms of groundwater prospect but the distribution of termite mounds on hill crest along seep-lines in Kruger National Park should counter this understanding. For future studies, the use of invasive electrical surveys on mounds to reveal the extent of regolith, underlying rock formation and its structural disposition beneath mounds can be explored. Across broad geology, distinction on termite mound distribution has only been made between granitic and basaltic rock covers; how this pattern varies across other rock types is not known. Finally, the use of the Geographic Information System (GIS) to integrate data from the three scales of observation discussed can prove very effective in further shaping our understanding of the relationship that exists between termite mounds and groundwater and other factors that control their distribution.

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