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Spatial characterization of scaled hydraulic conductivity functions in the internal drainage process leading to tropical semiarid soil management

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A B S T R A C T

Knowledge of water movement is critical to agricultural water use. An internal drainage experiment for assessing downward movement of soil water under the influence of gravity was conducted on a semiarid sandy soil at ICRISAT-Sadore in Niger. The objectives were to estimate unsaturated hydraulic conductivity functions $K(\theta)$ at multiple scales using soil water (θ) data determined over the drainage process, and to determine spatial characteristics of $K(\theta)$ functions for water management in the semiarid environment. The study site was a naturally rolling field and the soil was a sandy Labucheri soil series. The experimental design consisted of a nested grid with three scales, 1 × 1-m, 5 × 5-m and 20 × 20-m, using 182 neutron access tubes. Soil water movement in space was examined in the 0.15–1.50 m depth throughout the drainage course. Mean soil water downward movement varied between 0.029–1379 mm h^{-1}, depending on water content and soil depth. Elevation features contributed to 16–40% of the variation in hydraulic conductivity functions ($K(\theta) = e \cdot \theta^f$). The best fit for $K(\theta)$-model coefficients was a normal distribution and $K(\theta)$ functions were correlated at the three scales ($0.81 \le R^2 \le 0.96$, $P < 0.01$). The scaled $K(\theta)$ functions were auto-correlated in space within 25–60 m. Management zones based on geostatistical semivariograms and interpolated map patterns were practical for water management planning in the naturally rolling environments.

1. Introduction

Soil hydraulic conductivity $K(\theta)$, an indispensable, non-linear function of soil water content (θ), has been generally recognized as the single most important transport property to describe the ability of a soil to permit water movement (Germer et al., 2010; Green et al., 1986; Lilly, 2006). Knowledge of soil hydraulic conductivity could assist in establishing sustainable soil and water management (Abit et al., 2012; Mudgal et al., 2010). Water transport and hydraulic conductivity functions have been useful for controlling soil water infiltration and percolation, water balance, reducing nutrient ions NO_3, PO_4 and pesticide leaching from agricultural lands and planning water management projects (Abit et al., 2012; Carof et al., 2007; Germer et al., 2010; Udawatta et al., 2008). Yet, there was a lack of information about variation of soil water holding and hydraulic conductivity function in the semiarid areas/countries such as Niger, West Africa. Water shortage has been the major limitation to cause extremely crop yield variation in these very hot and dry areas, where crops most resistant to drought and heat such as pearl millet (*Pennisetum americanum* L.) and cowpea (*Vigna unguiculata* L.) have been the favorable crops due to their drought-tolerance and adaptation to grow in limited, short raining seasons under high temperature conditions in the semiarid tropics. In such regions extreme variability in crop stands was evident as pearl millet yield could diminish significantly over distances as short as 2 m (Scott-Wendt et al., 1988). Water management was very important for crop production in such dry, hot regions (Craufurd et al., 2006; Klaij and Vachaud, 1992; Singh et al., 2013).

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Water distribution and movement in unsaturated zone (above the water table in soil profile) were critical to water use and management in agriculture (Evett et al., 2009; Fuentes et al., 2004; Green et al., 1986). Water was not evenly distributed in agricultural soils and the impact of soil water was greater than other factors (such as nutrient availability) on crop yield (Li et al., 2004; Li and Lascano, 2011). Soil water deficiency could result in plant water stress, reduced nutrient uptake and diminished yield formation of many crops including pea, sorghum, strawberry, broccoli and cotton (Li et al., 2010, 2011, 2008; Li and Lascano, 2011; Payne et al., 2001). It was also reported that soil water and soil nitrate uneven distribution patterns were associated with topographic features to affect plant development (Law et al., 2012; Li et al., 2002).

Soil water variability in space and time could be determined using hydraulic conductivity functions assessed across the landscape (Regalado and Munoz-Carpena, 2004; Price et al., 2010). Changes in soil water content (θ) could reflect the changes in hydrogen (H_2O) concentrations in the soil (Green et al., 1986). Emitted neutrons from isotope source (neutron detector) could lose energy as they impacted hydrogen atoms (water) and neutron detector responses could weaken as soil water content increased (Evett et al., 2009). The neutron detection method has been considered more accurate than other electronic method such as time domain reflectometry to determine soil water content (θ) in deep depths (Evett et al., 2009; Strickland et al., 2010).

Hydraulic conductivity function $K(\theta)$ functions estimated from measured θ values were dynamic, which could be affected by many factors (Abit et al., 2012; Mudgal et al., 2010). Variability in $K(\theta)$ values depended on different interrelated factors including soil drainage, aggregate stability, porosity, organic amendment use and tillage operations (Abit et al., 2012; Asadi et al., 2011; Lilly, 2006; Osunbitan et al., 2005; Price et al., 2010). Management practices and land use types could affect water retention, saturated hydraulic conductivity and water balance (Boulain et al., 2009; Fuentes et al., 2004; Udawatta et al., 2008). There were significant correlations between soil hydraulic conductivity and soil structure that affect water movement (Dungan et al., 2007; Lilly, 2006; Mudgal et al., 2010).

Heterogeneity of soil hydraulic properties should be evaluated at multiple scales for better management planning for crop irrigation, land use and tillage practices (Carof et al., 2007; Green et al., 1986; Mudgal et al., 2010). Environmental assessments of semiarid soil and water variables found that soil organic matter, C/N and groundwater nitrate contamination varied with spatial scales, land use and topographic features (Hu et al., 2007, 2005; Law et al., 2012). The errors in hydraulic conductivity estimations were associated with scaling gradients (Green et al., 1986; Price et al., 2010). Simple regression and cross-autocorrelation with GIS information were useful for effective farming management purposes (Li et al., 2008).

The data gap in soil hydrology and water movement included the lack of knowledge of hydraulic conductivity at multiple scales in internal drainage process in hot and semiarid areas. There was also a lack of knowledge of planning effective management strategies for water use in cultivation lands with rolling topographic constraints. Our objectives were to (i) estimate unsaturated hydraulic conductivity in the internal drainage process at different nested scales (i.e. 1 × 1-m, 5 × 5-m and 20 × 20-m grids) using neutron-probed soil water (θ) measurement data, (ii) determine spatial variability and correlations of model-fit hydraulic conductivity functions, and (iii) planning water management zones based on correlation ranges from geostatistical semivariograms and patterns of interpolated maps for hydraulic conductivity functions. Understanding the directions and magnitudes of water movement at multiple scales should be useful for getting a better insight to water management purposes in semiarid environment.

2. Materials and methods

2.1. Field site description and nested-grid design

The internal drainage experiment was conducted on a tropical sandy soil during the dry seasons from early January to late April at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Experimental Station (13°15′N, 2°18′E) in Sadore, Niger in West Africa, where the climate is mainly very hot and dry (Singh et al., 2013). In the regions, the 30-year mean temperature was 29.5 °C during the growing season (June–October) with mean max-temperature of 35.3 °C and min-temperature of 23.6 °C (Singh et al., 2013). Low rainfall could be as little as 240 mm per year (Scott-Wendt et al., 1988). Long-term (30-year) rainfall averaged yearly 540 mm, occurring mainly in the spring and the summer. The potential evapotranspiration was high, up to 2000–2300 mm per year (Craufurd et al., 2006).

The study site was typically a natural rolling field in the region, as shown the elevation declined from the northern-west to the southern-east across the field (Fig. 1). The relative elevation at the neutron probe access tubes varied between 28.2 ± 13.5 m (mean and standard deviation, $n = 182$), assessed using a survey grade GPS unit of Trimble Dual Channel RTK system (Model 4700, Trimble, Sunnyvale, CA). The soil, evolved from eolian sand deposits, was classified as Sandy Siliceous Isohyperthermic Psammentic Paleustalfs, Labucheri soil series (Scott-Wendt et al., 1988; Singh et al., 2013). The soil was poor in organic carbon (2 g kg^{-1}) and sand content decreased from 920 g kg^{-1} in the top layer (0.15 m) to 870 g kg^{-1} in the depth of 1.50 m (maximum crop rooting depth in the area), determined prior to the experiment. The field had been used for nitrogen fertilization trials of pearl millet, the drought resistant, dominate crop in the region (Klaij and Vachaud, 1992; Scott-Wendt et al., 1988).

The internal drainage experiment was established in a large area of 100 m × 80 m (8000 m^2, Fig. 1). The experimental design consisted of a nested grid at three scales arranged using 182 aluminum

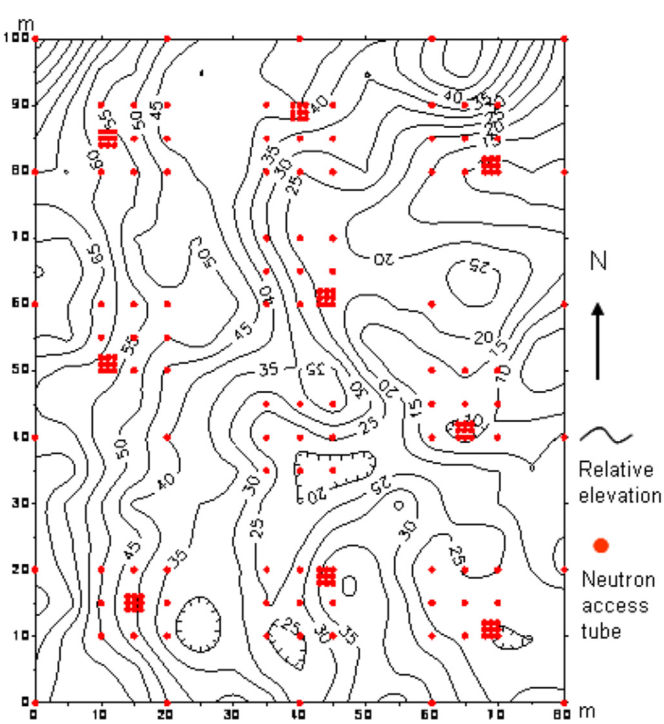

Fig. 1. Field relative elevation, experimental design, and nested grids at three spatial scales at 20 × 20 m, 5 × 5 m and 1 × 1 m using 182 neutron access tubes.