PREDICTING SALT MOBILITY FROM SOIL MOISTURE CONTENTS AT SPECIFIC MATRIC POTENTIALS IN REGOLITH MATERIALS

K.P. Tan[1], M. Glover[2], M. Turner[3], R. Cresswell[4] & K. Lawrie[1]

[1]CRC LEME, Geoscience Australia, PO Box 378, Canberra, ACT, 2601
[2]CSIRO Land and Water, Black Mountain, Canberra, ACT, 2601
[3]CRC LEME, Department of Applied Mathematics, Australian National University, Canberra, ACT, 2600
[4]CRC LEME, CSIRO Land and Water, Indooroopilly, QLD, 4068

INTRODUCTION

Groundwater flows and pore water retention in the regolith are governed by several factors. Of these, permeability governs the potential rates of water movement and is primarily controlled by the effective porosity, i.e., connected macro-pores that can transmit fluids readily. Sands, especially well sorted sand, have high permeability whereas fine textured materials such as sandy mud, mud and clay have low permeability. On the other hand, materials with high clay (phyllosilicate) abundances have high chemical (i.e., micro- and nano-) and total-porosity (Aplin *et al.* 1999), which allows these materials to store more moisture. Besides, clay minerals can also retain more pore fluids at a given matric potential compared to sand. The distribution of regolith materials with varying permeability gives rise to preferential flow paths and the difference in matric potential results in a range of moisture contents in the regolith.

The available moisture content, matric potential and porosity of soils have been widely documented due to its importance in agriculture. For example, the available moisture for plants is the pore volume between saturation (or more commonly at field capacity) and the 'wilting point' at -15 bar matric potential. Most plants are unable to extract the remaining moisture below -15 bar, where the soil-water is being held tightly in the interstitial spaces in the matrix or adsorbed onto the clays.

In contrast, the above parameters have not been systematically documented for sediments, especially those occurring from a few metres to tens of metres depths. The permeability and hydraulic conductivity of thick aquifer units such as the Shepparton Formation and Lachlan Formation have been well characterised. In contrast, multiple semi-confined to confined aquifers, bounded by sandy mud and muddy sand, are common in catchments and sub-catchments flanking the Murray Basin. Characterising the hydro-physical attributes of these regolith materials is necessary to determine the mobility of groundwater and aid in assessing the potential salinity risks.

AIM AND SCOPE

As part of the salinity dynamics project, this sub-project aims to establish the physical attributes of regolith materials in controlling salt store and mobility. This paper discusses the preliminary results obtained from various experiments, including the water contents at matric potentials of 0 and -15 bar, field moistures and permeability measurements conducted on some sedimentary cores. In addition, X-ray computer tomography (X-ray CT) is utilised to establish the porosity and matrix distribution at a micro-scale.

METHODS

The materials used in this study were obtained from the Cainozoic sediments from the Bland sub-catchment (Figure 1). Three diamond cored holes (GDH01, GDH03 and GDH04b) were drilled in 2001 as part of the GILMORE project (Lawrie *et al.* 2003), and core plugs were sampled for moisture contents by Jones in 2001. Permeability measurements done using the column saturation method were conducted on intact cores. Intact clods of samples were sent for grain size distribution analysis using the laser diffraction technique (Malvern Master Sizer instrument) following pre-treatment of standing in hydrogen-peroxide solution overnight. The results were presented in volume percent. Other samples were lightly ground and passed through a 2 mm sieve, and were tested for the water contents at matric potentials of 0 and -15 bar, using the methods and apparatus described by Cresswell (2002). In addition, 4 standard reference materials were selected and also tested for the water contents at matric potentials of 0 and -15 bar to provide reference for comparison. These powder standards are ordered and non-ordered kaolinite (KGa-1 and KGa-2 respectively), sodium and calcium montmorillonite (Swy-2 and SAz-1 respectively). Known amounts of these standards were mixed with various proportions of quartz sand to simulate the various texture range found in most regolith. These mixtures include 20, 40, 60, 80 and 100 volume % clay. Moderately sorted medium to coarse sand obtained from the Murray River bed was also use as the null standard (i.e., 0 % clay).

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STRATIGRAPHIC UNITS

The main sedimentary fill of the Bland Creek palaeo-valley in the study area can be divided into five depositional units (Units A – E), based on grain size (according to Uden-Wentworth's scale) and location within the stratigraphic column. Fine grained sediments predominate in the thousands of sediment samples studied within the project (Gibson *et al.* 2002). Examples of the sedimentary units and various attributes (pore fluid salinity, moisture content and textures) are shown in Figure 2.

Unit A was deposited as low angle fan, channel and debris flow deposits, and appears brown (Munsell colour 10YR5/3) with conspicuous ferruginous mottles in a grey matrix. This unit consists of silt-rich mud and mud-rich sand (50-80 % mud) within a locally sandier aquifer. This unit directly overlies Units B and C, but may encompass the entire sedimentary sequence in some areas. Pore fluid salinity is relatively low for the top 10 m but commonly increases to 10,000 mg/l TDS at depth.

Unit B is interpreted as a lake or swamp deposit, and is dominantly grey (2.5Y6/2) with less conspicuous Fe-oxide segregation. This unit is generally muddy (95-100 % mud) and has been sub-divided into 2 parts, upper and lower, based on clay and silt components. The lower part is dominated by coarse silt (16-62 μm), similar to Unit A, whereas the upper part is dominantly clay (< 4 μm).

Unit C was deposited as low angle fan, channel or sheet flow sediment, and is mostly gravel-bearing sand with minor mud. Quartz content in the sand-rich layers may reach above 90 %. This unit underlies A or B, but locally extends to the surface, and is one the main aquifers.

Unit D was deposited as debris and sheet flows, or as low angle fan sediment. This unit is brown, with massive ferruginous stains, which grade vertically down into conspicuous mottles. This unit has interlayer of mud, mud-rich sand and gravel-bearing sand, and kaolinite is the dominant clay mineral.

Unit E represents winnowed fluvial sediment and consists dominantly of sand and gravel-bearing sand, the gravel being rounded to sub-angular quartz. This unit is light grey and leached (10YR7/2), and is generally present only in lowest parts of the palaeo-landscape, and is underlain by the saprolite. This unit is one of the main aquifers and occurs in part of the study area.

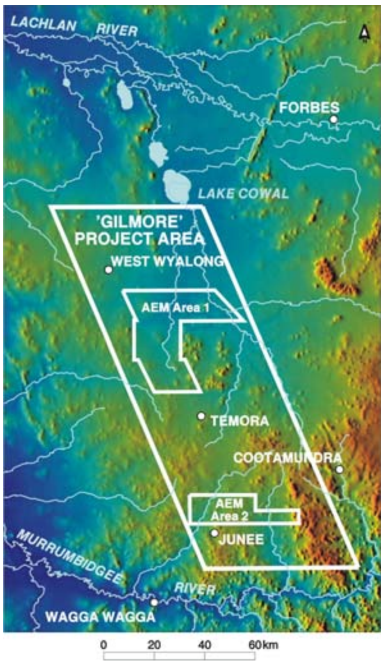

Figure 1: The study area (AEM area 1) is part of a catchment of the Lachlan River, NSW.

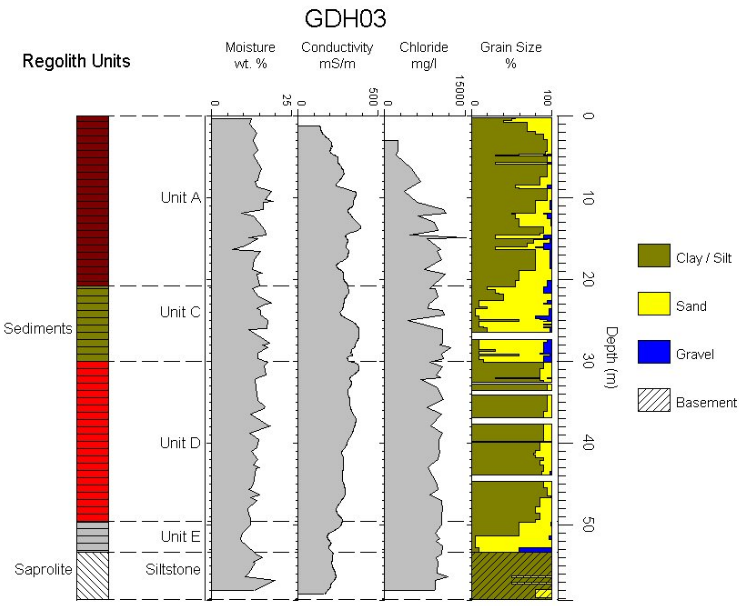

Figure 2: Visual display of drill log information of core hole GDH03 showing the stratigraphic units, geophysical logs and regolith attributes.

MATRIC POTENTIALS AT ZERO AND -15 BAR

For both kaolinite and montmorillonite, the moisture contents at both saturation (0 bar) and at -15 bar increases with increasing clay abundance. Amongst these, Na-montmorillonite can hold up to 6 times its dry weight at saturation and 3 times its dry weight at -15 bar (Figure 3a). In comparison, Ca-montmorillonite can contain moisture up to nearly twice its dry weight and 60 % of its dry weight at -15 bar. The volumes of both these smectite phases increase up to 2 and 3 times their dry volume following the uptake of water (based on visual assessment). Saturated kaolinite on the other hand does not hold as much moisture. Non-ordered kaolinite holds up to 95 % of its dry weight, whereas crystalline kaolinite contains 80 % (Figure 3b). At -15 bar, the former retains 35 wt. % whereas the latter retains 22 wt. % moisture. No apparent increase in volume accompanying the wetting was observed.

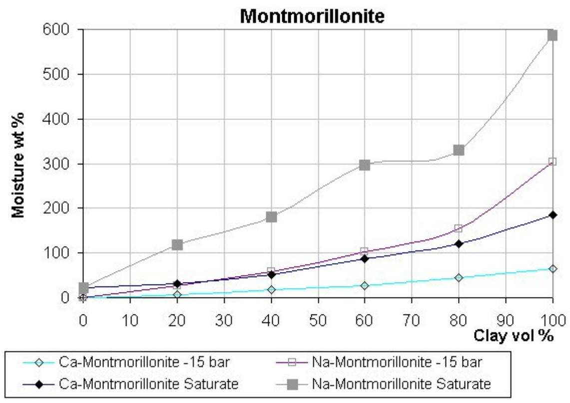

Figure 3a: Water contents of montmorillonite and quartz sand mixtures at saturation and at -15 bar matric potentials.

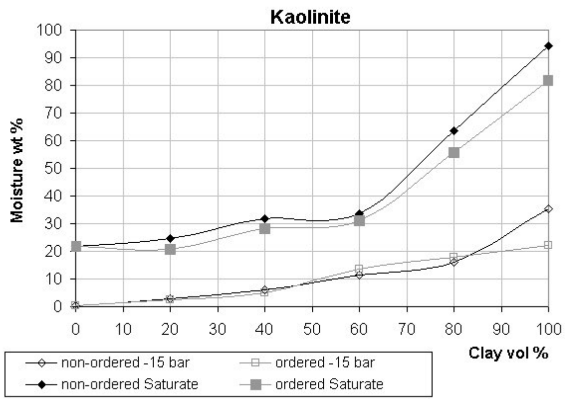

Figure 3b: Water contents of ground kaolinite and quartz sand mixtures at saturation and at -15 bar matric potentials.

At saturation, the water contents of the ground sediment from all three cores range from 30 to 90 wt. % of the dry masses (Figure 4). Grinding and saturating the materials under unconfined conditions will result in higher moisture contents compared to *in situ* materials. This has been observed from soil profiles (Glover *pers. comm*.). Overall, the saturation capacity increases with increasing clay abundance. The spread of data indicates two populations are present (i.e., P1 and P2, Figure 4). The first population with higher water holding capacity at given clay contents reflects the presence of smectite in the clay fraction. The second population with lower water contents reflects the presence of kaolinite dominating the clay fraction. Spectral analysis using short wavelength infra red (PIMA instrument) affirms the presence of the clay types (Lawrie *et al.* 2003).

At -15 bar matric potential, the sediments exhibit water contents ranging from 5 to 35 wt. %, with increasing water retention as the fine texture increases. The data has a lesser spread (Figure 4) and appears to be of a single population. The field moistures of the sediments range from 8 to 20 wt. %, with few samples holding more than 20 wt. % (up to 34 wt. %) moisture. In comparison, more than half of the population has field moisture contents similar to or lower than the water contents held at -15 bar. This suggests that the *in situ* sediments are dryer than that which can be extracted by plants. The higher moisture contents of the other population are still considerably lower compared to the saturated ground materials.

CAINOZOIC SEDIMENTS OF THE BLAND SUB-CATCHMENT

The field moisture and water contents at matric potentials of 0 and -15 bar are plotted against depths for the three boreholes GDH01, 03 and 04b (Figures 5a-c respectively). A point to note is the similarity between the field moisture and at -15 bar for Units A and D (GDH01 and 03), and some samples in Unit C (GDH04b).

Permeability results from saturated column experiment indicates that the permeability of the sediments are in the order of 10^{-8} to 10^{-11} m/s. Core plugs analysed using X-ray computer tomography shows that most of the mud-rich sediments do not have noticeable macro-pores (> 9 µm). Up to 1 volume % has been observed but are isolated and not connected to other macro-pores (Figure 6a). On the other hand, sandier sediment contains higher abundance of macro-pores (Figure 6b).

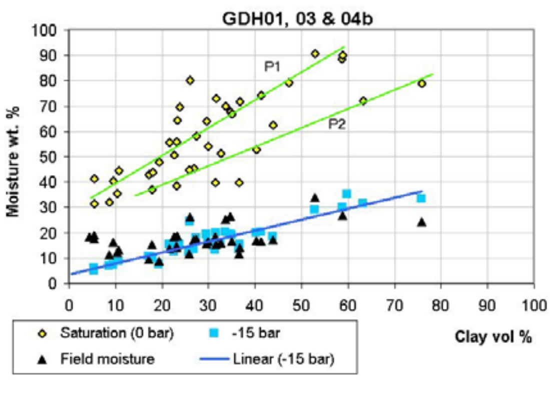

Figure 4: Graph showing the field moistures and water contents of ground sediments at saturation and at -15 bar matric potentials.

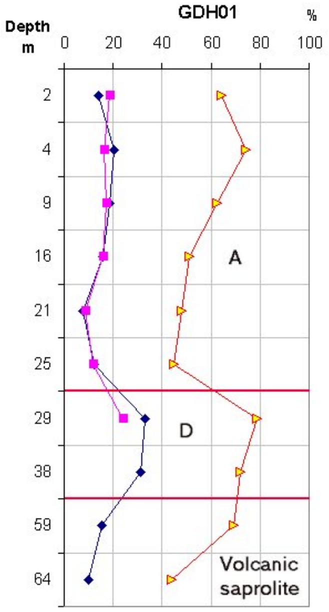

Figure 5a: Water contents at various matric potentials of borehole GDH01.

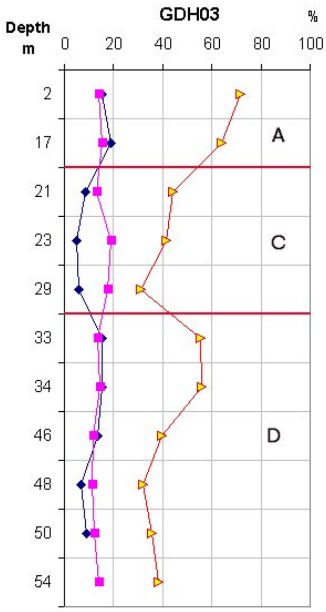

Figure 5b: Water contents at various matric potentials of borehole GDH03.

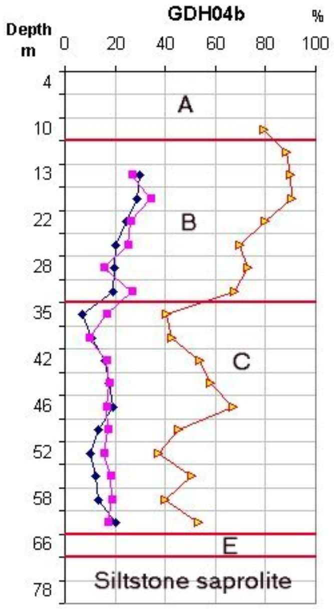

Figure 5c: Water contents at various matric potentials of borehole GDH04b.

Legend

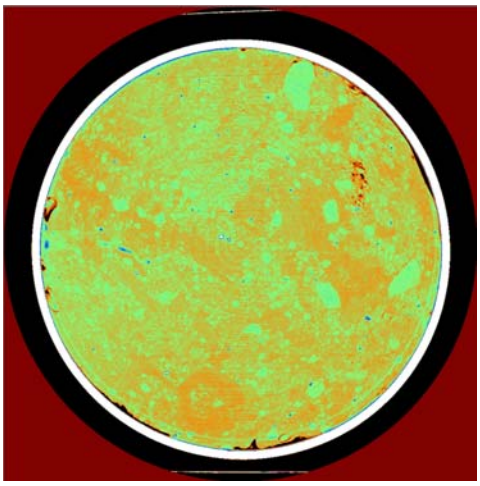

Figure 6a: X-ray tomogram of mud-rich sediment (GDH03, 49.3m, Unit D) showing isolated macro-pores to be < 1 % (black). Diameter of the plug is 17 mm.

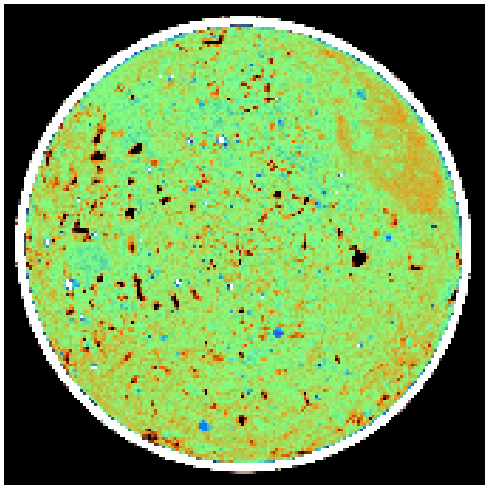

Figure 6b: X-ray tomogram of sandy sediment (GDH03, 20.9m, Unit C) showing approximately 8 % connected macro-pores present (black). Diameter of the plug is 17 mm.

DISCUSSION

The differences in moisture holding capacity of various clay minerals and phyllosilicates phases, i.e., ordered and non-ordered kaolinite, sodium and calcium montmorillonite, have significant implications to the amount of water stored in the regolith. In an unconfined environment where the materials are allowed to expand following the uptake of water (e.g., soils) a minor increase in smectite abundance, especially Na-montmorillonite, will increase the water holding capacity and retention.

In confined environments (e.g., buried sediment) the loading of the overburden does not allow the sediment to expand and absorb as much moisture as compared to the surface materials. The presence of smectite would have some influence, but may not increase the water content considerably. In the saturated environment, the water contents only range from 10 to 34 wt. %, which is much lower than the 30 – 90 wt. % contained in the laboratory segregated materials. For the mud-rich sediments (Units A, B, D and upper part of C in GDH04b), the similarity in water contents between the field moisture and at -15 bar suggests that the fluids are predominantly held in the mud matrix. X-ray tomograms show that less than 1 % isolated macro-pores (i.e., > 9 µm resolution) are present for the mud-rich sediments, and further indicates that the pore fluids are being held by the micro- and nano-pores amongst the mud matrix. Overall, the lack of connected macro-pores results in low permeability (in the order of 10^{-8} to 10^{-11} m/s).

The sand-rich materials (Unit C in GDH03 and lower part of Unit C of GDH04b) contain more moisture than those at -15 bar, suggesting that some moisture may be held in the macro-pores. The X-ray tomogram shows the presence of approximately 8 % connected macro-pores, indicating a higher permeability for this sandy unit.

Based on stable isotope results, the distribution of salt appears to be dependent on the physical properties of the regolith and proximity to recharge areas (Lenahan *et al.* 2004). Lower ^{36}Cl/Cl ratio suggests that older, more saline water is residing in lower permeability regolith materials (mud and clay). Within the aquifer, water residing in pore spaces (muddy sand and sandy mud) is saltier than the groundwater. This suggests that groundwater is moving along preferential flow paths, resulting in a heterogeneous distribution of salts within the saturated aquifer unit. Similar ion ratios, despite variation in salinity, indicate mixing between these saline pore fluids and groundwater (Lenahan *et al.* 2004).

From the spatial distribution of the lithologic units (Lawrie *et al.* 2003), the Bland sub-catchment consists of multiple semi-confined to confined aquifers. Except Units C and E, the remaining sedimentary units have low permeability and the saline pore fluids are tightly held within the mud matrix, especially for smectite-bearing sediment. Diffusion would be the main process for the fluids to migrate from these units into the aquifers. Mixing of the saline pore waters and the groundwater may take place in a geological time frame (thousands of years). As such, the salinity risk posed by these saline mud-rich units is considered low due to the low permeability and high matric potentials.

CONCLUSION

The water holding and retention capacity amongst the clay types vary considerably. Except for some sandy aquifer units where connected macro-pores are present, the majority of the mud-rich units lack macro-pores, resulting in low permeability. The presence of low water contents, which are similar to those at -15 bar matric potential, suggests that the moisture in these sediments is held tightly within the mud matrix, especially those containing smectite. These low permeability units are the source of solute to the groundwater contained in sandy aquifer units, and mixing between these fluids is likely to take place by diffusion. The overall rate of mixing should be slow, and the risk from the stored salts in most sediment is thought to be low.

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