

Water entry, retention and movement in soils of warm humid regions

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Abstract This paper reports the results of *in situ* measurements of near-surface hydrological parameters, namely: infiltration rates, saturated hydraulic conductivity, and moisture retention characteristics, in a variety of earth materials, including: natural undisturbed soils, disturbed soils in urban areas, and reclaimed lands, under a wide range of land use/cover, such as: primary and secondary forests, agricultural crops, landscaped gardens and unattended grounds in urban areas, and unvegetated areas. The experiments were confined mainly to Singapore – a small island very near the equator, having warm-humid climatic conditions throughout its space and time. The results indicate that the values of these hydrological parameters are different, in magnitude and in temporal and spatial variations, from other areas. The importance of these results in explaining other hydrological processes, such as the contribution to surface runoff, is also discussed. The paper also evaluates the applicability of testing procedures for determining these hydrological parameters under warm-humid conditions and makes recommendations based on extensive field work.

INTRODUCTION

Considerable information is available on retention and movement of water in soils of humid tropics, but there are many aspects of soil-water phenomena in these areas which are not clearly understood. Heterogeneity of climatic and morphological characteristics of soils of warm-humid regions may be cited as one of the reasons for the lack of such data. Physical hardships in collecting such data with limited resources allocated for such investigations may be another reason. To compound the problem, many such areas especially in the Pacific rim countries are also undergoing a frenzied pace of (economic) development which alters the land cover/vegetation posing difficulties for systematic studies but also necessitating the need for such studies. These changes are associated with a myriad of problems such as accelerated soil erosion, flooding, etc. Singapore has been a good laboratory for studying the various near-surface hydrological processes and phenomena in a rapidly changing (soil-water) environment in a warm-humid area. For several years the author has been conducting field investigations, measuring the various hydrological parameters and processes. This paper summarizes some of the results of these studies.

OBJECTIVES

The study reports the results of *in situ* measurements of the following near-surface hydrological parameters:

infiltration rates, saturated hydraulic conductivity, moisture retention characteristics,

in a variety of earth materials, including:

natural (relatively) undisturbed soils, disturbed soils in urban areas, reclaimed lands,

under a wide range of land cover/vegetation, such as:

primary and secondary forests, agricultural crops, landscaped grounds and unattended grounds (covered with shrubs, etc) in urban areas, open unvegetated areas.

The paper also evaluates the applicability of testing procedures for determining the various hydrological parameters under warm- humid conditions and makes recommendations based on extensive field work.

METHODOLOGY

The study area

Singapore is a small (around 600 km²) island-state located very close to the equator (approximate longitude 104°E, latitude 1°N). It experiences relatively uniform and high temperature (mean monthly temperature variation within 1.1 °C and mean annual value 26.6 °C), high humidity (mean annual relative humidity of 84%) and abundant rainfall (mean annual rainfall is nearly 2400 mm) (Meteorological Services, 1991). The rainstorms in Singapore are highly variable in terms of their spatial-temporal distribution (Watts, 1955). Most storms bring high intensity rainfall, are short lived, cover small areas and are quite mobile (Rahman, 1984). Under these climatic conditions most rocks (comprising mostly of Triassic granites to Recent sediments, according to the Public Works Department, 1976) undergo intense weathering (Nossin & Levelt, 1967) and give rise to well developed soils (Ultisols/Ferralsols, Acrisols, Nitisols according to Rahman, 1991). The native vegetation over most places had been forests which is being replaced by built-up areas consisting mostly of buildings, paved areas, and landscaped gardens. Some areas are occupied by an intermediate state of tall grass and shrubs or a rapidly disappearing land use of agricultural activities. Thus these four land covers (forests, tall grass/shrubs/crops, landscaped grounds, paved areas) blanket most of the land area of Singapore. Over 10% of the area of the Singapore island is reclaimed from the sea and is covered by similar vegetation (Tham, 1984). Different hydrological processes operate, if not in kind then in magnitude, in these areas.

Instrumentation

At all sites, infiltration rates were measured using multiple ring flooding type infiltrometers similar to those described by Ahuja *et al.* (1976). At selected sites,

tensiometers were placed strategically in and around the rings to monitor the flow path following the entry of water into the ground. In most cases water was applied (generally for 2 h) till a steady state was reached, and at selected sites, tests were conducted continuously for several days.

Hydraulic conductivity was measured using three methods: (a) laboratory measurements on undisturbed cores, using falling head permeameter, (b) *in situ* measurements using double-tube permeameter (modified after Bouwer 1962), and (c) *in situ* measurements using a Guelph permeameter (Tamsir, 1988). In view of the highly heterogeneous nature of warm-humid soils, all these measurements were conducted repetitively at various depths (up to and/or within the C-horizons) or on samples collected at these depths.

Moisture retention characteristics were determined using Tempe cells and hanging columns in the lab on undisturbed core samples. These samples were also collected at various depths up to or within the C-horizon. Three dimensional network of tensiometers installed within experimental field plots have also yielded similar and additional information, but their details are reported elsewhere (Rahman & Varughese, 1988). Data collected (by the author) through pressure membranes have not yet been analysed and reported.

RESULTS AND DISCUSSION

Infiltration rates

Infiltration rates for some major soil series in Singapore are presented in Table 1 and for the same soil series but under different vegetation cover in Table 2. Highlights of these results are discussed below.

The infiltration rates decline rapidly after the introduction of water into the ground and a near steady-state is reached rather quickly, sometimes within a few minutes and in every case less than an hour. This does not conform to the generalized models of exponential decrease. For most cases, tests need not be conducted for long periods as only a slight decrease in infiltration rates was noted when the tests were prolonged to several days. According to many classifications (e.g. Landon, 1984), most of these rates would be considered high. Even though the rates are influenced by underlying parent material, greater influence is exerted by the overlying vegetation; rates decreasing an order of magnitude as the vegetation changes from the forested to shrubs, tall grass or crops and then to landscaped gardens. The effects of ground disturbance play a very significant role as lawn mowing reduced the infiltration rates (up to 50% or more) and these rates increased (to several fold) when the grounds were left unattended for several months or years. The subsurface flow pattern interpreted through multiple ring infiltrometers and multiple depth tensiometers indicated that the proportion of lateral flow (as opposed to vertically downward flow) decreased with increasing moisture content. The proportion of lateral flow was also greater in coarse textured soils (as opposed to finer textured soils). These results are easily explained considering the morphological characteristics of these soils (Rahman, 1991).

Table 1 Summary of infiltration rates in major soil series of Singapore.

Underlying geology	Soil type	Infiltration rates* (cm h ⁻¹)	Duration for final rates to establish (minutes)
Granitic rocks	Rengam series (a sandy clay)	45-100	40
Granodioritic and other basic igneous rocks	Jerangau series (a clay)	12-30	30
Coarse-grained sedimentary rocks	Peng Siang series (a sandy clay loam)	25-45	40
Fine-grained sedimentary rocks	Ayer Terjun series (a clay/ clay loam)	2-15	35
Mixed (grained) sedimentary rocks	Lokyang series (a clay loam)	10-23	45
Semi-indurated sedimentaries	Harimau series (a sandy clay loam)	35-75	60
Semi-indurated sedimentaries (ferruginous)	Tampoi series (a sandy clay loam)	6-20	40
Marine sediments	Kranji series (a sandy loam)	0-5	25

*Final rates in the inner 30 cm ring with 90 cm buffer ring, both inserted 10 cm into the ground. Ground for all tests covered by lallang (tall grass).

Table 2 Infiltration rates in Rengam Series (a sandy clay soil) under different types of vegetation/land-cover.

Soil type	Type of vegetation/ground cover	Final rates of infiltration* (cm h ⁻¹)	Duration for final rates to establish (minutes)
Rengam series (a sandy clay)	Primary forest	220-410	20
	Secondary forest 1	96-106	5
	Secondary forest 2	115-175	10
	Botanic garden	180-230	10
	Tall grass	45-100	40
	Golf course (turf)	3-25	5-10
	Public park (turf)	0.3-2	5-10
	University campus (turf)	0.5-3.5	5-10
Harimau series (a sandy clay loam)	Bare ground	0-1	10
	Rubber trees	175-215	65
	Tall grass	35-75	60
	Public park (turf)	2-9	15-35

*Final rates in the inner 30 cm ring with 90 cm buffer ring, both inserted 10 cm into the ground.

Hydraulic conductivity

Methods using double tube permeameter and lab measurements on core samples provided highly varied results offering some generalizations. More consistent results were obtained using the Guelph permeameter. These are shown in Table 3. The trends are similar to those noted for infiltration rates. Higher (by an order of magnitude) flow rates are noted in top soils than the subsoils; the difference decreasing with ground disturbance. Comparing these flow rates with rainfall intensities indicates that with increasing ground disturbance and decreasing vegetation the flow rates approach rainfall intensities, increasing the flood potential in such areas. This has been also observed by Lee (1982), Pitts (1986) and Varughese (1986).

Table 3 Summary of *in situ* hydraulic conductivity values measured by the Guelph permeameter.

Vegetation/ground cover	Depth (m)	Saturated hydraulic conductivity (m s^{-1})	Vegetation/ground cover	Depth (m)	Saturated hydraulic conductivity (m s^{-1})
Rengam series (sandy clay)*			Harimau series (contd)		
Secondary forest	0.05	3.7×10^{-3}	Mown grass (turf)	0.05	1.6×10^{-4}
	0.15	2.6×10^{-4}		0.15	6.8×10^{-5}
	0.50	1.0×10^{-5}		0.50	5.9×10^{-5}
Mown grass (turf)	0.05	1.6×10^{-5}	Tall grass, shrubs	0.05	1.7×10^{-4}
	0.15	2.8×10^{-6}		0.15	8.4×10^{-5}
	0.50	1.0×10^{-7}		0.50	5.1×10^{-5}
Tall grass, shrubs	0.05	1.8×10^{-5}	Bare ground	0.15	9.9×10^{-5}
	0.15	5.0×10^{-6}		0.50	2.2×10^{-5}
	0.50	8.0×10^{-7}		Ayer Terjun series (clay/clay loam)	
Bare ground	0.15	2.0×10^{-7}	Secondary forest	0.05	5.9×10^{-4}
	0.50	1.0×10^{-6}		0.15	1.7×10^{-5}
Harimau series (sandy clay loam)				0.50	6.0×10^{-6}
Secondary forest	0.05	5.4×10^{-3}	Mown grass, (turf)	0.05	3.5×10^{-5}
	0.15	3.0×10^{-4}		0.15	3.0×10^{-6}
	0.50	1.7×10^{-5}		0.50	6.0×10^{-7}

*For details about the soils, see the previous tables and also Rahman (1991).

Moisture retention

Laboratory measurements on core samples yield widely ranging values for moisture retention parameters but some generalizations are still possible. A greater amount of moisture is retained in topsoil (than subsoils), in finer grained soils and under greater

TOPSOILS UNDER MOWN GRASS

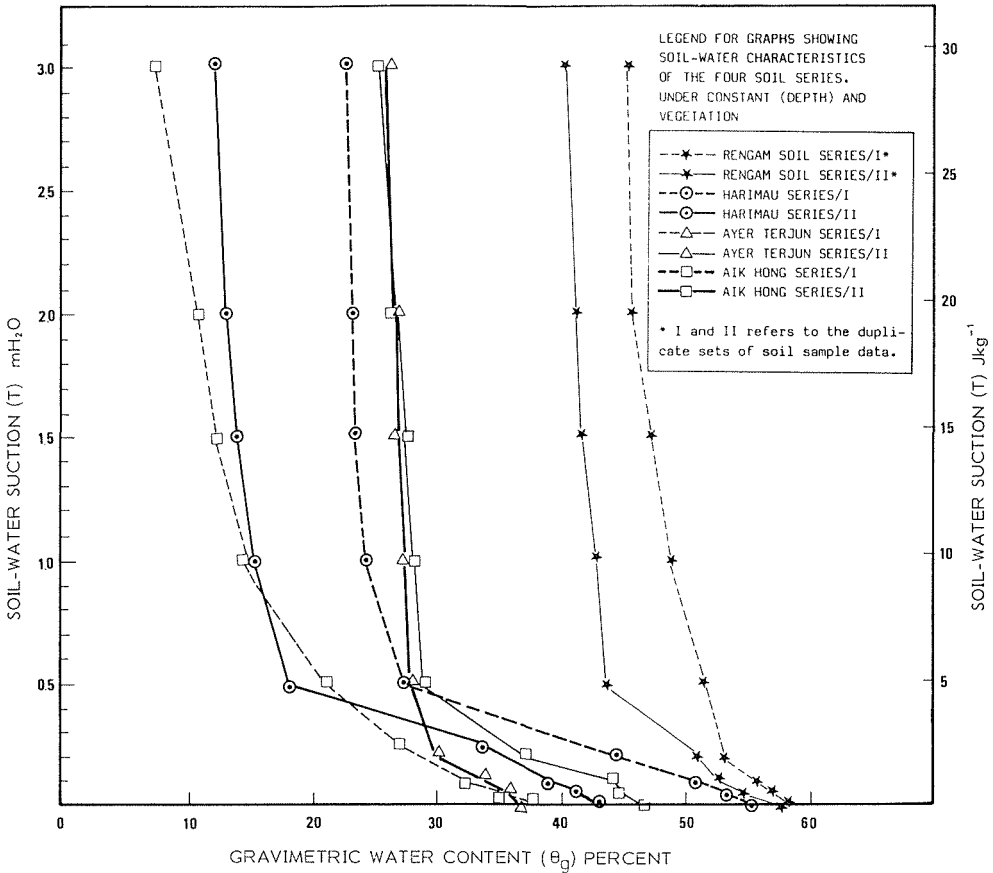


Fig. 1 Moisture release curves determined through hanging-columns experiments on undisturbed cores.

vegetation. Thus porosity values of around 60% were noted in the topsoils under forests over fine grained parent material and around 45% in subsoils over coarse grained parent material. Subsoils show almost inconclusive trend of variations with depth. Moisture release curves indicate that most soils release substantial amount of water within 50 cm of suction, thereafter the moisture release is slower (in rate) and lower (in amount). An example of moisture release curves is shown in Fig. 1. These curves reflect the bimodal pore size distribution of these soils which is due to bimodal particle size distribution as well as aggregation (Rahman, 1991). These data can also be used for determining the water holding capacity of these soils for various purposes. Fine grained soils under forests could hold around 500 mm of water per metre depth of soil, while coarse grained soils under mowed lawns could hold around 300 mm m⁻¹. As the graphs in Fig. 1 indicate, only a small proportion of this water would be involved in rapid active exchange with the surrounding environment. Hill (1972) also had found a maximum of 12% (volumetric) change, over several months, in the maximum and minimum moisture content of topsoil (0-10 cm) and 4% in subsoil (at 60-75 cm depth) in medium textured soil under forest. Thus a moderate storm of 40 mm rainfall could saturate such soils up to a depth of 75 cm on level grounds.

Water movement following infiltration

Rainfall intensities experienced in Singapore are of the same order of magnitude as the infiltration rates in unvegetated areas or turf/grass over disturbed grounds. Most of the time Horton's overland flow (quick-flow) would dominate in these areas. Rainfall intensities do not reach the magnitude of infiltration rates in either the tall grass/shrubs or forests and under these vegetation conditions, contribution to runoff are mainly through saturated overland flow or interflow (and pipe flow). Even in a grassed field plot where the soils were not excessively disturbed, interflow dominated the contribution towards the streamflow (Varughese, 1986). The interflow at the boundary of A and E horizons dominated over the overland flow and interflows from lower layers such as between E and B, etc. In a similar field plot where the ground was excessively disturbed, overland flow dominated over the interflows (Goh, 1988).

Analyses of tensiometer records and moisture content measurements at the field plots indicated that the moisture introduced into the soil following the rainstorms did not move (down and laterally) uniformly throughout the field plot. It seemed to move in greater amounts and with greater speed through some well defined subsurface paths similar to a streamflow pattern one observes at the ground surface. During the installation of the tensiometers, no noticeable differences in soil characteristics or (subsurface) pipes were noted at these higher flow sites.

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