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Spatial variability of hydraulic properties on a bauxite residue disposal area in Western Australia

W. Gwenzi *Centre for Land Rehabilitation, School of Earth and Environment, The University of Western Australia, Australia*

C. Hinz *Centre for Land Rehabilitation, School of Earth and Environment, The University of Western Australia, Australia*

I. Phillips *Alcoa of Australia, Australia*

I.J. Mullins *Centre for Land Rehabilitation, School of Earth and Environment, The University of Western Australia, Australia*

Abstract

Engineered cover systems based on the store-release concept are commonly used to restrict drainage into buried reactive rock wastes. In principle, store-release covers are designed to store infiltrating water, and release it slowly through evapotranspiration. A typical store-release cover should have a top layer with high water holding capacity overlying a low permeability base layer designed to act as a hydraulic barrier. The capacity of a cover system to support vegetation, which is considered a key component, depends on soil moisture availability. Hydraulic properties, in particular soil moisture retention and hydraulic conductivity, control soil moisture storage, water flux and plant available soil moisture. Accordingly, hydraulic properties are key inputs in water flow, soil-plant-atmosphere and biogeochemical models. The main objective of this study was to investigate whether a rehabilitated bauxite residue disposal area (RDA) constructed from residue sand can act as a store-release cover. To achieve this objective, Philip-Dunne and Guelph permeameters, and a constant head laboratory method were used to measure saturated hydraulic conductivity (K_s). Geostatistics was used to evaluate K_s spatial variability. Results indicate that K_s was very high (> 100 cm hr^{-1}), but showed low spatial variability (coefficient of variation: < 45%). In general, K_s decreased from 209–400 cm hr^{-1} in the top 90–115 cm hr^{-1} at 300 cm depth. The decline was negatively correlated ($r^2 = 0.7$) to mean dry soil bulk density (dry soil bulk density = mass of dry soil/total volume), which increased from 1313.8 kg m^{-3} at 15 cm to approximately 1500 kg m^{-3} at 300 cm depth. Correlation analysis showed that K_s for residue sand can be estimated from a simple equation based on dry soil bulk density. On the basis of the high K_s, rapid vertical movement of water is expected during rainfall events. In addition, the low water-holding capacity could lead to severe vegetation water stress particularly in the dry season. In conclusion, a cover system constructed from residue sand cannot act as a store-release cover system. It is therefore recommended that, materials with high K_s should not be used to construct a store-release cover system. To meet the objectives of a store-release cover, a redesign of the bauxite RDA is highly warranted.

1 Introduction

The application of engineered cover systems is a key strategy for minimising environmental and public health risks associated with mine wastes. In water-limited environments, store-release covers designed to restrict deep drainage by storing infiltrated soil moisture until it is released through evapotranspiration are common (Benson et al., 2004; Campbell, 2004). A typical store-release cover should have a top layer with high water holding capacity overlying a low permeability base layer designed to act as a hydraulic barrier. In most instances, the top cover layer consists of soil or relatively inert rock material supporting a vegetation community (Breshears et al., 2005). Compared to natural soils, rehabilitated mine sites may exhibit adverse physical and chemical properties. These properties arise from the nature of the rock wastes and degree of weathering (Mengler et al., 2006). In addition, transport and construction procedures, and material settling after placement may influence physical properties of cover systems. For example, high penetration resistance and bulk densities have been observed on some rehabilitated bauxite and gold mines in Western Australia

(Mengler et al., 2006; Arunachalam et al., 2004). In Germany, Buczko et al. (2001) observed that particle segregation during material transport and dumping increased bulk densities and reduced hydraulic conductivity in the surface layers of coal spoils.

On rehabilitated mines sites, hydraulic properties control water and contaminant flow and storage. Knowledge of hydraulic properties and their spatial variability is crucial in design of cover systems and modelling of water and contaminant transport (Gupta et al., 2006). Numerous field and laboratory methods for measuring soil hydraulic properties have been developed and evaluated. Among them, permeameters, rainfall simulators, infiltration rings and constant head method are often used to measure K_s (Reynolds et al., 2002). However, hydraulic properties are difficult to measure, and most existing methods are time-consuming, costly and require sophisticated equipment. Efforts to overcome these limitations have led to the development of indirect and relatively fast and cheap methods. For example, Muñoz-Carpena et al. (2002) developed a prototype and field protocol for a simple and inexpensive Phillip-Dunne permeameter for measuring field K_s. The method is ideal for rapid measurements of hydraulic conductivity for evaluation of spatial variability. Besides simple field methods, substantial progress has been made in the development of indirect approaches commonly classified as pedotransfer functions (PTFs). PTFs estimate hydraulic properties on the basis of easily measured soil properties such as bulk density, particle size distribution (PSD) and organic matter content (Wösten et al., 2001). However, limited studies have evaluated the performance of PTFs on rehabilitated mine sites.

Although substantial literature is available on hydraulic properties of natural and agricultural soils (Gupta et al., 2006), data on rehabilitated mine sites is still limited. In addition, the extent of spatial variability of hydraulic properties on rehabilitated mine sites has received little attention. Geostatistics offer an opportunity to investigate spatial variability of cover hydraulic properties on rehabilitated mine sites. Geostatistics rely on variogram analysis and kriging to model spatial variability and estimate values for unsampled locations (Gómez et al., 2005).

The main objective of the present study was to investigate whether a rehabilitated bauxite RDA constructed from residue sand can act as a store-release cover. To achieve this objective K_s, PSD and dry soil bulk density (ρ_b) were measured on a rehabilitated bauxite RDA. K_s data were subjected to geostatistical analysis to determine spatial variability. In this paper, results of K_s measurements, geostatistical modelling of spatial variability and a simple empirical model for estimating K_s based on ρ_b are discussed. Observed results are interpreted in the context of vertical water movement and plant water relations.

2 Materials and methods

2.1 Description of the study site

The study was conducted on rehabilitated bauxite RDA in Kwinana, where the site experiences a mediterranean climate characterised by rainfall, about 700 mm yr^{-1}, occurring mainly in winter. The RDA is a disposal facility for residue rock wastes from a bauxite refinery. The residue is separated into alkaline mud (<150 µm in diameter, pH ≈ 12) and residue sand (>150 µm in diameter). As part of the mining company's rehabilitation programme, the mud is discharged into tailings dams, whose embankments are constructed at about 6% slope using the residue sand. After incorporating 2.25 t gypsum ha^{-1} and 2.75 t ha^{-1} of diammonium-based fertiliser to a depth of about 150 cm, the embankments were revegetated from seedlings and seed. Details of the rehabilitation process are described in Koch and Samsa (2007). A typical cross-section of the RDA consists of six to ten metres of residue sand supporting a mixed stand of tree and shrub species, overlying the mud layer. Vegetation at the study site is dominated by woody species *Acacia rostillifera*, *Melaleucas nesophila, Acacia saligna* and other species endemic to coastal dune ecosystems of Western Australia. The study plot was established in 2004 and had an average stem density of 188 ± 50.7 plants ha^{-1} at the time of the study.

2.2 Measurement of K_s

Field K_s was measured using a Philip-Dunne permeameter (Muñoz-Carpena et al., 2002) on a 56 × 26 m plot at 4 m lag intervals, giving a total of 112 data points. Briefly, a 10 cm diameter auger was used to make a 10 cm deep hole every 4 m. The permeameter was comfortably inserted into the auger hole and filled with water to the 30 cm mark. Time required for water to reach 15 cm and 30 cm height was monitored using a stopwatch. Initial and final soil moisture was measured using a calibrated Theta probe (Measurement Engineering Australia). K_s was calculated using the computer routine developed by Muñoz-Carpena et al. (2002).

Additional field measurements and samples were collected at a trenching site to determine the depth variation of K_s. Near-surface K_s was measured using Guelph and Philip-Dunne permeameters before excavation. A mini-backhoe was used to excavate a six metre long and three metre deep trench running downslope. Metal cylinders (7 × 7 cm) were used to collect soil core samples for laboratory determination of K_s, ρ_b and particle size analysis.

In the laboratory, K_s was determined by the constant head method (Reynolds et al., 2002). A 200 µm nylon mesh was put at the bottom and secured tightly with a rubber band. A filter paper was put on top of each core, and a metal core tightly secured to act as a reservoir. Samples were saturated from the bottom in a water bath filled with distilled water for 48 hours. A system consisting of a raised water tank was used to deliver water at a constant head to the core reservoirs. The mass of water eluted from each core was monitored by electronic balances connected to a computer configured to record mass and time. Darcy's law was used to compute K_s (Reynolds et al., 2002).

2.3 Dry soil bulk density (ρ_b) and particle size determination

At the end of the K_s measurements, the core method was used to measure ρ_b (Blake and Hartge, 1986). Core samples were oven-dried at 102°C for 24 hours, and used to compute ρ_b as follows:

$$\rho_b = \frac{M_s}{V_t} \tag{1}$$

where:

M_s = oven dry mass of soil (kg).

V_t = total volume of soil core (m^3).

Particle size analysis was determined by sieving for the sand fraction and pipette method for silt and clay (Gee and Bauder, 1986). Soil was dispersed by adding sodium hexametaphospate followed by centrifuging. The dispersed suspension was sieved through a 50 µm sieve to separate sand from silt and clay. Silt and clay in the suspension were determined by sedimentation using the pipette method.

2.4 Data analysis

Univariate statistics were computed for K_s, ρ_b and PSD. One way analysis of variance was used to test the effects of K_s method and depth on K_s, PSD and ρ_b at 5% probability level. Regression and correlation analyses were used to test the relationship between hydraulic properties and ρ_b and PSD. In all cases, SAS program (SAS Institute Inc., Cary, NC, USA) was used for statistical analysis. Variogram analysis was used to evaluate spatial variability. In semivariogram analysis, a semivariogram model is fitted to observed or experimental semivariance (Gomez et al., 2005). On the basis of the variogram model that best fitted the data, kriging was used to estimate K_s at unsampled points. Geostatistical analysis was performed using the Spatial Analysis and Decision Assistance (SADA 5.0) program.

3 Results and discussion

3.1 Summary statistics

Table 1 shows summary statistics for K_s, ρ_b and PSD for near-surface and trench measurements. The residue sand consisted of 96% sand and about 4% clay plus silt. Coefficients of variation for PSD decreased in the order; clay (25%) > silt (8%) > sand (2%). Mean K_s for the Phillip-Dunne method (K_s-PD) and constant head method (K_s-CH) were of similar magnitude, but higher than that of Guelph permeameter (K_s-GP) (Table 1). However, mean K_s-GP was within the range for K_s-CH (Figure 1). Mean K_s was very high (>150 cm hr^{-1}) at all depths regardless of method of measurement. Observed K_s values were several orders of magnitude higher than those reported in literature. For example, using the constant head method to measure K_s of residue sand from a bauxite refinery at Alcan Gove in the Northern Territory, Australia, Wehr et al. (2005) observed a mean value of 18 cm hr^{-1}. This discrepancy could be due to differences in material properties, and site-specific material handling and construction procedures. For example, Wehr et al. (2005) reported higher bulk densities (1660 kgm^{-3}), silt (3%) and clay (5%) than those observed in this study. Variability of K_s was generally low for both field and laboratory methods (< 5%). Compared to studies published in literature for natural and agricultural soils, coefficient of variation (CV) of less that 50% is considered very low. Similarly, the coefficients of variation for ρ_b were very low (5%) for both near-surface and trench measurements. However, a distinct increase in ρ_b with depth was observed for the trench measurements. Similar trends were observed for PSD, which increased gradually with depth probably due to self-filtration or particle segregation after placement. Consequently, K_s followed the same trend as ρ_b and PSD (Figure 1). The effects of particle segregation and self-filtration on K_s are well-documented (Buczko et al., 2001; Dikinya et al., 2008). Moreover, colloid dispersion was evident in some of the samples collected below 120 cm depth. In general, dispersion was confined to depths below the zone of gypsum incorporation.

Overall, all measured soil properties showed limited variability compared to observations reported in literature. This observation is in contrast with general trends observed on natural soils, where spatial heterogeneity in soil properties is often reported (Gupta et al., 2006). Moreover, K_s values in the order of 100 cm hr^{-1} are very rare in natural and agricultural soils. Considering that the study site represents a reconstructed artificial ecosystem, it can be speculated that the high K_s values and low spatial variability could be attributed to material properties and construction procedures. For example, artificial separation of the residue into sand and mud could have resulted in poorly graded material dominated by the sandy fraction.

Table 1 Summary statistics of K_s, ρ_b and PSD. K_s-PD, K_s-CH and K_s-GP: K_s measured by constant head, Philip-Dunne and Guelph permeameters, respectively

Property	Mean	Range	CV (%)
K_s-PD (cm hr^{-1})	346	146–667	36
K_s-CH (cm hr^{-1})	268	24–485	41
K_s-GP (cm hr^{-1})	145	79–216	36
Dry soil bulk density (ρ_b) (kg m^{-3})	1401	1086–1586	5
Particle size distribution (PSD) (%)			
Sand	96	93–97	2
Silt	1	0.4 – 1.2	8
Clay	3.8	1–5	25

Conversion of K_s units: 1 cm hr^{-1} = 2.78 x 10^{-4} cm s^{-1}

3.2 Depth variation of K_s

K_s significantly ($P < 0.05$) decreased with increasing depth (Figure 1). The decline was negatively correlated ($r^2 = 0.67$) to mean ρ_b, which increased significantly ($P < 0.05$) with depth from 1313.8 kg m^{-3} at 15 cm and to about 1500 kg m^{-3} at 300 cm depth (Figure 2). The inverse relationship between K_s and ρ_b was expected, and has been observed in other studies (Gupta et al., 2006). In addition, % silt plus clay slightly increased with depth, although the relationship with K_s was very weak ($r^2 = 0.09$). Moreover, soil dispersion was evident below about 150 cm depth, which coincides with the maximum depth of gypsum incorporation. Downward movement of fine soil particles has been reported to reduce hydraulic conductivity on rock residues from mine sites (Dikinya et al., 2008).

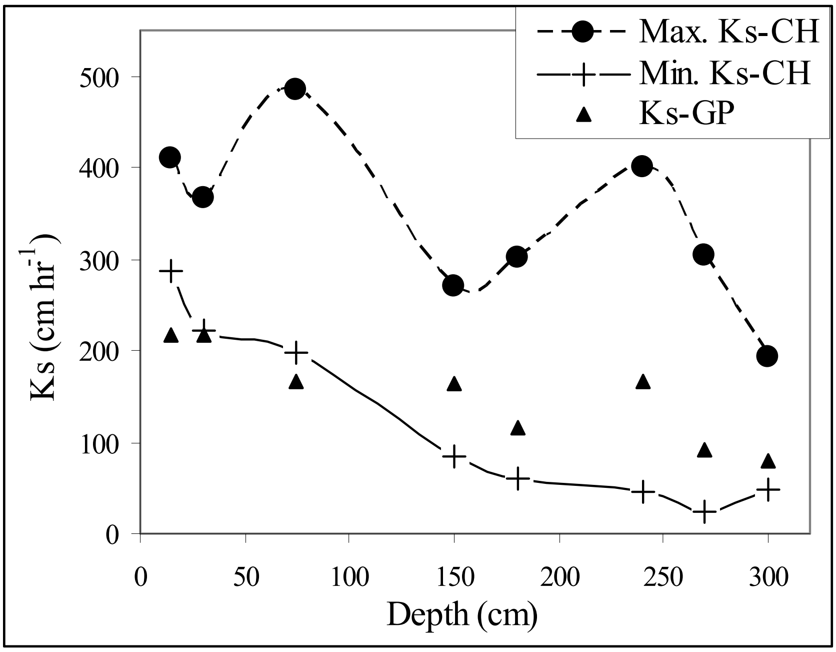

Figure 1 **Depth variation of K_s-GP and minimum (Min. K_s-CH) and maximum (Max. K_s-CH) values for the constant head method**

3.3 Relationship between K_s and soil properties

The effects of ρ_b and PSD on K_s measured were tested using regression analysis. The objective was to use the two soil properties as predictors of K_s. Correlation results showed no apparent relationship between % sand and silt and K_s. However, K_s appeared to decrease with increasing % clay, and clay plus silt although the relationship was very weak ($r^2 = 0.09$).

While studies conducted on natural and agricultural soils have often reported, PSD as a key control of hydraulic conductivity (Wösten et al., 2001), the effects were very minimal in this study. This could be explained by the low variability of PSD attributed to artificial separation. On the other hand, the degree of material packing as indicated by ρ_b was observed to be a better predictor of K_s (Figure 2) than PSD. To a large extent, ρ_b of rehabilitated mine sites is influenced by material handling and construction procedures and subsequent settling. Negative correlation between ρ_b and K_s has been observed in previous studies conducted on natural soils (Wösten et al., 2001). It is noteworthy that most existing pedotransfer functions (PTFs) for estimating K_s are based on % sand, silt and clay content (Wösten et al., 2001). Given that the relationship between K_s and PSD was very weak, the applicability of such PTFs on the study site appears very limited. Evaluation of some of the prominent PTF models based on % sand, silt and clay confirmed that none of the models predicted K_s comparable to measured values (results not shown). In all cases, the PTF models grossly underestimated K_s. Moreover, studies have shown that most PTFs are valid for the conditions or soil for which they were developed.

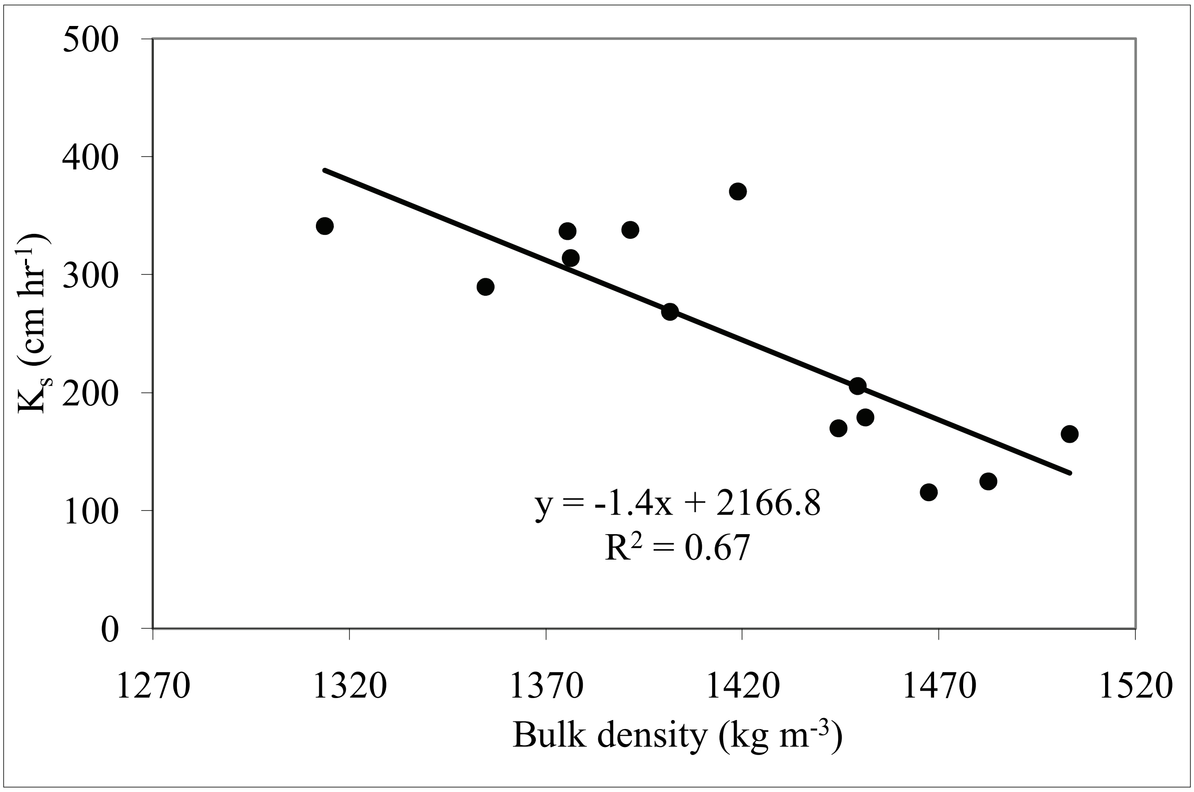

Figure 2 Relationship between ρ_b and K_s

Given that PTF models based on ρ_b are very limited, correlation analysis was used to develop a simple PTF based on ρ_b alone. Using the mean data, ρ_b was a good predictor ($r^2 = 0.7$) of K_s (Equation 2):

$$K_s = -1.4\rho_b + 2167 \tag{2}$$

These preliminary results suggest that existing PTF models based on PSD have limited potential to estimate K_s for artificially separated residue material at the study site. However, ρ_b was a better predictor of K_s than PSD. Accordingly, the $\rho_b - K_s$ relationship can be used to provide first order estimates of K_s on residue sands. ρ_b, which is the only input data to be measured directly, is simple and easy to measure. This simple approach has great potential to provide large-scale data for water flow modelling on a RDA. However, caution should be exercised when using PTFs beyond the study site because their validity is reported to be highly site-dependent.

3.4 Spatial variability of K_s

An exploratory investigation was conducted to determine the presence of spatial structure and estimate distances of spatial correlation for K_s. Variogram analysis indicated the presence of spatial structure in hydraulic conductivity (Figure 3). For near-surface measurement, K_s variation across the slope was evident on the kriged map (Figure 5). The spatial pattern seems to be indicative of movement of traffic during material placement and construction. Spatial pattern from trench measurements was dominated by the depth effect (Figure 4). In general, near-surface K_s values separated by a lag distance of 7.7 m were spatially correlated, while for the trench measurements the distance was reduced to about 2.4 m. These distances coincided with the sill value, which is the maximum variance of a variogram. The data implies that a higher sampling resolution for K_s determination may be required for trench measurements than near-surface hydraulic conductivity. This observation is in agreement with the relatively higher CV observed for trench (41%) than near-surface measurements (36%). However, given the high K_s measured at all sampling points, it is unlikely that the spatial patterns observed will have a pronounced effect on water flow patterns at the study site.

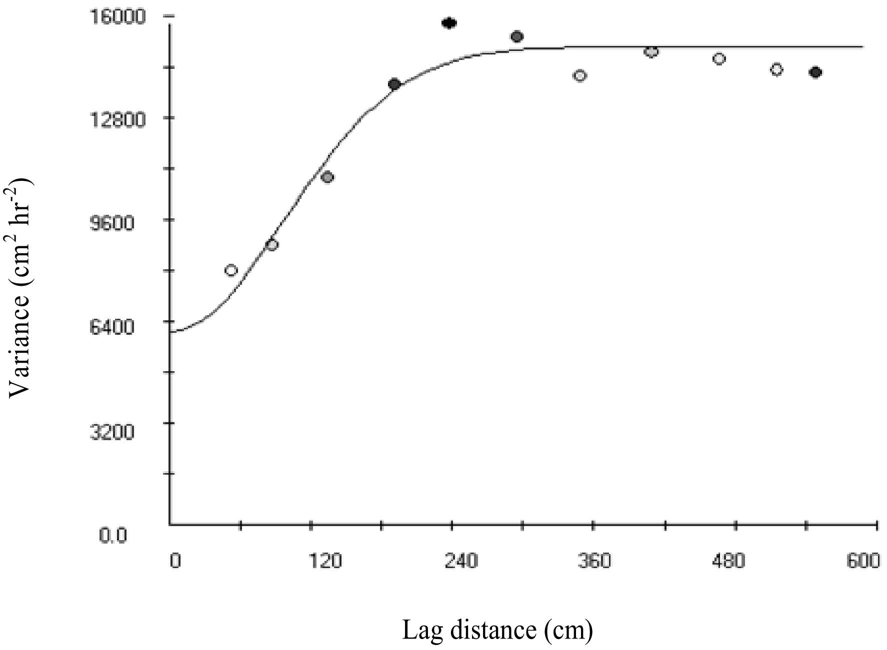

Figure 3 A variogram for trench K_s measurements

3.5 Implications for deep drainage and plant water relations

The results for the site are interpreted in the context of the store-release concept, based on the belief that in water limited environments, rehabilitated mine sites with a substantial vegetation component are capable of restricting deep drainage by storing soil moisture during the wet season, and slowly release it during the dry season as evapotranspiration. The data are discussed in the context of downward water movement and plant water relations.

On the basis of high K_s and low spatial variability, rapid downward water flow is expected under saturated conditions. Moreover, the high K_s values suggest that saturated water flow is not K_s-limited. Field observations showing that surface runoff and erosion at the study site were negligible attest to this. Consequently, the magnitude of deep drainage during a rainfall event will be highly dependent on rainfall intensity, root water uptake and bare soil evaporation. Bare soil evaporation is often limited to the top few centimetres of the profile and can be neglected during rainfall events. Considering that most plant roots are confined to the top 40 cm of the profile, the rapid downward movement implies that the residence time of water in the root zone is likely to be very low. Rapid loss of soil moisture through drainage could lead to plant water stress and mortality, particularly during prolonged dry seasons. Using column experiments, Wehr et al. (2005) investigated the effects of high hydraulic conductivity of layered reconstructed soils on plant water stress at Alcan Gove, Northern Territory. Wehr et al. (2005) concluded that soil material with high hydraulic conductivity, such as residue sand, lost water and dried out quickly, giving plants limited time to invoke water stress tolerance mechanisms. To mitigate the problem, Wehr et al. (2005) suggests a prototype consisting of 60 cm of subsoil overlying a residue sand layer of similar thickness. However, their conclusions were based on column experiments focussing on Rhodes grass as a test species. The performance of the prototype has not best tested under field conditions where ecosystem interactions may be important. Data presented in this paper seems to suggest that a cover system built from residue sand with high hydraulic conductivity cannot store water as widely expected. Moreover, rapid downward flow and drying are likely to lead to plant water stress during the dry season when plants are expected to release water through transpiration.

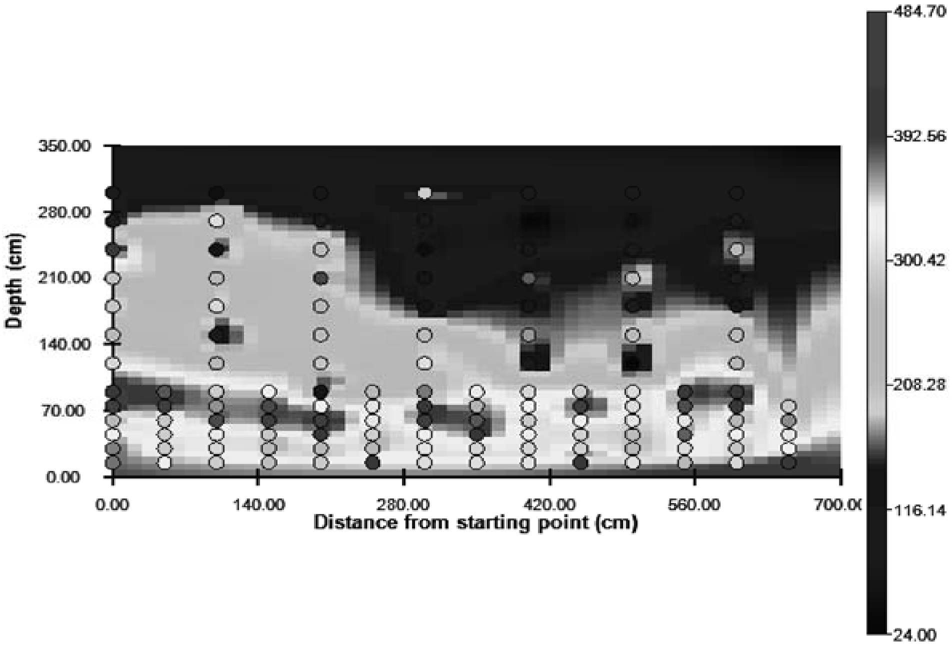

Figure 4 Kriged map of K_s (cm hr^{-1}) for the trench

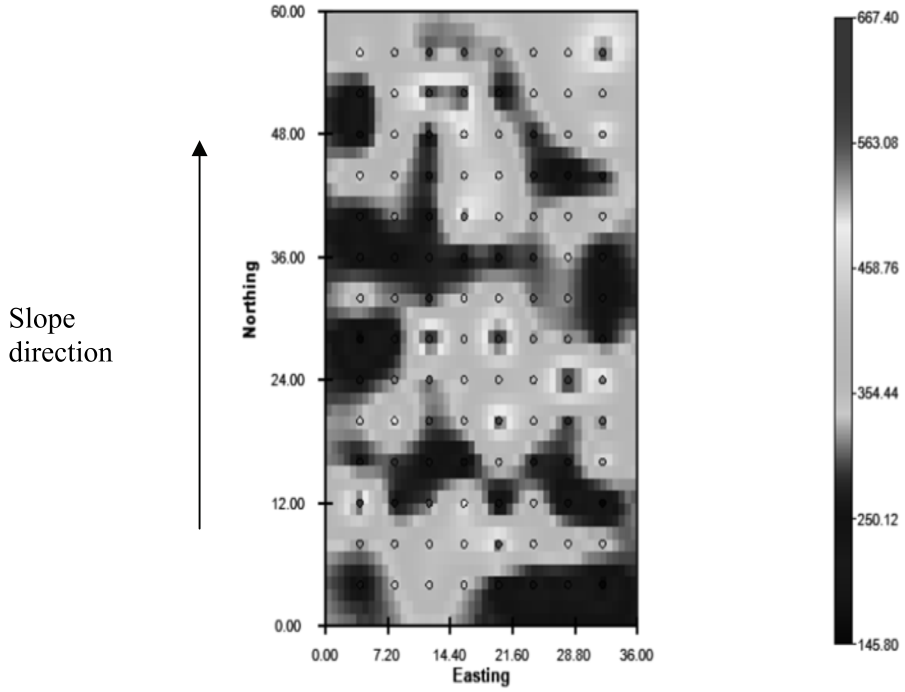

Figure 5 Kriged map of near-surface K_s (cm hr^{-1}) measured using a Philip-Dunne method. Distances in both directions are in metres

4 Summary and conclusions

The study investigated the magnitude and spatial variability of K_s on a rehabilitated bauxite RDA. K_s, ρ_b and PSD showed very low spatial variability compared to observations reported in literature. ρ_b gradually increased with depth, resulting in a corresponding decline in K_s with increasing depth. Variogram analysis showed that K_s had spatial structure with a characteristic correlation distance. However, from a water flow perspective, K_s was very high regardless of method of measurement, suggesting rapid downward water flow. High K_s values suggest that the current design and placement procedures based on residue sand as construction material have limited capacity to store soil moisture. Consequently, the potential for downward water movement and deep drainage is likely to be much higher than initially thought. In addition, given that the site experiences distinct wet and dry seasons, rapid water loss through deep drainage could lead to severe plant water stress particularly during extended dry periods. In conclusion, a cover system constructed from residue sand cannot act as a store-release cover system. It is therefore recommend that materials with high K_s should not be used to construct a store-release cover system. A redesign of the RDA is highly warranted if it has to meet the objectives of a store-release cover. Considering that K_s is difficult and time consuming to measure, a simple model based on ρ_b was developed for providing a first order estimate of K_s for residue sand. Further research work is planned to determine soil moisture retention characteristics and temporal dynamics of relative plant available moisture in dry and wet seasons. The validity of PTFs based on ρ_b and PSD will be explored further.

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