Reuse of laundry greywater as affected by its interaction with saturated soil

Rabindra K. Misra*, Amphone Sivongxay

Faculty of Engineering and Surveying
Australian Centre for Sustainable Catchments and CRC for Irrigation Futures
University of Southern Queensland
Toowoomba, Queensland 4350, Australia

SUMMARY

We conducted laboratory experiments on a well aggregated, non-swelling clay soil to measure water retention, saturated hydraulic conductivity (K_s) and salts present in the irrigation and drainage water to study the impacts of reusing untreated laundry greywater (GW) to irrigate soils in the residential garden beds. We used undisturbed (field) and disturbed (loose and compacted) soil cores to represent situations typical in old and recently established garden beds. Using tap water (TW), soil water retention within 0-10 kPa matric suction was found to be significantly lower and hysteresis significantly higher for the loose soil than the field or compacted soil. Measured values of K_s with TW were in the order loose >field >compacted soil, but these values were reduced to 5-16% when GW was used. Further measurements of K_s with application of TW to soil cores which had been previously saturated with GW, greater reduction in K_s occurred with $K_s \rightarrow 0$ for the compacted soil. A comparison of the quality of GW with TW as irrigation water indicated an approx. increase in pH of GW by 3 pH units over TW, two-fold increase in EC, 5-fold increase in Na concentration and a 10-fold increase in Sodium Adsorption Ratio (SAR). Measurements of drainage water during the water flux measurements for K_s showed that the soil was able to reduce pH and EC of infiltrating water, store some salts (Na and K) and released Ca and Mg from soil so that the quality of drainage water improved substantially to become similar in quality to TW. Thus, long-term use of untreated laundry greywater may reduce salt contamination of groundwater, but predispose soils to future environmental hazards from excess sodium accumulation.

Keywords: greywater, hydraulic conductivity, irrigation, laundry greywater, SAR, water retention

Introduction

Soil is generally considered as an ideal medium for solid and liquid waste disposal (Brady and Weil, 1999) due to its ability to degrade, filtrate and retain contaminants present in the waste material. Irrigation of agricultural and urban areas with poor quality water (e.g. treated or untreated wastewater) may affect a range of physical and chemical properties of the soil. When the pollutant

* Corresponding author. Tel: +61 7 46312805; fax: +61 7 46312526.
Email addresses: misrar@usq.edu.au (R.K. Misra), d1230489@mail.connect.usq.edu.au (A. Sivongxay).

load in the irrigation water exceeds the soil's capacity to retain pollutants, the scope for groundwater contamination from irrigation with wastewater is increased. Most of our experience with the use of poor quality irrigation water is derived from studies focussing on the use of saline water for irrigation of crop fields (e.g. Rhoades et al., 1992; Ayars et al., 1993) and use of urban and industrial wastewater in forestry and amenity areas (Miyamoto and Chacon, 2006; Thwaites et al., 2006). Irrigating soils with wastewater containing excess salts with sodium as the dominant ion may adversely affect infiltration, hydraulic conductivity and aggregate stability (Abu-Sharar and Salameh, 1995; Suarez et al., 2006; Eltaif and Gharaibeh, 2007).

Greywater is a non-toilet component of household wastewater that originates from the laundry and bathroom. Although greywater is considered as a potentially reusable water resource for irrigation of household lawns and gardens (Al-Jayyousi, 2003), studies on its interaction with soil is limited. Greywater reuse has been implemented around the world in many countries, but in Australia it is a relatively recent idea as regulations and guidelines have been only developed recently (DHWA, 2002; DLGPSR, 2007). Laundry activities in a typical household in Australia generate 94-139 L d^{-1} of greywater (Radcliffe, 2004) which is around one-fifth of the total indoor water used in a typical residential house in Queensland (ABS, 2000). Australian public have increasingly acknowledged the benefits of greywater reuse, particularly laundry and bathroom water for garden/lawn watering. Manual bucketing and diverter valve are the two commonly used methods of untreated greywater application (DLGPSR, 2007) as treatment, storage and subsurface application of greywater into soil can be expensive (Nolde, 1999; Jeppesen, 1996).

Laundry greywater contains varying levels of suspended solids, salts, nutrients, organic matter and pathogens (Christova-Boal et al., 1996; Howard et al., 2005) which arise from clothes and residue of laundry detergents and fabric softeners. Public health risks associated with the reuse of greywater are well known (e.g. Nolde, 1999) and strategies of disinfection have continued to improve (Winward et al., 2008). Irrigation by bucketing or subsurface irrigation has been suggested as a reuse strategy that can reduce health risks by minimising exposure (Jeppesen, 1996). However, there appears to be little information on the environmental risks associated with infiltration of greywater into soil during irrigation and the fate of pollutants in greywater and the combined impact of these pollutants on soils, plants and receiving waters (Eriksson et al., 2003).

Laundry detergents contain surfactants, builders, bleaching agents and auxiliary agents or additives (Smulders, 2002). Although surfactants are used as a less toxic substitute for soap in laundry detergents (Smulders, 2002), they are found in numerous household cleaning and personal care products and therefore a dominant source of xenobiotic organic compounds (XOCs) found in greywater (Eriksson et al., 2003) and municipal wastewater (Brunner et al., 1988). XOCs constitute a long list of complex organic compounds which can be broadly classified into emulsifiers, fragrances and flavours, preservatives and antioxidants, softeners and plasticisers, solvents, surfactants and other miscellaneous compounds (Eriksson et al., 2003). According to Van Lyssel and Crull (1998), powder laundry detergents contain 31% builders, 18% surfactants, 36% dry fillers, 9% silicates and other compounds, whereas liquid detergents contain 26% surfactants, 20% builders, 35% water and 8% solublizers. A large proportion of laundry detergents are salts and are non-volatile compounds. Hence, a portion of these salts (which is not retained on clothes and on various parts of the washing machine) is expected to be present in the laundry effluent.

Recent studies on greywater indicate significant accumulation of surfactants when soils are irrigated with greywater for a year (Shafran et al., 2005) and it is suggested that accumulation of surfactants from greywater may ultimately lead to water repellent soils with significant impact on agricultural productivity and environmental sustainability. Significant changes in hydraulic conductivity of soils have been also reported in simulated greywater studies of Abu-Zreig et al. (2003) using solutions of anionic and non-ionic surfactants in tap water.

These studies demonstrate that our understanding of the interaction of greywater with soil is limited and hence, warrants further studies to illustrate the environmental impact that may arise from the widespread use of greywater for irrigation. In this paper, we examine the effects of greywater on saturated hydraulic conductivity by simulating soil conditions and irrigation scenarios in typical residential gardens. The quality of drainage water (leachate) is also examined to determine the extent to which the soil is able to retain salts, especially cations.

Materials and Methods

For this study, we collected undisturbed and disturbed soil samples from the top 100 mm of the Agricultural Field Station complex (27°36′36″S, 151°55′48″E, 693 m elevation) of the University of Southern Queensland, Toowoomba, Australia. The soil at the experimental site is a moderately deep, well structured Red Ferrosol (Isbell, 1996) that represents most areas of Toowoomba plateau (Biggs et al., 2001). Some of the important properties of this soil are given in Table 1.

Table 1
Properties of the soil used for experiments.

Properties	Mean value ± SE[a]
Sand % (2.0–0.02 mm)[b]	38.5 ± 3.8
Silt % (0.02–0.002 mm)[b]	20.7 ± 3.8
Clay % (<0.002 mm)[b]	40.8 ± 0.6
Plastic limit (%)	26.6 ± 0.3
Field bulk density of soil (Mg m^{-3})	1.19 ± 0.04
Field moisture content of soil (m^3 m^{-3})	0.315 ± 0.011
pH (soil-water ratio 1:5)	6.35 ± 0.01
EC (electrical conductivity, μS cm^{-1})[c]	30.7 ± 0.3
Organic carbon (g kg^{-1})	35 ± 1
Cation Exchange Capacity ($mmol_c$ kg^{-1})[d]	163
Exchangeable Sodium Percentage (ESP)	0.9

[a]SE represents standard errors of mean values of replicated soil samples of *n* = 3, except for the plastic limit (*n* = 5), and soil moisture and bulk density (*n* = 10).
[b]By weight.
[c]Note: 1 μS cm^{-1} = 0.001 dS m^{-1}, EC reported at 25 °C.
[d]Estimated as sum of exchangeable cations Na, K, Ca and Mg.

Soil treatments
Undisturbed, cylindrical soil cores of 30 and 60 mm height and 53 mm diameter was sampled in either brass or stainless steel rings using a soil core sampler (Model 0200, Soil Moisture Equipment Corp., USA). Additional rings of similar dimensions were used for the preparation of disturbed soil cores. Soil samples retained in brass rings were used for moisture or bulk density measurements and those in stainless steel rings were used for hydraulic conductivity and leaching experiments with laundry greywater to avoid corrosion. Soil cores of 30 mm height were used only for the measurement of soil water retention.

All measurements were made on soil cores of three treatments, referred to as field, loose and compacted cores. Field soil cores here refer to the undisturbed soil cores collected within 0-100 mm depth from the field to represent the soil condition in the lawn of a typical residential house that is subject to traffic from mowing and occasional disturbance of the surface soil. Loose and compacted soil cores were prepared in the laboratory with light compaction (bulk density lower than the field core) and moderate compaction (bulk density similar to field cores) to represent the soil of two types of garden beds. Loose soil cores were used to simulate soil conditions in a recently prepared garden bed with little settlement and compacted soil cores to simulate an older garden bed with some settlement that had not been disturbed for some time.

In order to determine the bulk density required for disturbed soil cores, bulk density (ρ) and water content (θ) were measured initially on soil cores collected from 5 positions within an area of 4×4 m^2 at the experimental site. Ten soil cores (30 mm high) obtained from two depths: 20-50 mm and 50-80 mm. A paired t-test of these samples indicated no significant variation in bulk density or moisture content between the two sampling depths. Thus, soil cores from either depth were used as required throughout this experiment. Data for bulk density and moisture content for undisturbed soil cores are given in Table 1.

Sufficient soil (in excess of 20 kg) was collected from the top 100 mm depth and from the same area that was used for bulk density measurements. Soil was transported to the laboratory and dried in a convection oven at a temperature <40 ºC for 72 hours to achieve air-dry status and finally sieved to <2 mm in size. Sufficient quantity of air-dry soil was mixed with tap water up to a water content of 1.2 times the plastic limit and placed in an air-tight plastic container for over-night equilibration. Soil was then mixed for uniform distribution of moisture and moist soil of the required weight (depending on the bulk density) was placed in a stainless steel ring and compressed by hand using the method similar to that described by Misra and Li (1996). Loose and compacted soil cores had bulk densities of 1.05 and 1.20 Mg m^{-3}, respectively.

Soil water retention

All soil cores for the field, loose and compacted treatments were supported by cheesecloth and a coarse filter paper at the bottom of the ring to prevent loss of soil. A 10 mm high collar of the same diameter as the sample ring was attached to the top of each soil core to prevent loss of soil from the top during wetting and to aid measurement of vertical expansion / contraction of soil core at three fixed points marked on the collar. For soil water retention study, 3 replicate cores of each of the 3 treatments (field, loose and compacted) were used. All soil cores were saturated overnight by allowing tap water to rise from the bottom of the core and then placed over a porous ceramic plate of 30 cm diameter (Paton Scientific Pty Ltd, Victor Harbour, South Australia) for 24 h to equilibrate to a water potential of 0 kPa. The weight of each core was taken with an electronic balance (±0.01 g) after draining it for a period of 24 h at each of -1, -3, -5, -7, -10 and -33 kPa water potential to determine water content during desorption. At any change in water potential, a few drops of water were sprinkled over the plate to improve contact between the plate and soil core. At each change of water potential, the level of soil from the top edge of the collar was measured at 3 points to determine any swelling or shrinkage of sample. After all the cores reached -10 kPa, their weights were taken and then they were wetted for a period of 24 h to equilibrate to each of -10, -7, -5, -3 and -1 kPa water potential to determine soil water content during sorption. The final water content of each core was taken after removal of the sample from the core and drying it in an oven at 105 ºC for 48 h.

Saturated hydraulic conductivity and leaching

Saturated hydraulic conductivity of field, loose and compacted soil cores were measured using tap water (TW) and laundry greywater (GW). Soil cores of 60 mm height were used for these measurements. There were four sets of soil cores (two sets for each of TW and GW) of each treatment (field, loose and compacted) used to measure saturated hydraulic conductivity and the characteristic of the outflow water for three scenarios. First scenario included application of TW (representing common irrigation practice) or GW (alternative irrigation practice) to the unsaturated soil cores. In the second scenario, GW was applied as an automated irrigation event over the saturated soil cores to represent a situation when the soil had become saturated due to a prior irrigation event with potable water or rainfall. The third scenario included application of TW to soil that has been saturated with GW from a previous irrigation. Two replicate soil cores were used to represent each scenario and treatment.

During measurement of hydraulic conductivity, each soil core was supported by a clamp stand over a plastic funnel to direct drainage into a 100 cm^3 measuring cylinder. A constant head device was used over each soil core to maintain a pressure head of 10±1.5 mm at the soil surface. A number of 100 cm^3 measuring cylinders were used to separate the collected drainage water (leachate) for estimation of pore volume and subsequent measurements of pH and EC of drainage water. Typically discharge was measured at 5 minute intervals for up to 2 h. Darcy's law for vertical, saturated flow of water at steady state was used to estimate saturated hydraulic conductivity of soil.

The pH and EC of the collected leachate were measured using a pH meter (TPS model MC80, Brisbane, Queensland) and EC meter (TPS model MC84, Brisbane, Queensland) fitted with calibrated electrodes following the manufacturer instructions. Three samples of tap water (TW), one sample of laundry greywater (GW) and two samples of drainage water for each of the soil treatments was analysed in the laboratory to determine the concentration of Na, K, Ca and Mg. All water samples except the sample of laundry greywater was analysed using the method of Rayment and Higginson (1992). The laundry greywater sample was analysed using the standard method for the analysis of wastewater (APHA, 1998). The precision associated with the measurements of ion concentration in various water samples varied from 0.007-0.08 mg L^{-1}.

Laundry greywater

For all our measurements, we collected laundry greywater from a single wash using a Simpson Esprit600 top loading clothes washing machine that was fitted with a T-shaped flow splitter (Howard et al., 2005). The sample of greywater was approx. 6.7% of the total greywater generated by the washing machine (from the wash and rinse cycles, combined together). Dynamo brand liquid detergent (Colgate-Palmolive Pty Ltd, Sydney) was added according to detergent manufacturer's recommendation for washing a full load of clothes without any fabric softener. For health reasons, untreated laundry greywater could not be stored (Jeppesen, 1996). Therefore, all greywater was used up for the experiment with reduced number of replicated measurements within 4 hours of collection.

Results

Soil water retention

Soil water retention and bulk density data for various simulated garden beds are summarised in Table 2. Compacted garden beds had similar bulk density to that found in older garden beds (field), but retained significantly more water at -10 and -33 kPa than the latter, possibly due to a difference in pore size distribution because there was no significant difference in water content at saturation for these two treatments. Loosening of soil during establishment of garden beds tend to increase porosity, with significantly lower water retention than the field and compacted soils at -10 and -33 kPa (Table 2). Both porosity and pore size distribution has implications to entry and redistribution of water from rainfall and irrigation with potable water and laundry greywater.

Table 2

Bulk density and soil water retention for various treatments.

Parameters	Mean value ± SE (n = 3)		
	Field	Loose	Compacted
Bulk density (Mg m^{-3})	1.21 ± 0.037	1.05 ± 0.001	1.20 ± 0.001
Volumetric water content at saturation (m^3 m^{-3})	0.540 ± 0.013	0.600 ± 0.006	0.545 ± 0.004
Volumetric water content at -10 kPa (m^3 m^{-3})	0.378 ± 0.014	0.365 ± 0.013	0.454 ± 0.013
Volumetric water content at -33 kPa (m^3 m^{-3})	0.361 ± 0.015	0.348 ± 0.010	0.424 ± 0.014

Detailed analysis of soil water retention during drainage (desorption) and wetting (sorption) in the 0-10 kPa range indicated that the difference in soil water retention between wetting and drying was significantly high for loose cores that became negligible for field cores (Fig. 1). This difference in soil water retention is referred to as hysteresis that occurs because pores of different sizes fill and drain in different order during wetting and drying (Hillel, 2004). Interconnected pores of different sizes also tend to have different water contents at the same water potential due to "ink bottle effect" and air may become entrapped in large pores during wetting compared with drying. Increased porosity evident with loosening of soil (from the data on volumetric water content at saturation in Table 2) is important not only for irrigation and redistribution of water in soil, but also water losses during evaporation and drainage.

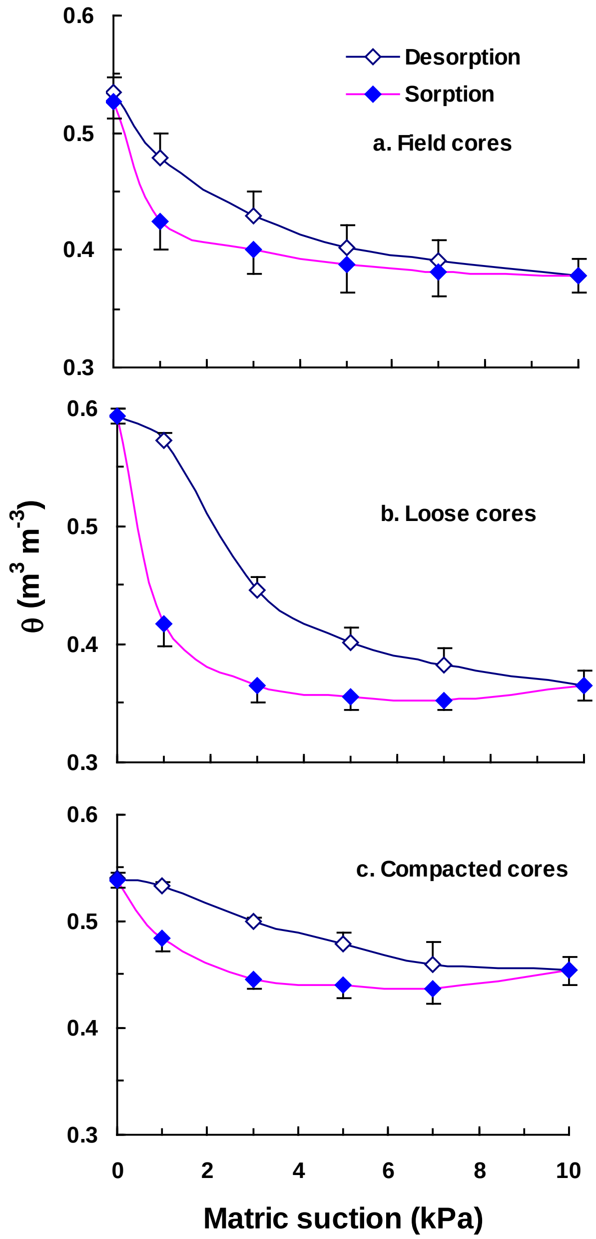

Fig. 1. Variation in volumetric water content of soil (θ) as a function of matric suction in soil during desorption (drainage) and sorption (wetting) for (a) field, (b) loose and (c) compacted soil cores. Vertical lines over mean values indicate SE (n = 3), shown in one direction for clarity.

Hydraulic conductivity of soil

A comparison of saturated hydraulic conductivity (K_s) for various soil treatments with tap water (TW) and laundry greywater (GW) is shown in Fig. 2. When the unsaturated soil cores were wetted with tap water, K_s was highest for the loose soil and it decreased with increased bulk density following a trend of loose>field>compacted. Wetting unsaturated soil cores with laundry greywater did not change this trend in K_s, but the magnitude of K_s was substantially reduced to only 5-16% of that measured with tap water. Maximum reduction in K_s with greywater was evident for the loose soil that had the highest hydraulic conductivity with tap water.

Saturated hydraulic conductivity data for sequential leaching of soil with tap water and laundry greywater are shown in Fig. 3. For all soil treatments, whether the soil was initially dry or saturated with tap water did not appear to affect values of K_s significantly (Figs. 2 and 3). However, significant reduction in K_s occurred for all soil treatments when tap water was used following irrigation with the greywater. Among all the soil treatments, water transport through the compacted soil was most severely affected when K_s approached smaller values. These results indicate significant interruption to the flow path of water in soil possibly due to a change in the size and/or continuity of water conducting pores when the soil is sequentially wetted with tap water following greywater.

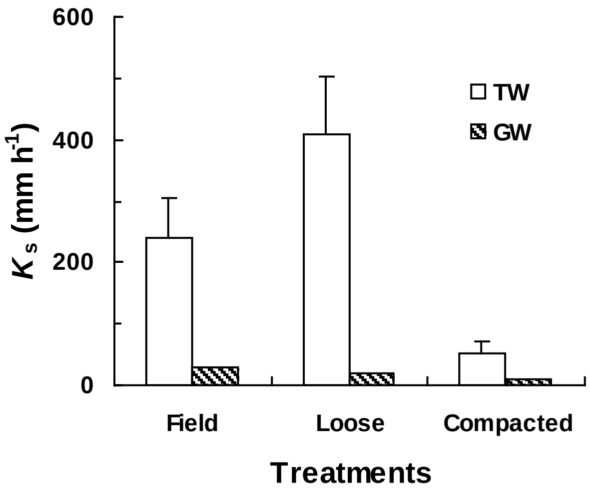

Fig. 2. Variation in saturated hydraulic conductivity (K_s) of initially unsaturated soil for various treatments using tap water (TW) or laundry greywater (GW). Vertical lines over mean values for TW indicate SE (n = 3).

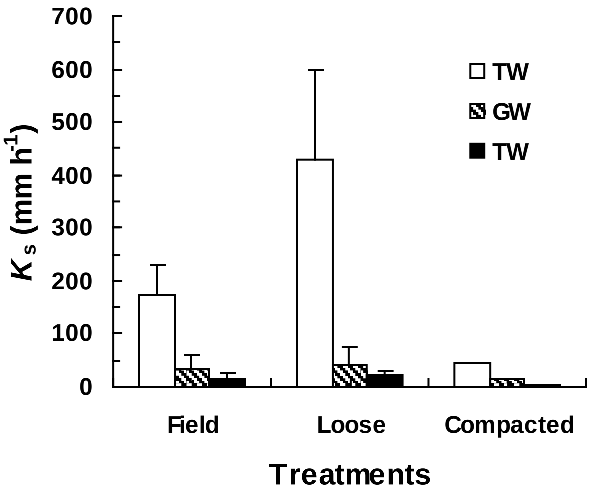

Fig. 3. Variation in saturated hydraulic conductivity (K_s) with sequential wetting of soil with tap water (TW), laundry greywater (GW) followed by tap water for various treatments. Vertical lines over mean values indicate SE (n = 2).

Chemical properties of irrigation and drainage water

Changes in pH and EC of the drainage water during the hydraulic conductivity measurements were analysed to elucidate possible chemical changes in soil that may contribute to soil's physical behaviour when it interacts with different types of irrigation water. Analysis of the quality of tap water (TW) and laundry greywater (GW) used for irrigation in our experiment shows that GW had a significantly higher pH and was alkaline (Table 3). It also contained twice as much salt as TW, with Na as the dominant ion that contributed to a significantly higher SAR value than TW.

Table 3

Chemical properties of the irrigation and drainage water with sequential application of tap water (TW) and laundry greywater (GW) to field, loose and compacted soil cores.

Parameters	Mean value ± SE[a] for irrigation and drainage water			
	TW	Field	Loose	Compacted
pH	6.69 ± 0.01	6.25 ± 0.01	5.84 ± 0.14	6.04 ± 0.05
EC (µS cm^{-1})	388 ± 5	324 ± 11	312 ± 1	294 ± 4
Na concentration ($mmol_c$ L^{-1})	1.48 ± 0.00	1.24 ± 0.02	1.28 ± 0.02	0.94 ± 0.02
Ca concentration ($mmol_c$ L^{-1})	1.05 ± 0.00	0.95 ± 0.05	0.85 ± 0.05	0.90 ± 0.00
Mg concentration ($mmol_c$ L^{-1})	1.32 ± 0.00	0.95 ± 0.04	0.82 ± 0.08	0.86 ± 0.05
K concentration ($mmol_c$ L^{-1})	0.12 ± 0.00	0.074 ± 0.031	0.069 ± 0.003	0.072 ± 0.003
SAR	1.36 ± 0.00	1.27 ± 0.01	1.41 ± 0.03	1.00 ± 0.01
	GW	Field	Loose	Compacted
pH	9.21 ± 0.00	6.51 ± 0.25	6.23 ± 0.24	6.38 ± 0.29
EC (µS cm^{-1})	752 ± 2	436 ± 22	416 ± 2	384 ± 24
Na concentration ($mmol_c$ L^{-1})	5.74	2.37 ± 0.46	1.74 ± 0.04	1.39 ± 0.04
Ca concentration ($mmol_c$ L^{-1})	0.11	1.02 ± 0.18	1.17 ± 0.02	1.07 ± 0.08
Mg concentration ($mmol_c$ L^{-1})	0.33	1.03 ± 0.12	1.19 ± 0.04	1.03 ± 0.04
K concentration ($mmol_c$ L^{-1})	0.15	0.070 ± 0.037	0.091 ± 0.007	0.082 ± 0.003
SAR	12.32	2.39 ± 0.63	1.60 ± 0.02	1.36 ± 0.01

[a]SE is based on n = 3 for TW used as irrigation water, n = 2 for all drainage water collected from field, loose and compacted soil cores. Single sample of GW was used to measure concentration of Na, Ca, Mg and K.

For all soil treatments, the concentration of cations (Na, Ca, Mg and K) declined slightly in the drainage water (leachate) compared with irrigation water (Table 3) when soil was irrigated with tap water indicating the possibility of some cation storage in soil. The pH, EC and SAR of the drainage water was also lower than the irrigation water, which supports the hypothesis that soil acted as a filtering medium in retaining salts and purified the drainage water. Compacted soil appeared to be the most efficient in retaining salts within the soil. Using GW as irrigation water reduced the pH of drainage water considerably (by nearly 3 pH units compared to the pH of GW). There was also a 40% reduction in the EC of GW. The concentrations of Na and K in the drainage water were reduced to 40-60% of GW and the concentration of Ca and Mg in drainage water increased by an order of magnitude with the net effect of a significant reduction in the SAR of drainage water to 11-19% of the SAR of GW. These results indicate preferential storage of K and Na in soil and exclusion of Ca and Mg from soil via leaching during laundry greywater application.

Detailed examination of the variation in pH and EC for successive pore volumes of drainage water with application of TW and GW to soils of varying treatment is shown in Figs. 4 and 5. It is worth noting that these data are for single samples because the time needed to collect each pore volume of drainage water varied greatly due to the variation in hydraulic conductivity (Figs. 2 and 3) and thus can not be represented on a single time scale. Application of TW to previously unirrigated soil caused slight decline in pH of drainage water with successive pore volumes. The pH of drainage water remained lower than the pH of TW (Fig. 4) and soil (Table 1) for loose and compacted soils, but remained similar to the pH of irrigation water and soil for the field soil. In contrast, EC of drainage water decreased initially, but became relatively constant with successive pore volumes of drainage supporting retention of some salts within soil.

Application of GW to previously unirrigated field soil caused a dramatic decline in pH of drainage water with successive pore volumes (Fig. 5). For loose soil, a moderate increase in pH was evident. As saturated hydraulic conductivity of soil with application of GW to soil was low (Figs. 2 and 3), only a small number of pore volumes of drainage was available for analysis of pH and EC. Our results indicate a similar but slow decline in pH and EC of drainage water when greywater is applied to soils.

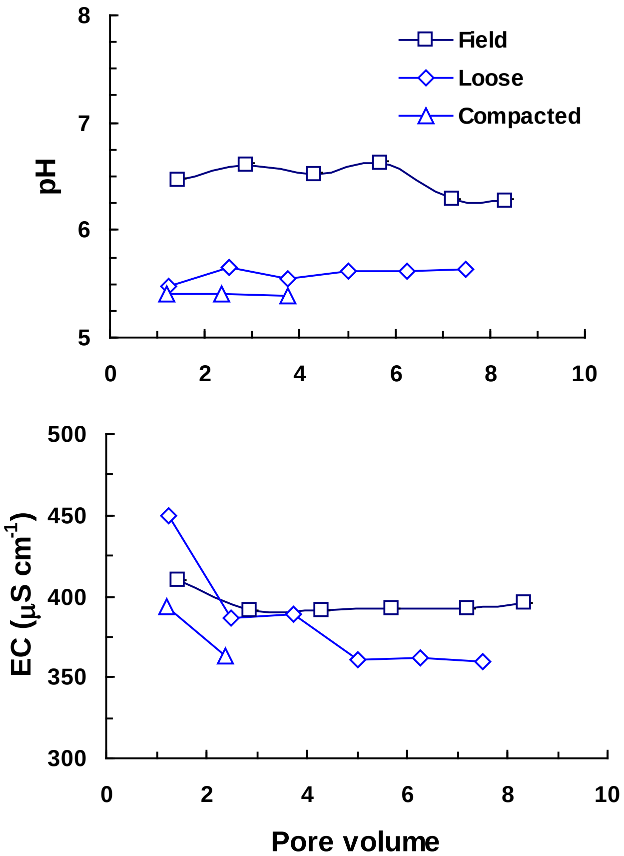

Fig. 4. Variation in pH and EC of the drainage water with successive pore volumes after continued leaching of initially unsaturated soil with tap water (TW).

The nature of variation in pH and EC with sequential application of TW, GW and TW was similar to that seen in Figs. 4 and 5. With application of GW in this sequence, pH and EC of drainage water initially increased but decreased slowly with subsequent application of TW (Data not shown).

Discussion

During rainfall and irrigation, infiltration of water into unsaturated soil produces a thin zone of saturated soil the thickness of which increases as the wetting front advances downward. The wetting front advance in an unsaturated soil is initially influenced by a steep water potential gradient that becomes negligible as steady state infiltration condition is reached so that the infiltration rate approximates the saturated hydraulic conductivity under continuous ponding (Hillel, 2004). Dissolved and suspended chemicals present in irrigation water tend to move with water while interacting with the resident soil water (soil solution). When the suspended material in water does not readily react with the soil components, some of the suspended material would be partially filtered by the surface soil, which may lead to partial blocking of pores and subsequent development of crust. Some reduction in hydraulic conductivity may be attributed to the suspended material depending on the size of material and its concentration. Recent studies on laundry greywater indicate modest concentration for total suspended solids (e.g. TSS ~100 mg L^{-1} in Howard et al. 2005). Thus, reduction in saturated hydraulic conductivity of soil with greywater irrigation may not be altogether due to the effects of suspended material. The dissolved chemicals (solutes) in greywater are expected to interact with both soil and soil water (soil solution) to influence the final distribution of solutes in soil and in the drainage water.

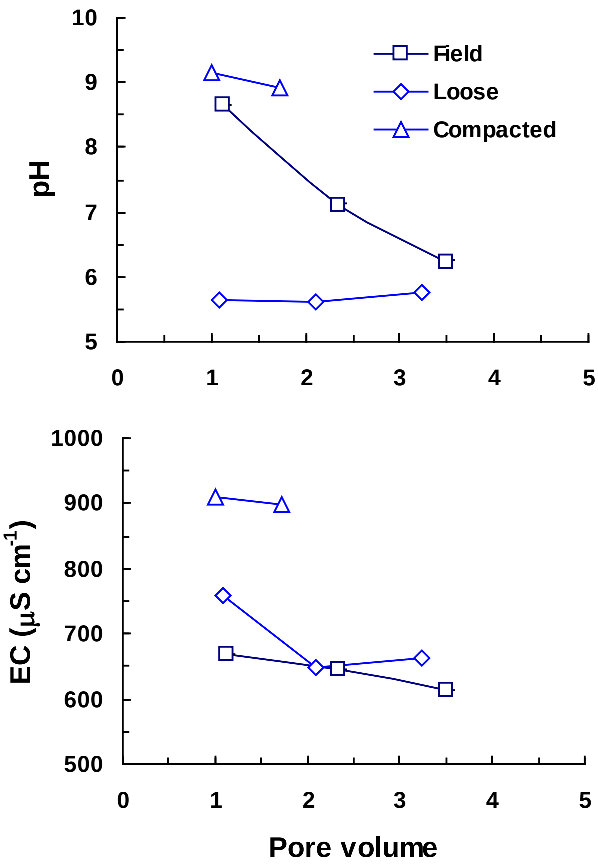

Fig. 5. Variation in pH and EC of the drainage water with successive pore volumes after leaching of initially unsaturated soil with laundry greywater (GW).

Despite developments in solute transport models to predict distribution of nutrient salts and pollutants, e.g. using the principles of miscible displacement (Hillel, 2004), infiltration under sequential application of rain and irrigation of variable water quality can be explained with some success for simple scenarios (Surarez et al., 2006).

Reduction in saturated hydraulic conductivity with the use of laundry greywater (GW) compared with potable water (TW) in our experiments (Figs. 2 and 3) indicates that reductions in K_s may be due to the effects of dissolved ions, especially sodium, present in GW that led to a ten-fold increase in SAR over TW (Table 3).

High SAR of irrigation water is known to cause some soil aggregates to collapse leading to soil sealing near the surface but also formation of clay skins at depths due to migration of clay with irrigation water that is often attributed to the loss of soil permeability (Abu-Sharar and Salmeh, 1995) as reported for septic tank drainage fields (p 178, Hillel 2004) and a number of wastewater studies (Balks et al., 1998; Menneer et al., 2001). As the soil used in our experiment was neither saline (low EC) nor sodic with an exchangeable sodium of 0.9% (Table 1), the soil would be capable of storing salts as evident from the decrease in the EC of drainage water (Fig. 5). The speed with which salts, particularly sodium, can be stored in the soil during application of tap water or greywater was dependent on soil conditions. Undisturbed soil in the field and loose soil (condition that may persist in recently established garden beds) are likely to maintain reasonable values of hydraulic conductivity during irrigation of soils by greywater and also have a greater ability to reduce the pH and EC of drainage water rapidly (Figs. 2, 3 and 5).

Coarse textured soils (this may possibly also apply to well aggregated clay soils in our experiments) tend to exhibit hysteresis to a greater extent than fine textured soils (Hillel, 2004). As the pores of coarse textured soils usually empty (or drain) at an appreciably higher suction than the suction at which they fill (p 118, Hillel, 2004), their capacity to retain water is reduced on rewetting once they are partially drained. Significant reduction in water retention between wetting and drying due to hysteresis observed for loose and compacted soils in our experiments suggest that repeated cycles of irrigation or rain will progressively reduce the water holding capacity of the soil. With greywater used for irrigation, the soil used in our experiment would be more vulnerable to runoff and/or persistent waterlogging conditions due to hysteresis and reduced K_s if it is disturbed.

Irrigating soils with GW, the pH, EC and SAR of the drainage water reduced considerably to the extent that the quality of drainage water became similar to the quality of TW (Table 3) after the soil was irrigated with approx. 3 pore volumes of GW (Fig. 5). Moreover, there was a reduction of >50% in the concentration of Na and a ten-fold increase in the concentration of Ca and Mg in the drainage water. Most of the Ca and Mg are expected to have originated from the soil because soils tend to balance cations through the exchange process such that the CEC of soil remains constant. Thus, the soil used in our experiments was essentially capable of storing sodium and was effective in modifying the leachate quality in a way that in the worst case scenario of irrigating a previously wet soil with laundry greywater, the scope for transfer of sodium to ground and surface water is substantially reduced. However, storage of sodium within soil indicates that the soil is vulnerable to salt accumulation which may cause subsequent degradation in soil fertility.

Conclusions

The results from our experiments on reusing laundry greywater (GW) to irrigate residential garden beds demonstrate that high pH and presence of salts, especially sodium in greywater that is not well balanced with Ca and Mg (high SAR), will reduce saturated hydraulic conductivity of soils which have not been previously irrigated with greywater. Irrigation with potable water, e.g. tap water (TW) used in our experiments, contains some salts but has little adverse impacts on hydraulic conductivity due to a low value of SAR. As the soil used in our experiments does not exhibit swelling or shrinkage behaviour and is non-saline, non-sodic in nature, excess sodium in laundry greywater is the likely cause of reduced permeability of this soil to water. It is suspected that this reduction in permeability arises from modification to the geometry and continuity of water conducting pores within the soil due to dispersion of soil aggregates exposed to irrigation water with high concentration of sodium salts. If we continue to irrigate soils with GW over time, soils could accumulate sodium until theoretically the CEC limit of soil is reached. Using less sodic water (e.g. TW) to irrigate soils, which have accumulated sodium from past irrigation with GW, sodium may enter drainage water and move in the direction of ground water. Residential gardens close to streams or shallow water tables should not be irrigated with GW to avoid pollution of unconfined aquifers and streams.

When a soil becomes saturated with GW, further entry and transport of good quality water (via rain or potable water) into that soil is greatly reduced. Additional measurements for the experimental soil used show that the soil is able to retain a large proportion of salts and sodium from the greywater within the soil such that the quality of drainage water is improved substantially. Indeed, the quality of drainage water approaches the quality of potable water. Nonetheless, enrichment of soils with sodium and other salts from long-term and widespread use of untreated laundry greywater as irrigation may predispose soils to future environmental hazards unless the water is treated to reduce SAR, modifications of laundry detergents to reduce sodium concentration in greywater or use biological control measures (e.g. plants or micro organisms) to remove excess sodium from the soil. Greywater still remains a valuable water resource for reuse in urban areas for growing plants which have the ability to remove sodium from soil provided plant growth is unaffected. In the context of this work, sodium has been found to be an undesirable ion for soils, but it is considered as a beneficial, nonessential plant nutrient that is essential for human and animal nutrition.

Acknowledgment

We thank Mr. Le-Minh Nhat for assistance with the collection of laundry greywater used in our experiments.

References

ABS, 2000. Water Account Australia 2000-01, Cat. No. 4610.0. Australian Bureau of Statistics, Canberra.

Abu-Sharar, T.M., Salameh, A.S., 1995. Reductions in hydraulic conductivity and infiltration rate in relation to aggregate stability and irrigation water turbidity. Agric. Water Manage. 2, 53-62.

Abu-Zreig, M., Rudra, R.P., Dickinson, W.T., 2003. Effect of application of surfactants on hydraulic properties of soils. Biosys. Eng. 84, 363-372.

Al-Jayyousi, O.R., 2003. Greywater reuse: towards sustainable water management. Desalination 156, 181-192.

APHA, 1998. Standard methods for the examination of water and wastewater, 20th ed., American Public Health Association, Washington DC.

Ayars, J.E., Hutmacher, R.B., Schoneman, R.A., Vail, S.S., Pflaum, T., 1993. Long term use of saline water for irrigation. Irrig. Sci. 14, 27-34.

Balks, M.R., Bond, W.J., Smith, C.J., 1998. Effects of sodium accumulation on soil physical properties under an effluent-irrigated plantation. Aust. J. Soil Res. 36, 821-830.

Brady, N.C., Weil, R.R., 1999. The Nature and Properties of Soils, 12th edition. Prentice Hall, Upper Saddle River, New Jersey.

Biggs, A.J.W., Clark, J., Hall, I.R., Finney, G.T., 2001. Soil Survey of the Eastern Darling Downs, Westbrook-Highfields-Oakey Area. Department of Natural Resource and Mines, Toowoomba, NR&M Ref. No. EDS-I-AO 3254.

Brunner, P.H., Capri, S., Marcomini, A., Giger, W., 1988. Occurrence and behaviour of linear alkylbenzenesulphonates, nonylphenol, nonylphenol mono- and nonylphenol diethoxylates in sewage and sewage sludge treatment. Water Res. 22, 1465–1472.

Christova-Boal, D., Eden, R.E., McFarlane, S., 1996. An investigation into greywater reuse for urban residential properties. Desalination 106, 391-397.

DHWA, 2002. Draft guidelines for the reuse of greywater in Western Australia. Department of Health, Government of Western Australia, Perth.

DLGPSR, 2007. Greywater. Department of Local Government, Planning, Sport and Recreation, Queensland, <http://www.lgp.qld.gov.au/?id=3044>, (viewed 28.03.07).

Eltaif, N.I., Gharaibeh, M.A., 2007. Effects of single and mixed ion solutions on hydraulic and physical properties of a clay soil. Water Air Soil Pollut. 181, 297-302.

Eriksson, E., Auffarth, K., Eilersen, A.M., Henze, M., Ledin, A., 2003. Household chemicals and personal care products as sources for xenobiotic organic compounds in grey wastewater. Water SA 29, 135-146.

Hillel, D., 2004. Introduction to Environmental Soil Physics. Elsevier Academic Press, New York.

Howard, E., Misra, R.K., Loch, R., Le-Minh, N., 2005. Laundry grey water potential impact on Toowoomba soils - final report. National Centre for Engineering in Agriculture Publication 1001420/2, USQ, Toowoomba, Australia, <http://eprints.usq.edu.au/641/>, (viewed 19.02.08).

Isbell, R.F., 1996. The Australian Soil Classification. CSIRO Publishing, Collingwood, Victoria.

Jeppesen, B., 1996. Domestic greywater re-use: Australia's challenge for the future. Desalination 106, 311-315.

Menneer, J.C., McLay, C.D.A., Lee, R., 2001. Effects of sodium-contaminated wastewater on soil permeability of two New Zealand soils. Aust J. Soil Res. 39, 877-891.

Misra, R.K., Li, F.D., 1996. The effects of radial soil confinement and probe diameter on penetrometer resistance. Soil Tillage Res. 38, 59-69.

Miyamoto, S., Chacon, A., 2006. Soil salinity of urban turf areas irrigated with saline water. II. Soil factors. Landsc. Urban Plan. 77, 28-38.

Nolde, E., 1999. Greywater recycling systems in Germany - results, experiences and guidelines. Water Sci. Tech. 51, 203-210.

Radcliffe, J.C., 2004. Water recycling in Australia. Australian Academy of Technological Sciences and Engineering, Parkville, Victoria.

Rayment, G.E., Higginson, F.R., 1992. Australian Laboratory Handbook of Soil and Water Chemical Methods. Inkata Press, Melbourne.

Rhoades, J.D., Kandiah, A., Mashali, A.M., 1992. The use of saline waters for crop production. FAO Irrigation and Drainage Paper No. 48, Rome.

Shafran, A.W., Gross, A., Ronen, Z., Weisbrod, N., Adar, E., 2005. Effects of surfactants originating from reuse of greywater on capillary rise in the soil. Water Sci. Tech. 52, 157-166.

Smulders, E., 2002. Laundry Detergents. Wiley-VCH Verlag GmbH, Weinheim, FRG.

Suarez, D.L., Wood, J.D., Lesch, S.M., 2006. Effect of SAR on water infiltration under a sequential rain-irrigation management system. Agric. Water Manage. 86, 150-164.

Thwaites, L.A., de Rooij, G.H., Salzman, S., Allinson, G., Stagnitti, F., Carr, R., Versace, V., Struck, S., March, T., 2006. Near-surface distributions of soil water and water repellency under three effluent irrigation schemes in a blue gum (*Eucalyptus globulus*) plantation. Agric. Water Manage. 86, 212-219.

Van Lyssel, M., Crull, A., 1998. C-090R Surfactants and Chemicals for the Detergent Industry. Business Communications Company Inc., Norwalk, CT, USA.

Winward, G.P., Avery, L.M., Stephenson, T., Jefferson, B., 2008. Chlorine disinfection of grey water for reuse: Effect of organics and particles. Water Res. 42, 483-491.