Journal of Contaminant Hydrology 115 (2010) 1–13

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

Review article

Optimizing the experimental design of soil columns in saturated and unsaturated transport experiments[☆]

Jeffrey Lewis [*], Jan Sjöstrom

Totalförsvarets forskningsinstitut FOI-CBRN, Cementvägen 20, Umeå, Sweden

ARTICLE INFO

Article history:
Received 2 October 2009
Received in revised form 26 March 2010
Accepted 1 April 2010
Available online 14 April 2010

Keywords:
Soil column
Design
Review

ABSTRACT

Soil column experiments in both the saturated and unsaturated regimes are widely used for applied and theoretical studies in such diverse fields as transport model evaluation, fate and transport of pesticides, explosives, microbes, heavy metals and non aqueous phase liquids, and for evapotranspiration studies. The apparent simplicity of constructing soil columns conceals a number of technical issues which can seriously affect the outcome of an experiment, such as the presence or absence of macropores, artificial preferential flow paths, non-ideal infiltrate injection and unrealistic moisture regimes. This review examines the literature to provide an analysis of the state of the art for constructing both saturated and unsaturated soil columns. Common design challenges are discussed and best practices for potential solutions are presented. This article discusses both basic principles and the practical advantages and disadvantages of various experimental approaches. Both repacked and monolith-type columns are discussed. The information in this review will assist soil scientists, hydrogeologists and environmental professionals in optimizing the construction and operation of soil column experiments in order to achieve their objectives, while avoiding serious design flaws which can compromise the integrity of their results.

Contents

[☆] The paper is a review of the literature to summarize the best practices and state of the art in designing and operating unsaturated and saturated soil columns.

[*] Corresponding author. Tel.: +46 90 10 6720; fax: +46 90 10 6800.
E-mail addresses: jeffrey.lewis@foi.se (J. Lewis), jan.sjostrom@foi.se (J. Sjöstrom).

0169-7722/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jconhyd.2010.04.001

1. Introduction

Soil columns have been used for over three centuries in the study of hydrogeological properties (De la Hire, 1703). More recently, soil columns and lysimeters have been used to evaluate transport models (Klein et al., 1997; Butler et al., 1999), to monitor the fate and mobility of contaminants in soil (Jin et al., 1997; Hrapovic et al., 2005; Dontsova et al., 2006) and for evapotranspiration studies (Liu et al., 2002; Prueger et al., 1997; Sahoo et al., 2009). For the purposes of this review, a soil column is characterized as a discrete block of soil located either outdoors or in a laboratory, allows control or measurement of the infiltration, incorporates equipment for the total recovery of the effluent and models one-dimensional flow. This is usually achieved by encasing the soil column in a rigid and impermeable shell material, both for structural reasons and to prevent fluid loss.

With the exception of the groundbreaking work by Darcy (1856), most early studies involving soil columns were performed using unsaturated soil columns or lysimeters. An exhaustive bibliography and history of early experimental work involving lysimeters was compiled by Kohnke et al. (1940). Early work was largely concerned with the rate and amount of percolate passing through the soil (Dalton, 1802; De la Hire, 1703; Lawes et. al., 1882). Soil column studies concerning the chemistry and movement of solutes in the pore water began to appear in the early 20th century (Burgess, 1921; Parker, 1921; Schreiner and Failyer, 1906) and soil column analyses of the mechanics of flow and permeability in porous media were being published by the 1940s (Christiansen, 1944; Fireman, 1944; Kirkham and Feng, 1948). A vast number of articles have been published since 1950 in the fields of hydrogeology, agriculture and soil sciences which rely primarily on results obtained from soil column experiments. Despite this, no attempt has ever been made to standardise or compile the best practices for constructing soil columns and a review of the literature reveals a bewildering array of technical approaches. Some of the smallest columns reported in the literature measure 1 cm in diameter and 1.4 cm in length (Voegelin et al., 2003) while the largest measure up to 2 m × 2 m × 5 m (Mali et al., 2007) and weigh over 50 tonnes.

The purpose of this article is to review the state of the art for soil column design, rather than to provide a rigorous review of the history of soil column experimentation. Given the thousands of publications which describe results obtained from soil columns, it would be impossible to cite even a small fraction of them in a single article. Therefore, citations have been limited to those which concisely illustrate a given concept. A great many other references may exist which are historically and factually valid.

Soil columns operating in the unsaturated regime are generally and historically referred to as lysimeters. This term has usually been applied to large outdoor soil columns, although no definition exists which establishes minimum size requirements. These columns are characterized as having both air and water (or another liquid) in their pore spaces and they are typically used to reproduce conditions encountered in soil found between the earth's surface and the top of the groundwater table, otherwise known as the vadose zone or unsaturated zone.

In contrast, soil columns which operate in the saturated regime have no air or gaseous phase present in their pore spaces. In such a situation, the pores are entirely filled with a liquid such as water or a non aqueous phase liquid such as oil. These soil columns are typically used to reproduce the conditions found in an aquifer. Substantial design differences exist between soil columns used to reproduce saturated and unsaturated conditions.

Soil columns may be classified either according to their level of saturation as discussed above, or according to the method of their construction. Two broad categories of construction have been reported in the literature: packed columns that use disturbed soil and monolithic columns that use undisturbed soil. Packed soil columns are built using soils which have been excavated or "disturbed", then backfilled into a rigid container and compacted. In contrast, monoliths are extracted whole and intact from natural soil. Packed columns are typically much more homogeneous than monoliths, which may or may not be desirable depending on the experimental objectives. It has been shown that the choice of packed or monolithic columns will have a direct impact on the experimental results. For example, Camabreco et al. (1996) showed that there is a lower leaching rate of trace metals and dissolved organic matter from packed columns than in intact soil columns. Similarly, Smith et al. (1985) reported less leaching of *Escherichia coli* from packed soil columns than undisturbed soil columns.

The selection of methodology in soil column construction will therefore have an impact upon the results obtained and investigators need to reflect on how their choice of methodology relates to the hypothesis they are attempting to prove or disprove. Packed soil columns using screened, homogenized soils can be expected to have fewer macropores, which will result in better reproducibility at the expense of realism. Use of intact monoliths may better reproduce field conditions at the possible expense of reproducibility.

If the behaviour of the soil columns is to be modelled numerically, the boundary and initial conditions must be well defined. In most cases, the boundary conditions of soil column experiments involve no-flow boundaries along the column walls and constant head boundaries of different values at each end of the column. This arrangement forces steady-state one-dimensional flow along the longitudinal axis of the soil column. In most soil column experiments, the objective of the initial conditions is to reproduce the prevailing environmental conditions — specifically the flow rate of pore water and moisture content profile if the experiment is unsaturated. Since most column studies are performed at steady-state rather than under transient conditions, the initial conditions are usually maintained for the duration of the experiment.

Of the four types of soil columns discussed above-packed, monolith, unsaturated and saturated — the first two deal with a construction method while the last two deal with soil saturation levels. Given the substantially different design issues associated with these four soil column types, each will be reviewed separately.

1.1. Packed soil columns (saturated and unsaturated)

Although the packing of laboratory columns has received relatively little attention in the literature, Bromly et al. (2007) have demonstrated that it will significantly influence the resulting solute transport behaviour of the columns. The goal of packing is to produce a homogenous soil column having a bulk density similar to that observed naturally, while avoiding the formation of stratifying layers or preferential flow pathways. Several packing methods have been reported in the literature. The most common approach is dry or damp packing (Begin et al., 2003; Communar et al., 2004; Ghodrati et al., 1999; Hrapovic et al., 2005; Phelan et al., 2003; Seol and Lee, 2001).

Dry or damp packing involves loading small discrete amounts or “lifts” of dry or damp soil into the column and then mechanically packing it either by hand or with some type of ram or pestle. Oliveira et al. (1996) demonstrated that in order to produce homogeneous sand packing, dry deposition must be in increments of 0.2 cm followed by compaction with a metal pestle. However, the literature shows few studies in which dry deposition is done in lifts smaller than 1 cm (Communar et al., 2004; Hutchison et al., 2003; Jin et al., 1997) and some in which the lifts were as much as 15 cm (Plummer et al., 2004). Several studies which employed dry or damp packing also noted the importance of lightly scarifying the soil surface after compaction and before addition of another lift in order to ensure hydraulic connectivity between the layers (Plummer et al., 2004; Seol and Lee, 2001).

Another common approach is slurry packing (Jin et al., 1997; Powelson and Mills, 2001; Sentenac et al., 2001; Simon et al., 2000), which involves saturating the soil with an excess of water, then letting it settle at the bottom of the column. This is achieved either by stirring the soil into the water prior to pouring it into the column as a slurry, or by filling the column with water and then slowly pouring or sprinkling dry soil into the column while stirring. Oliveira et al. (1996) found that the best wet packing technique involved depositing thin layers of saturated sand into water while vibrating the column. They observed that this technique produced the highest density of uniform packing without causing any lateral particle size segregation. A significant downside to this technique is the potential loss of aqueous solutes during the filling process. If the soil to be studied is of interest because of the presence of aqueous contamination, this filling method will be unsuitable.

Several less common packing methods have also been employed. One of these involves using a series of wetting and drying cycles to assist compaction (Bowman, 1988; Corwin, 2000; Jones et al., 1974; Shih and Rosen, 1985). Corwin (2000) added increments of 0.5 cm or less of soil at a time, followed by several wetting–drying cycles. Any shrinkage away from the soil–column interface was filled with additional soil. Vibration has also been used as a packing technique (Darnault et al., 2004; Ripple et al., 1974) although Ripple subsequently found that radial particle segregation can be induced by vibrating the soil during deposition, and furthermore found that this led to more rapid solute breakthrough.

A packing technique which has been used with larger outdoor lysimeters is passive weathering. Both Aronsson and Bergstrom (2001) and Colman and Hamilton (1947) report allowing their very large lysimeters to sit outside undisturbed for 3 to 8 years prior to any experimental investigations being performed. Colman and Hamilton (1947) reported that measurements of how much the soil in the lysimeters settled over time indicated that after 3 years maximal density had been achieved.

Achieving homogenous, reproducible packed soil columns is challenging and time consuming (Oliveira et al., 1996). Corwin (2000) reported that filling a 0.6 m i.d. by 1.83 m tall column took six months. Mechanized systems have been described for dry packing columns (Ripple et al., 1974; Yaron et al., 1966) which have been shown to greatly reduce the amount of time required for packing (Nimmo and Akstin, 1988).

A major advantage to packed soil columns is their reproducibility. The lack of heterogeneities and macropores should lead to reproducible bulk densities and dispersivities. However, Bromly et al. (2007) showed that the bulk density of packed soil columns having an internal diameter of ≥ 7.59 cm influenced the dispersivity and by extension the fluid transport characteristics of the column. They further found that columns with bulk densities <1.01 g cm^{-3} had significantly lower dispersivities than columns having bulk densities exceeding this value. The scaling effect of column diameter should not influence the dispersivity. Bromly et al. (2007) suggest that this effect may be caused by practical difficulties in packing larger soil columns.

The bulk density of a soil is the total mass of the column divided by the volume of the soil column. Since it is easily measured, it is a commonly reported parameter for packed soil columns. It is a measure of how much the soil is compacted and is related to porosity by the following relationship:

$$n = \rho_b / \rho_s$$

where ρ_s is the particle mass density, which is the oven-dried mass divided by the volume of the solid particles, as determined by a water displacement test. Unless great accuracy is required, $\rho_s = 2.65$ g/cm^3 is an appropriate estimate for most mineral soils (Freeze and Cherry, 1979). Table 1 provides information on common ranges for the two values, which should assist in determining whether a packed soil column has been sufficiently compacted.

1.2. Monolithic soil columns (saturated and unsaturated)

In contrast to packed soil column, the monolithic soil column allows testing of soil which is as close to actual field conditions as possible. The soil structure and stratigraphy are not destroyed during sampling which is ideal for applications which attempt to answer questions about a specific location. One of the major advantages to monoliths is that they allow the study of macropores which contribute significantly to solute transport in the field such as burrows, root cavities and cracks (Lawes et al., 1882). However, the inherent heterogeneity of monoliths means that there is no guarantee that these significant macropores will be part of the monolith which is sampled (Akhtar et al., 2003). Another significant disadvantage to monoliths is that depending on their size, extracting them can be prohibitively difficult (Corwin, 2000).

Several methods of obtaining undisturbed soil monoliths have been discussed in the literature. The first is to excavate around a column of soil and then sheathing it in a steel or plywood box (Bowman et al., 1994; Brown et al., 1974; Strock and Cassel, 2001). However, this method of construction is particularly prone to sidewall flow because of the gap that exists between the monolith and the sheathing. Fluids have a tendency of leaking into this gap, creating an undesirable preferential flow pathway. Sidewall flow issues will be further discussed in Section 1.3, but a mitigating technique relevant to this method of constructing monoliths has been recommended in several studies, and employs minimal-expansion closed cell structural foam to fill the gap between the soil and the sheathing (Dousset et al., 2004; Landry et al., 2004; Takamatsu et al., 2007).

A similar technique for extracting monoliths calls for pressing steel cylinders over exposed soil columns (Meshkat et al., 1999). While this method works well in clayey soils which have the structural strength to maintain a freestanding soil column during excavation, it will not work in sandy or coarser soils.

Another method of producing soil monoliths involves using a static load to press a heavy steel cylinder into the soil (Moyer et al., 1996; Schneider et al., 1996). Derby et al. (2002) proposed a method of fitting a cutting bit and driving head on a large PVC tube and then driving it into the ground with a 150 kg pile driver. Smaller monoliths have been obtained by driving 15 cm i.d. PVC tubes into the ground with a sledgehammer (Begin et al., 2003).

Monoliths for use in soil column experiments have been obtained from deeper formations through the use of Shelby tubes (Bruner and Lutenegger, 1994; MacKay et al., 1996; Stephens et al., 1984) and split spoon samplers (Bradbury and Muldoon, 1990; Hayden and VanderHoven, 1996). These monoliths are obtained by driving a sampling device into the bottom of a borehole using drilling equipment and are typically under 10 cm in diameter. Miller et al. (2002) showed that in clayey soils the soil compaction caused by these kinds of sampling techniques will have an effect on the soil water characteristic curve, which will influence transport behaviour in the soil column.

Observing preferential flow pathways is challenging to achieve non-destructively and generally requires the use of magnetic resonance imaging (Deurer et al., 2004; Greiner et al., 1997). Several studies have mapped out the preferential flow pathways of soil monoliths using X-ray computer tomography imaging (Crestana and Vaz, 1998; Langmaack et al., 1999). The probability that a monolith contains a significant preferential flow pathway has been addressed by Akhtar et al. (2003). This paper presented a probabilistic approach which suggests that an array of 10 discrete columns has an 82% chance of including one or more columns with a preferential flow pathway that is 1 standard deviation above the mean, but that the same 10 columns have only a 20% probability of having a preferential flow pathway which is 2 standard deviations above the mean. Therefore they suggest that monolith soil column studies require a considerable number of discrete columns (their study used 90) in order to have a significant probability of studying the macropores which contribute most to the flow of solutes.

1.3. Unsaturated soil columns (packed and monolithic)

Avoiding unnatural preferential flow paths is one of the most critical design issue associated with unsaturated soil columns. While natural preferential flow paths are expected or even desirable in monoliths, they may also be formed unintentionally in the construction of both packed and monolithic soil columns. Preferential flow paths will cause spatial heterogeneity in the transport of solutes through a porous medium and will therefore significantly bias any experimental results. For example, sidewall flow is a concern with both monolith and packed unsaturated columns. It refers to a preferential flow of fluid in proximity to the rigid outer wall of a soil column (Corwin, 2000; Ghodrati et al., 1999; Sentenac et al., 2001). Sidewall flow may be caused by improper packing of the column or flexing of the column walls during or after the soil has been packed.

Various strategies have been proposed in the literature to overcome sidewall flow including roughening the sidewall (Smajstrla, 1985), gluing sand to it (Sentenac et al., 2001) or by installing annular rings on the interior surface of the column prior to the addition of soil (Corwin, 2000). Charbeneau (2000) advocates confining the soil column with a flexible latex membrane to overcome side wall flow. Another (unpublished) approach cited by the United States Department of Agriculture recommends wetting the inside of the column then packing it with a swelling clay such as montmorillonite. The excess (dry) clay is allowed to fall out of the column while the hydrated clay forms a liner on the column wall. The soil to be investigated is then carefully packed into the column without disturbing the clay layer. Bergström (2000) suggests that lysimeters should have a surface cross section of at least 0.05 m^2 to minimize sidewall

Table 1
Average range of bulk densities and porosities of typical unconsolidated soils (adapted from Domenico and Schwartz, 1998, p.14).

Soil type	Porosity range (%)	Bulk density range (g/cm^3) [a]
Coarse gravel	24–36	2.0–1.7
Fine gravel	25–38	2.0–1.6
Coarse sand	31–46	1.8–1.4
Fine sand	26–53	2.0–1.2
Silt	34–61	1.7–1.0
Clay	34–60	1.7–1.0

[a] Assuming solid density of 2.65 g/cm^3.

flow, given a lysimeter depth of approximately 1 m. For cylindrical lysimeters, this equates to a diameter to length ratio of approximately 1:4.

The opposite effect – sidewall lag – has also been reported in the literature for monolithic soil columns (Schoen et al., 1999a; 1999b). This effect was attributed to decreased permeability caused by soil compression near the sidewalls of lysimeter. The method of obtaining these monoliths was to press a metal casing into the soil.

In packed soil columns, other undesirable forms of preferential flow include macropore flow or fingering (Wilson et al., 1995).

Macropore flow refers to any flow which takes place outside of the normal pore structure of the soil, such as in wormholes or decayed roots. While these may play a more significant role in monolith-type soil columns, macropores still exist in apparently homogeneous packed soil columns on account of the heterogeneity of the soil grains themselves (Cortis and Berkowitz, 2004; Oswald et al., 1997).

Fingering occurs when instability develops in the wetting front as it moves through coarse unsaturated soils such as sands (Selker et al., 1999). Parlange et al. (1990) showed that the size of the finger width were a function of the soil grain size, with silts having fingers on the order of 1 m in diameter and coarse sands having fingers on the order of 1 cm. While fingering has generally only been observed in practice in soils that are predominantly sand, water-repellency of the soil has also being implicated (Bauters et al., 1998; Ritsema et al., 1998). Selker et al. (1999) suggest that finger width is not strongly influenced by the flux through the system so long as the rate of infiltration is well below the saturated conductivity. When the flux is increased up to the rate of the saturated hydraulic conductivity of the soil, fingers will grow in width and frequency until they finally merge into a single wetted front without fingers. It has been demonstrated that once a finger has formed in a particular location it will persist until the soil has either been fully dried or fully saturated (Glass et al., 1989). Since soil column experiments usually attempt to maintain a steady moisture content, fingering, if it occurs, can strongly influence the results of an experiment. Liu et al. (1993) have shown that fingering is most likely to occur when the soil being infiltrated is initially extremely dry.

Sampling the effluent or soil solution in such a way that the column remains unsaturated is challenging. The pressure potential in unsaturated soil is always negative due to capillary and other forces, becomes zero at the water table and increases below the water table due to the pressure from the overlying water (Wierenga, 1995). This means that suction must be applied to unsaturated soil in order to extract the pore water. However, attempting to sample pore water by applying suction to an open ended pipe attached to the base of a soil column will fail because only air will be drawn in (Wilson et al., 1995). For this reason, rigid porous materials are used as an interface between the sampling device and the soil to ensure that pore liquids in the soil are in hydraulic contact with liquid within the sampling device (Chu et al., 2003; Hutchison et al., 2003; Magesan et al., 2003; Plummer et al., 2004; Powelson and Mills, 2001; Vogeler, 2001).

Rigid porous materials which have been used experimentally as soil solution sampling devices include ceramic, porous PTFE, fritted glass, porous stainless steel, porous plastic and fibreglass wicks. Two key considerations in the choice of a porous material is the bubbling pressure of the material (Everett and McMillion, 1985) and whether or not the material is chemically compatible with the solute under consideration, which will be considered later.

When choosing a rigid porous material for an experimental apparatus, the bubbling pressure of the material must be considered. This is the maximum suction that can be applied to soil water by a rigid porous material before air will begin to enter the plate instead of pore water. Table 2 shows the bubbling pressures and operational suction ranges of the most common materials used for suction plates. In most applications, the vacuum applied to the porous material need not be very high. Fig. 1 shows the water release curves for sand and clay, which is the relationship between the volumetric water content and the soil moisture tension.

The maximum theoretical suction that can be applied to the soil through a rigid porous material is 1 atm, or 1013 mbar. However, the hydraulic conductivity of a soil at or near 1013 mbar matric potential is so low that any column experiment would take a prohibitively long time (Wilson et al., 1995). As a result, most unsaturated soil column studies are conducted at or near the field capacity of the soil. In coarse textured soils, this means that the soil matric potential will be between 40 and 60 mbars and from 60 to 100 mbars in fine textured soils (Wierenga, 1995). These pressures can be easily achieved without pumps by using a hanging column of water.

It should also be noted that even under these favourable conditions, PTFE porous materials may not be able to achieve a sufficiently high operational suction to bring the water content of a soil down to field capacity. In finer textured soils such as silts and clays, the operational suction of porous PTFE is unlikely to successfully withdraw pore water at all. How much suction should be applied to a soil column is still under some debate, but a consensus is emerging that the methodology to obtain the most representative soil water samples is to apply a suction equivalent to the ambient matric potential which exists at the same depth in the soil (Barzegar et al., 2004; Kosugi and Katsuyama, 2004; Lentz and Kincaid, 2003; Mertens et al., 2005; Siemens et al., 2003). However, higher-than-ambient suctions will allow a faster collection of leachate. While this will create an artificial flow field within the column, this may be an acceptable trade off depending on the experimental objectives, particularly in soils which have very low permeabilities. In general, the suction applied will be dependent on the soil type, the amount of water required for analysis, the soil water content and the time of the applied suction (Weihermuller et al., 2005).

Table 2
Porous plate material characteristics (adapted from Wilson et al., p. 480).

Porous material	Maximum pore diameter (μm)	Bubbling pressure (bar)	Operational suction range (bar)
Ceramic	1.1–2.1	>1	<0.6–0.8
Stainless steel	06–14	0.2–0.5	<0.2–0.5
PTFE	25–35	0.07–0.2	<0.07–0.2
Quartz	6–7	0.4–0.5	<0.4–0.5
Fritted glass	6	0.5	<0.5

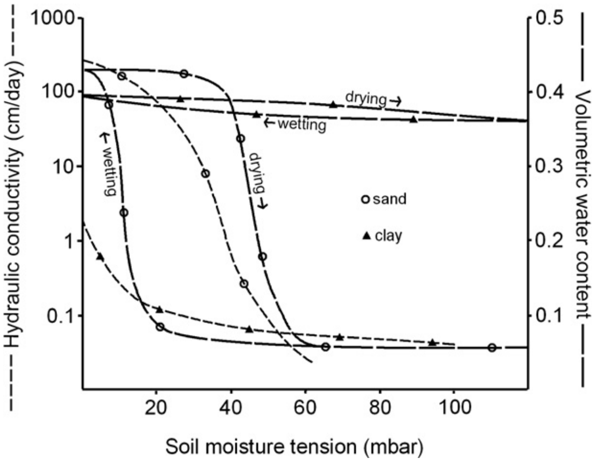

Fig. 1. Relationships between the soil moisture tension, unsaturated hydraulic conductivity and soil moisture tension for sand and clay. Adapted from Mercer and Spalding, 1991 and Bouma et al., 1972.

Determination of the ambient matric potential at a given depth in a soil may be measured directly through the use of tensiometers or, if the water release curve is known, through the measurement of the soil water content. However, as Fig. 1 shows, the water release curve — also known as the soil water characteristic curve (SWCC) is hysteretic, meaning the relationship between the soil moisture content and matric pressure is different depending on whether the soil is drying or wetting. Fig. 1 shows that this will have a strong impact on the hydraulic conductivity and therefore on the flow rate of both the fluid and the aqueous components the fluid is carrying. Determining the relationships which exist between the various soil parameters such as the SWCC is labour intensive but pedotransfer functions allow accurate estimations based on the grain size distribution of the soil (Fredlund et al., 2002).

A serious problem with the use of rigid porous sampling materials is pore clogging, and Everett and McMillion (1985) recommend the use of a silica flour pack between the rigid porous material and the experimental soil to prevent colloids in the soil from reaching and plugging the rigid porous surface. They found that the use of a silica flour pack was essential when using PTFE porous materials. Clogging of rigid porous surfaces in lysimeters may also be caused by biofilms (Andersson, 2003).

An experimental approach encountered frequently in the literature involves the free drainage (or zero tension) of soil pore water from the base of the soil column without any applied suction (Akhtar et al., 2003; Aronsson and Bergstrom, 2001; Branham et al., 1985; Colman and Hamilton, 1947; de Jonge et al., 2002; Derby et al., 2002; Mali et al., 2007; Pasteris et al., 2002; Rousseau et al., 2004; Troxler et al., 1997). Frequently, the soil column is installed on a layer of gravel or on a metal screen. This experimental approach requires that the soil matric potential increase to 1 bar before drainage begins. By definition this means that a saturated zone must form at the base of the soil column which is at a minimum the thickness of the capillary fringe. In sands this capillary fringe may be up to 30 cm thick and in loam it may be up to 90 cm thick (Boulding and Ginn, 2004). Therefore, in practice many unsaturated laboratory soil columns which operate under zero tension may in fact be mostly saturated. Since the hydraulic properties of soil change dramatically when the pores begin to desaturate, the transport and flow data obtained from such experimental setups is almost certainly biased (Derby et al., 2002; Flury et al., 1999).

Mechanical dispersion and molecular diffusion will also affect the results obtained from unsaturated soil columns (Jose, 2004; Toride et al., 2003). Mechanical dispersion is caused by deviations in the microscopic fluid velocity caused by differences in pore sizes and geometries, creating localized dilutions. Mechanical dispersion is a linear function of the dispersivity – which is an intrinsic property of the soil – and the fluid velocity. Molecular diffusion in contrast is driven by concentration gradients and will occur regardless of whether the fluid is moving. Unless the fluid is nearly immobile, mechanical dispersion dominates and molecular diffusion effects can often be neglected. These two processes are commonly combined into a single expression of hydrodynamic dispersion (Leij and van Genuchten, 2002). This combined behaviour is usually modelled by assuming that it is analogous to Fick's law of diffusion (Bear, 1972). However, Fick's law can only be valid when a fluid or solute has passed through enough micro scale heterogeneities that the overall behaviour becomes representative of the volume of soil as a whole (Selker et al., 1999). Given the numerous flow pathways in homogenous saturated soil, this distance is on the order of several thousand soil grains (Yeh, 1998) and therefore it is rarely an issue experimentally. However, because there are fewer flow pathways in unsaturated soil than in saturated soil – some of the pore spaces are filled with air and are therefore unavailable for fluid flow– a solute must travel a much longer distance through the soil before it's behaviour becomes representative of all possible flow paths in a representative volume of soil. This distance may be longer than the experimental soil column itself (Yeh, 1998). If the flow distance is insufficiently long to allow the application of Fick's law, the concentration profile of nonreactive solutes detected in the effluent is characterized by an early breakthrough, long tails and multiple peaks. These effects are even more pronounced in situations where macroscale heterogeneities exist, as is often the case with monolithic soil columns.

Several researchers have recently demonstrated that the dispersivity of unsaturated soils is inversely related to the soil moisture content (Bunsri et al., 2008; Hutchison et al., 2003; Toride et al., 2003; Torkzaban et al., 2006). Dispersivity may be nearly an order of magnitude higher in unsaturated soil than that of an identical saturated soil (Toride et al., 2003). The fluid flow velocity also appears to have a lesser effect on the dispersivity in unsaturated soil (Toride et al. (2003). These effects will influence the breakthrough curves obtained at different soil moisture contents.

Any one of the issues discussed above can have a significant influence on the experimental results obtained from unsaturated soil columns.

1.4. Saturated soil columns (packed and monolithic)

Bromly et al. (2007) have shown that the lateral and vertical geometry of saturated soil columns play a role in determining the flow characteristics. They performed regression analysis and classification and regression tree analysis of 291 packed saturated homogeneous laboratory column experiments, which showed that there is a significant relationship between the diameter of the column and the measured dispersivity. Larger column diameters ($\geq$7.59 cm) tend to produce greater experimental dispersivities than columns with diameters <7.59 cm, which may be on account of the greater difficulty in uniformly packing larger columns. However, they also note that apart from their regression analysis, very few studies have experimentally investigated this effect.

Bromly et al. (2007) also observed a lesser relationship between the column length and dispersivity. They found that dispersivities in larger columns having diameters $\geq$7.59 cm can be grouped according to their lengths. Columns longer than 10.7 cm produced greater dispersivities than columns <10.7 cm. While this appears inconsistent – scaling effects would suggest that the opposite be true –this may be on account of non-ideal solute inputs, which has also been shown to increase dispersivity (James and Rubin, 1972). Bromly et al. (2007) further argue that packing heterogeneities in shorter columns will be more significant than in longer columns, as longer travel distance attenuates the effect of the input heterogeneity.

Hydrodynamic dispersion, as mentioned in Section 1.3, is a linear function of the fluid flow velocity and the dispersivity. The limited literature available (Bunsri et al., 2008; Hutchison et al., 2003; Toride et al., 2003) suggests that unsaturated dispersivity is up to an order of magnitude higher than that of the saturated regime. By extension, once the fluid flow in a saturated soil column is forced to a value that is approximately an order of magnitude higher than that of the unsaturated regime, the saturated hydrodynamic dispersion can be expected to overtake the unsaturated dispersion. Pressure differentials in a saturated soil column between the upper and lower boundaries may be much greater than those of an unsaturated soil column, leading to potentially higher fluid flow velocities and consequently higher hydrodynamic dispersions.

Greiner et al. (1997) also observed the effects of non-ideal solute inputs. When water or solutes were added or removed through an orifice with a radius less than the column radius, they observed non-uniform velocity profiles at the ends. The zone of influence along the column length was calculated by Barry (2009) to be on the order of the column radius, but it may be as high as 1.5 column radii. This effect was also noted experimentally by Deurer et al. (2004) who estimated that the zone of influence along the length of the column was 11.5 mm from the entrance and exit surfaces in a column that was 7 mm in diameter.

Macropore flow and sidewall flow, both of which have been described in Section 1.3, can impact soil columns which operate in the saturated regime as well, with similar effects on the spatial heterogeneity in the transport of solutes. Sentenac et al. (2001) observed that in the saturated regime, the flow velocity at a column wall can be between 1.11 and 1.45 times the flow velocity in the column center. They also observed that sidewall flow increased with larger soil particle sizes and that it is more exaggerated at small hydraulic gradients.

Ensuring that the column is fully saturated is critical to the experimental results. Air bubbles can substantially influence the flow of liquids through pore spaces (Hillel et al., 1982). Therefore, once the column is saturated it should be allowed to sit for at least a week to allow any entrapped air to dissolve and disperse in the pore liquids (Boulding and Ginn, 2004). Alternatively, flushing the soil column with carbon dioxide prior to saturation will help avoid bubbles (Perret et al., 2000) Carbon dioxide is several orders of magnitude more water soluble than the component gasses of air, so carbon dioxide bubbles will dissolve into the pore water and disappear more rapidly than air bubbles. The initial saturation should be done from the base upwards. Common practice in saturated soil column experiments is to maintain flow from the bottom to the top of the column to ensure total saturation for the duration of the experiment (Casey et al., 2000; Jin et al., 1997; Liu et al., 2008). The initial saturation should initially be done at zero pressure, allowing the moisture to wick upwards through the soil by capillary action.

2. Selection of column materials

Materials which have been experimentally used for constructing the outer shell and rigid porous interfaces of soil column experiments include stainless steel (Branham et al., 1985; de Jonge et al., 2002), glass (Batterman et al., 1996; Seol and Lee, 2001), acrylic (Plexiglas) (Ahmad et al., 2005; Rockhold et al., 2005), PTFE-lined steel (Lewis et al., 2009), PVC (Clay et al., 2004; Guber et al., 2005), polybutyrate (Powelson and Mills, 2001), fibreglass (Aronsson and Bergstrom, 2001), and concrete (Colman and Hamilton, 1947). A review of the literature indicates that the three most common materials by a considerable margin are acrylic, glass and stainless steel, together accounting for over 60% of the experimental setups which were reviewed. The choice of materials for constructing the external shell of the soil column must take into consideration the structural strength of the material, whether or not the material will interfere chemically with the solute of interest, whether or not transparency is required, and the ease of installing instrumentation. Furthermore, the commercial availability of a product will strongly influence the cost of fabrication. While few papers discuss the reasoning behind the choice of materials for the soil columns, a poor choice may have a significant impact on results, either through leakage, adsorption of solutes, or the inability to weather years or decades outdoors.

The structural strength of the external shell is largely a function of the size of the column being considered. Rigidity is essential, and achieving this will require different engineering approaches depending on the other requirements of the experiment. For soil columns larger than 1 m^3 it is strongly recommended that a structural engineer with relevant experience be included in the experimental design team.

Stainless steel offers adequate strength for most soil column applications. Seamless stainless steel tubing is commercially available in a wide variety of outer diameters (OD) up to 20 cm. Spiral welded stainless steel tubing is commercially available in outer diameters up to 1.8 m. Galvanized steel pipe and concrete tubing is cheap and widely available, and can be obtained in a wide variety of outer diameters up to several meters. For extremely large column setups, these options may be the only reasonable choice, although the interior surfaces may have to be treated prior to use by lining or spraying the interior with an impermeable layer.

Plastics, including PTFE, PE, acrylics and polycarbonates, are relatively flexible and wall thickness is therefore a critical parameter when choosing these materials. All four of these plastics can be obtained commercially in outer diameters (OD) of at least 20 cm and with wall thicknesses up to 1.3 cm. Therefore, plastics can be easily and economically used in most bench scale applications. Applications requiring columns which are larger than 20 cm OD will usually require custom fabrication. However, plastics are generally impractical for larger applications requiring an OD of 1 m or larger because they are not rigid enough. A column shell which flexes under the considerable stress of soil compaction will be more susceptible to undesirable preferential flow at the column wall.

In some cases such as dye tracer experiments, it is desirable that the column shell be constructed of a transparent material. If this is the case, choices are limited to glass, polycarbonates (Lexan™) and acrylic (Plexiglas™). Acrylics are less likely to scratch and are generally easier to cut and machine than polycarbonates. Cast acrylic tubes are commercially available in a variety of outer diameters up to 24 in. (61 cm) and wall thicknesses up to 0.5 in. (1.3 cm). Polycarbonates are generally available in outer diameters only up to 8 in. (20 cm). Heavy wall glass tubes are commercially available in diameters up to about 2 in. (5 cm) and wall thicknesses up to 0.25 in. (0.6 cm).

Whether or not the column shell material will interfere with the chemistry of the solute of interest is another critical consideration. In particular, the choice of a porous material must be carefully considered given the very high surface area which will be exposed to the leachate. No sampling system will allow optimal sampling of all test substances, and the experimental objectives must guide the choice of soil column materials.

2.1. Interactions with trace metals (Al^{3+}, Cr^{3+}, Cr^{6+}, Cu^{2+}, Fe^{2+}, Fe^{3+}, Mn^{2+}, Ni^{2+}, Pb^{2+}, and Zn^{2+})

Most porous ceramic materials contain aluminum (hydr) oxides. Heavy metals have been shown sorb to metal hydroxides (Wenzel et al., 1997), so ceramics are generally not appropriate materials for use in heavy metal studies. Ceramics containing Al should also be avoided when the solute of interest is Al. Various types of stainless steel contains a large number of heavy metals including Cr and Va and should also be avoided when sampling trace metals.

While nylon, polyethylene and Teflon™ (PTFE) are generally more suitable than ceramics and stainless steel when investigating trace metals, Rais et al. (2006) have reported that suction cups made from PTFE and a silicate adsorbed Cu and Pb, so care must still be taken when these materials are used and appropriate evaluation of any possible interactions performed prior to the experiment. Furthermore, heavy metals are complexed by dissolved organic compounds (DOC), so soil column materials which have been shown to sorb DOC's such as oxide ceramics (Guggenberger and Zech, 1992) should be avoided.

2.2. Interactions with organic compounds

Organic compounds have a wide range of physical properties, not least of which is water solubility. Plastics adhesives and elastomers all absorb organic compounds and are therefore not well suited for these types of soil columns (Weihermuller et al., 2007). The adsorption of dissolved organic matter on ceramics has already been mentioned. Glass and stainless steel are generally more suitable for sampling organic compounds.

2.3. Interactions with nutrients (Ca^{2+},Mg^{2+},K^{+},Na^{+}, NO_3^-; PO_4^{3-}, and CO_3^{2-})

Phosphate ions have been shown to have a strong affinity to metal hydroxides (Bottcher et al., 1984), making most porous ceramics an inappropriate choice in studies where phosphates will be examined. The sorption of phosphate ions can be prevented by using porous PTFE or glass (Weihermuller et al., 2007). New ceramic and glass components may contain considerable amounts of Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}. Such components should therefore be cleaned by rinsing in 0.1 mol/L HCl and deionized water (Grover and Lamborn, 1970; Wessel-Bothe et al., 2000).

2.4. Interactions with microbes and colloids

Microbes and colloids travel as suspended particles through soil pore water. Since the retention of these particles strongly depends on the parameters of the system, it is imperative that experimental setups be individually tested prior to the start of an investigation to confirm the system is operating as expected. One serious concern with sampling microbes and colloids is size exclusion. Porous materials will tend to filter out particles above a certain size. For this reason, experiments involving microbes and colloids are typically performed using free drainage at or above 1 bar pressure to avoid the need for porous pressure plates (Guber et al., 2005; Rockhold et al., 2005). Alternatively, materials are used which contain pore sizes considerably larger than the colloid or microbe being considered (Chu et al., 2003; Schafer et al., 1998). Ilg et al. (2007) concluded that nylon membranes with a mesh of 16 μm at zero tension are the best choice for experiments involving goethite colloids.

3. Instrumentation, sensors and sampling apparatus

A thorough review of the instrumentation of soil columns is beyond the scope of this article. However, a brief discussion will be presented which is intended to direct the interested reader to appropriate literature. This discussion is limited to invasive instrumentation and sampling apparatus which are inserted in the soil column itself. Non-invasive instrumentation of soils, including spectroscopy, microscopy, X-ray, gamma ray and NMR tomography has been reviewed and discussed by Crestana and Vaz (1998).

In saturated situations, there is limited amount of information that can be extracted invasively from the soil column and in most saturated transport studies the soil columns themselves are not instrumented. Sampling ports to extract pore water at the ends or along the length of the soil column are the most common form of invasive apparatus reported in the literature (Adams and Reddy, 2003; Dowd et al., 1998; Simon et al., 2000). Specialized saturated column experiments have involved the use of salinity and thermal-conductivity probes (Gowing et al., 2006), oxygen sensors (Ouangrawa et al., 2009) and redox probes (Nay et al., 1999). Pressure gages or transducers are generally found on soil columns which are used to examine the application of Darcy's Law or Fick's law to unusual flow situations such as high solute concentration aqueous flow (Anderson and Barry, 1997), miscible density dependant flow (Watson et al., 2002) or flow in constrained swelling soils (Towner, 1978). Little guidance is available in the literature with respect to structural considerations for sampling ports or instruments beyond ensuring that they are water-tight. However, it can be safely assumed that larger sampling structures that are placed within the soil column will have an effect on fluid flow. Therefore, it would be good practice to test a potential experimental setup both with and without instruments or sampling ports to ensure that these items are not having an effect on the experimental outcome.

In unsaturated soil columns, the two most common forms of instrumentation are time domain reflectometers (TDR) to measure volumetric soil content or solute concentration and tensiometers to measure soil pore water pressure. The data from both of these instruments is required to produce a soil–water characteristic curve. The use of these tools is ubiquitous in the literature, and Noborio (2001) provides an excellent review of the theory and practical application of TDR technology. A discussion of the use of TDR in the context of soil column experiments was written by Heimovaara et al. (1993). Similarly, Kirkham (2005) offers an excellent review of the theory and practical use of tensiometer technology. The various specialized sensor applications which have been used in saturated soil columns could be used in unsaturated soil columns as well.

4. Discussion and recommendations

The design of soil columns must be tailored to the specific hypotheses and objectives of the experiment. There is no single experimental setup which will be suitable for all applications. As Bromly et al. (2007) pointed out, the experimental setup in soil column studies will strongly influence the results obtained. Weihermuller et al. (2007) concludes that it is difficult and perhaps impossible to obtain pore water samples which are not altered or biased by the sampling process. It is therefore important to define the experimental goals and to design the soil columns in a way that will minimize sources of bias.

The boundary and initial conditions necessary for soil columns to achieve Fickian dispersion must be determined by measuring the breakthrough curve of a nonreactive tracer prior to the start of any transport experiment. If the breakthrough curve shows non-normal distribution such as isolated peaks, the experimental conditions must be changed prior to the start of the experiment. The dispersion must be increased either by lengthening the soil column or by increasing the average linear velocity of the infiltrating fluid.

In all soil column experiments, the chemical and physical properties of the soil used must be rigorously reported for the purposes of allowing reproducibility. These soil properties include but are not limited to pH, cation exchange capacity (CEC), total organic carbon, clay content, salinity, grain size distribution, porosity, hydraulic conductivity and, for unsaturated soils, the water release curve.

4.1. Best practices for packed soil columns

Best practices to ensure heterogeneity in smaller scale packed experiments requires dry or slurry packing according to the recommendations of Oliveira et al. (1996). In larger experiments, slurry packing appears to be the best alternative as long as the experimental goals permit the initial soil state to be saturated. Slurry packing appears superior to other methods for large soil columns because dry packing is both labour intensive and prone to causing heterogeneities (Corwin, 2000). Alternatively, column packing equipment as described by Ripple et al. (1974) or Yaron et al. (1966) appears to be effective in producing homogeneous soil columns. However, the cost effectiveness of such equipment will depend on the number and size of columns which need to be packed. A detailed description of the packing method must be documented in the description of the apparatus.

4.2. Best practices for monolithic soil columns

For monolith columns, the method of sampling is less important than rigorously characterizing any significant preferential flow pathways. Characterization of these preferential flow paths either by non-destructive (Crestana and Vaz, 1998; Greiner et al., 1997) or dye staining followed by destructive analysis (Binley et al., 1996; Seyfried and Rao, 1987) is strongly recommended as these play a fundamental role in monolithic flow experiments.

Several papers report that the mechanical pressure required to obtain smaller monolith samples could affect the hydraulic properties, especially in clayey soils (Miller et al., 2002; Tinjum et al., 1997). Therefore, the technical details of the extraction process must be well-documented and any effects that the extraction method may have had on the soil properties must be discussed.

4.3. Best practices for unsaturated soil columns

Zero tension or “gravity flow” setups should be avoided unless another experimental concern – such as the potential for colloidal clogging in the rigid porous interface material – is judged to take precedence. Exceptionally large soil column lysimeters which are arguably representative of the entire vadose zone are also an exception to this generalization. The use of some form of suction apparatus at the base of the column will give more realistic results for unsaturated conditions. Until further research is performed concerning sidewall flow, the size constraint on unsaturated soil columns identified by Bergström (2000), which recommended that a minimum surface area for the column of 0.05 m^2 should be adhered to for columns 1 m in length. For cylindrical columns this equates to a ratio of approximately 1:4 diameter:length. Furthermore, the methods of Corwin (2000), Sentenac et al. (2001), or Smajstrla (1985) should be employed to minimize sidewall flow.

Furthermore, in unsaturated experiments, the water release curve should be reported along with an indication of where the experimental conditions lay on the hysteretic curve. This information will greatly increase the subsequent reproducibility of the experiment. If direct measurement of this curve is not possible, the use of pedo transfer functions to obtain an estimate should be considered.

The mechanism used to direct influent onto the surface of the unsaturated soil column must distribute the fluid uniformly both spatially and temporally, and must be described in detail.

4.4. Best practices for saturated soil columns

The column dimensions and inlet/outlet apparatus have a significant influence on the flow behaviour in saturated soil column and the technical parameters of these must be fully documented to allow experimental reproducibility (Bromly et al., 2007). Furthermore, to avoid non-ideal flow patterns at the inlet and outlet, a baffle which is at least as thick as the diameter of the column should be considered (Barry, 2009; Deurer et al., 2004). It is irrelevant what material is in the baffle zone as long as 1) the flow there satisfies Laplace's equation and 2) the boundary between the baffle and the soil is perpendicular to the longitudinal axis of the column (Barry, 2009). Depending on the chemistry of the solute, glass, PTFE or stainless steel beads would be appropriate.

Although sidewall effects appear to be less of an issue in saturated columns than they are for unsaturated columns, they have still been observed experimentally (Sentenac et al., 2001; Watson et al., 2002). Therefore, it is recommended that the 1:4 ratio of diameter to length recommended by Bergström for cylindrical unsaturated soil columns also be applied to saturated soil apparatus pending further research.

5. Conclusions

Despite at least 300 years of experience in the use of soil columns, no standardisation of experimental methods has occurred. Many of the experimental techniques and approaches described in the literature are unique to a single researcher or to a research team, making direct comparisons of results from different studies difficult. In large part, this is necessary because different types of experiments require radically different experimental approaches. By providing a review of the best practices associated with various types of soil column experiments, this article will hopefully provide researchers with solutions to common design challenges. Ideally, it will also contribute to better reproducibility in the experimental results obtained.

Acknowledgements

This work was funded by the Swedish Armed Forces as part of their research into the effects of military activity on the environment, under the project “Spridning i mark och vatten”. Thanks also to Luc Trépanier of INRS-ETE (Quebec City) for suggesting that this article be written.

References

Adams, J.A., Reddy, K.R., 2003. Extent of benzene biodegradation in saturated soil column during air sparging. Ground Water Monitoring and Remediation 23 (3), 85–94.

Ahmad, R., Katou, H., Kookana, R.S., 2005. Measuring sorption of hydrophilic organic compounds in soils by an unsaturated transient flow method. Journal of Environmental Quality 34 (3), 1045–1054.

Akhtar, M.S., Steenhuis, T.S., Richards, B.K., McBride, M.B., 2003. Chloride and lithium transport in large arrays of undisturbed silt loam and sandy loam soil columns. Vadose Zone journal 2, 715–727.

Anderson, S., Barry, D., 1997. Experimental investigation of brine transport through sand. In: Bouazza, A., Kodikara, J., Parker, R. (Eds.), Environmental Geotechnics. A.A. Balkema, Rotterdam, pp. 353–358.

Andersson, P., 2003. Amino acid concentration in sampled soil water: effects of sampling and storage using lysimeters with small pore-size and sterile pre-evacuated sampling tubes. Communications in Soil Science and Plant Analysis 34 (1–2), 21–29.

Aronsson, P.G., Bergstrom, L.F., 2001. Nitrate leaching from lysimeter-grown short-rotation willow coppice in relation to N-application, irrigation and soil type. Biomass & Bioenergy 21 (3), 155–164.

Barry, D.A., 2009. Effect of nonuniform boundary conditions on steady flow in saturated homogeneous cylindrical soil columns. Advances in Water Resources 32 (4), 522–531.

Barzegar, A.R., Herbert, S.J., Hashemi, A.M., Hu, C.S., 2004. Passive pan sampler for vadose zone leachate collection. Soil Science Society of America Journal 68 (3), 744–749.

Batterman, S., Padmanabham, I., Milne, P., 1996. Effective gas-phase diffusion coefficients in soils at varying water content measured using a one-flow sorbent based technique. Environmental Science & Technology 30 (3), 770–778.

Bauters, T.W.J., DiCarlo, D.A., Steenhuis, T.S., Parlange, J.Y., 1998. Preferential flow in water-repellent sands. Soil Science Society of America Journal 62 (5), 1185–1190.

Bear, J., 1972. Dynamics of Fluids in Porous Media. American Elsevier Pub. Co, New York. xvii, 764 p. pp.

Begin, L., Fortin, J., Caron, J., 2003. Evaluation of the fluoride retardation factor in unsaturated and undisturbed soil columns. Soil Science Society of America Journal 67 (6), 1635–1646.

Bergström, L., 2000. Leaching of agrochemicals in field lysimeters — a method to test mobility of chemicals in soil. In: Cornejo, J., Jamet, P., Lobnik, F. (Eds.), Pesticide/Soil Interactions: Some Current Research Methods. INRA, Paris, p. 479.

Binley, A., Shaw, B., HenryPoulter, S., 1996. Flow pathways in porous media: electrical resistance tomography and dye staining image verification. Measurement Science & Technology 7 (3), 384–390.

Bottcher, A., Miller, L., Campbell, K., 1984. Phosphorus adsorption on various soil–water extraction cup material: effect of acid wash. Soil Science 137, 239–245.

Boulding, J.R., Ginn, J.S., 2004. Practical Handbook of Soil, Vadose Zone, and Ground-Water Contamination: Assessment, Prevention, and Remediation. Lewis Pub, Boca Raton, Fla. London, 691 p. pp.

Bouma, J., Ziebell, W.A., Walker, W.G., Olcutt, P.G., McCoy, E., Hole, F.D., 1972. Soil Disposal of Septic Tank Effluent: A Field Study of some Major Soils in Wisconsin. Wisconsin Natural History Survey, Information Circular 20, Madison, WI. 240 pp.

Bowman, B.T., 1988. Mobility and persistence of metachlor and aldicarb in field lysimeters. Journal of Environmental Quality 17 (4), 689–694.

Bowman, B.T., Brunke, R.R., Reynolds, W.D., Wall, G.J., 1994. Rainfall simulator grid lysimeter system for solute transport studies using large, intact soil blocks. Journal of Environmental Quality 23 (4), 815–822.

Bradbury, K., Muldoon, M., 1990. Hydraulic conductivity determinations in unlithified glacial and fluvial materials. In: Neilson, D., Johnson, A. (Eds.), Ground Water and Vadose Zone Monitoring. ASTM, Philadelphia, pp. 138–151.

Branham, B., Wehner, D., Torello, W., Turgeon, A., 1985. A microecosystem for fertilizer and pesticide fate research. Agronomy journal 77, 176–180.

Bromly, M., Hinz, C., Aylmore, L.A.G., 2007. Relation of dispersivity to properties of homogeneous saturated repacked soil columns. European Journal of Soil Science 58 (1), 293–301.

Brown, K.W., Gerard, C.J., Hipp, B.W., Ritchie, J.T., 1974. A procedure for placing large undisturbed monoliths in lysimeters. Soil Science Society of America Journal 38, 981–983.

Bruner, D., Lutenegger, A., 1994. Measurement of saturated hydraulic conductivity in fine grained glacial till in Iowa: comparison of in-situ and laboratory methods. In: Daniel, D., Trautwein, S. (Eds.), Hydraulic Conductivity and Waste Contaminant Transport in Soil. ASTM, Philiadelphia, pp. 255–265.

Bunsri, T., Sivakumar, M., Hagare, D., 2008. Influence of dispersion on transport of tracer through unsaturated porous media. Journal of Applied Fluid Mechanics 1 (2), 37–44.

Burgess, P.S., 1921. The soil solution, extracted by Lipman's direct-pressure method, compared with 1: 5 water extracts. Soil Science 14 (3), 191–216.

Butler, A., et al., 1999. Performance assessment studies of models for water flow and radionuclide transport in vegetated soils using lysimeter data. Journal of Environmental Radioactivity 42 (2–3), 271–288.

Camabreco, V., Richards, B., Steenhuis, T., Peverly, J., McBride, M., 1996. Movement of heavy metals through undisturbed and homogenized soil columns. Soil Science 161, 740–750.

Casey, F.X.M., Ewing, R.P., Horton, R., 2000. Automated system for miscible displacement through soil of multiple volatile organic compounds. Soil Science 165 (11), 841–847.

Charbeneau, R.J., 2000. Groundwater Hydraulics and Pollutant Transport. Prentice Hall. 593 pp.

Christiansen, J.E., 1944. Effect of entrapped air upon the permeability of soils. Soil Science 58 (5), 355–365.

Chu, Y.J., Jin, Y., Baumann, T., Yates, M.V., 2003. Effect of soil properties on saturated and unsaturated virus transport through columns. Journal of Environmental Quality 32 (6), 2017–2025.

Clay, D.E., Zheng, Z., Liu, Z., Clay, S.A., Trooien, T.P., 2004. Bromide and nitrate movement through undisturbed soil columns. Journal of Environmental Quality 33 (1), 338–342.

Colman, E., Hamilton, E., 1947. The San Dimas Lysimeters. U.S. Forestry Service, Berkeley, CA.

Communar, G., Keren, R., Li, F.H., 2004. Deriving boron adsorption isotherms from soil column displacement experiments. Soil Science Society of America Journal 68 (2), 481–488.

Cortis, A., Berkowitz, B., 2004. Anomalous transport in "classical" soil and sand columns. Soil Science Society of America Journal 68 (5), 1539–1548.

Corwin, D.L., 2000. Evaluation of a simple lysimeter-design modification to minimize sidewall flow. Journal of Contaminant Hydrology 42 (1), 35–49.

Crestana, S., Vaz, C.M.P., 1998. Non-invasive instrumentation opportunities for characterizing soil porous systems. Soil & Tillage Research 47 (1–2), 19–26.

Dalton, J., 1802. Experiments and Observations to Determine whether the Quantity of Rain and Dew is Equal to the Quantity of Water Carried Off by the Rivers and Raised by Evaporation. Manchester Literary and Philosophical Society, Manchester. pp. 360–372.

Darcy, H., 1856. Les fontaines publiques de la ville de Dijon : exposition et application des principes a suivre et des formules a employer dans les questions de distribution d'eau. [s.n.], [S.l.], microfilm. pp.

Darnault, C.J.G., et al., 2004. Preferential flow and transport of *Cryptosporidium parvum* oocysts through the vadose zone: Experiments and modeling (vol 3, pg 262, 2004). Vadose Zone Journal 3 (2), 736.

de Jonge, H., de Jonge, L.W., Blicher, B., Moldrup, P., 2002. Transport of di(2-ethylhexyl)phthalate (DEHP) applied with sewage sludge to undisturbed and repacked soil columns. Journal of Environmental Quality 31, 1963–1971.

De la Hire, P., 1703. Sur l'origine des rivières. L'Academie Royale des Sciences, Paris, pp. 1–6.

Derby, N.E., Knighton, R.E., Montgomery, B.R., 2002. Construction and performance of large soil core lysimeters. Soil Science Society of America Journal 66 (5), 1446–1453.

Deurer, M., Vogeler, I., Clothier, B.E., Scotter, D.R., 2004. Magnetic resonance imaging of hydrodynamic dispersion in a saturated porous medium. Transport in Porous Media 54 (2), 145–166.

Domenico, P.A., Schwartz, F.W., 1998. Physical and Chemical Hydrogeology. Wiley, New York. Chichester, xiii,506p. pp.

Dontsova, K.M., Yost, S.L., Simunek, J., Pennington, J.C., Williford, C.W., 2006. Dissolution and transport of TNT, RDX, and Composition B in saturated soil columns. Journal of Environmental Quality 35 (6), 2043–2054.

Dousset, S., Chauvin, C., Durlet, P., Thevenot, M., 2004. Transfer of hexazinone and glyphosate through undisturbed soil columns in soils under Christmas tree cultivation. Chemosphere 57 (4), 265–272.

Dowd, S.E., Pillai, S.D., Wang, S.Y., Corapcioglu, M.Y., 1998. Delineating the specific influence of virus isoelectric point and size on virus adsorption and transport through sandy soils. Applied and Environmental Microbiology 64 (2), 405–410.

Everett, L., McMillion, L., 1985. Operational ranges for suction lysimeters. Ground water monitoring review 51 (5), 51–60.

Fireman, M., 1944. Permeability measurements on disturbed soil samples. Soil Science 58 (5), 337–353.

Flury, M., Yates, M.V., Jury, W.A., 1999. Numerical analysis of the effect of the lower boundary condition on solute transport in lysimeters. Soil Science Society of America Journal 63 (6), 1493–1499.

Fredlund, M.D., Wilson, G.W., Fredlund, D.G., 2002. Use of the grain-size distribution for estimation of the soil–water characteristic curve. Canadian Geotechnical Journal 39 (5), 1103–1117.

Freeze, R.A., Cherry, J.A., 1979. Groundwater. Prentice-Hall, Englewood Cliffs. London, xv,604p. pp.

Ghodrati, M., Chendorain, M., Chang, Y.J., 1999. Characterization of macropore flow mechanisms in soil by means of a Split Macropore Column. Soil Science Society of America Journal 63 (5), 1093–1101.

Glass, R., Steenhuis, T., Parlange, J.-Y., 1989. Mechanism for finger persistence in homogeneous, unsaturated, porous media: theory and verification. Soil Science 148 (1), 60–70.

Gowing, J.W., Konukcu, F., Rose, D.A., 2006. Evaporative flux from a shallow watertable: the influence of a vapour–liquid phase transition. Journal of Hydrology 321 (1–4), 77–89.

Greiner, A., Schreiber, W., Brix, G., Kinzelbach, W., 1997. Magnetic resonance imaging of paramagnetic tracers in porous media: quantification of flow and transport parameters. Water Resources Research 33 (6), 1461–1473.

Grover, B., Lamborn, R., 1970. Preparation of porous ceramic cups to be used for extraction of soil water having low solute concentrations. Soil Science Society of America Journal 34, 706–708.

Guber, A.K., Shelton, D.R., Pachepsky, Y.A., 2005. Transport and retention of manure-borne coliforms in soil. Vadose Zone Journal 4 (3), 828–837.

Guggenberger, G., Zech, W., 1992. Sorption of dissolved organic-carbon by ceramic P-80 suction cups. Zeitschrift Fur Pflanzenernahrung Und Bodenkunde 155 (2), 151–155.

Hayden, N.J., VanderHoven, E.J., 1996. Alcohol flushing for enhanced removal of coal tar from contaminated soils. Water Environment Research 68 (7), 1165–1171.

Heimovaara, T.J., Freijer, J.I., Bouten, W., 1993. The application of TDR in laboratory column experiments. Soil Technology 6 (3), 261–272.

Hillel, D., Hillel, D.F., Hillel, D.A., 1982. Introduction to Soil Physics. Academic, New York. London, xiii,364p. pp.

Hrapovic, L., Sleep, B.E., Major, D.J., Hood, E.D., 2005. Laboratory study of treatment of trichloroethene by chemical oxidation followed by bioremediation. Environmental Science & Technology 39 (8), 2888–2897.

Hutchison, J., Seaman, J., Aburime, S., Radcliffe, D., 2003. Chromate transport and retention in variably saturated soil columns. Vadose Zone journal 2, 702–714.

Ilg, K., et al., 2007. Comparing unsaturated colloid transport through columns with differing sampling systems. Soil Science Society of America Journal 71 (2), 298–305.

James, R., Rubin, J., 1972. Accounting for apparatus-induced dispersion in analyses of miscible displacement experiments. Water Resources Research 8, 717–721.

Jin, Y., Yates, M.V., Thompson, S.S., Jury, W.A., 1997. Sorption of viruses during flow through saturated sand columns. Environmental Science & Technology 31 (2), 548–555.

Jones, M., Street, J., Williams, W., 1974. Leaching and uptake of nitrogen applied to annual grass and clover-grass mixtures in lysimeters. Agronomy Journal 66, 256–258.

Jose, S.C., 2004. Experimental Investigations of Longitudinal Dispersive Mixing in Heterogeneous Aquifers. University of Stuttgart. 182 pp.

Kirkham, M.B., 2005. Principles of Soil and Plant Water Relations. Elsevier Academic Press, Amsterdam. London, xvii, 500 p. pp.

Torkzaban, S., Hassanizadeh, S.M., Schijven, J.F., de Bruin, H.A.M., Husman, A., 2006. Virus transport in saturated and unsaturated sand columns. Vadose Zone Journal 5 (3), 877–885.

Kirkham, D., Feng, C.L., 1948. Some tests of the diffusion theory, and laws of capillary flow, in soils. Soil Science 67 (1), 29–40.

Klein, M., et al., 1997. Validation of the pesticide leaching model PELMO using lysimeter studies performed for registration. Chemosphere 35 (11), 2563–2587.

Kohnke, H., Dreirelbis, F.R., Davidson, J.M., 1940. A Survey and Discussion of Lysimeters and a Bibliography on their Construction and Performance, Miscellaneous Publication No. 372. United States Department of Agriculture, Washington, D.C.

Kosugi, K., Katsuyama, M., 2004. Controlled-suction period lysimeter for measuring vertical water flux and convective chemical fluxes. Soil Science Society of America Journal 68 (2), 371–382.

Landry, D., Dousset, S., Andreux, F., 2004. Laboratory leaching studies of oryzalin and diuron through three undisturbed vineyard soil columns. Chemosphere 54 (6), 735–742.

Langmaack, M., Schrader, S., Rapp-Bernhardt, U., Kotzke, K., 1999. Quantitative analysis of earthworm burrow systems with respect to biological soil-structure regeneration after soil compaction. Biology and Fertility of Soils 28 (3), 219–229.

Lawes, J., Gilbert, J., Warington, R., 1882. On the Amount and Composition of the Rain and Drainage Water Collected at Rothamstead. William Clowes and Sons, Ltd, London.

Leij, F.J., van Genuchten, M.T., 2002. Solute transport. In: Warrick, A.W. (Ed.), Soil Physics Companion. CRC Press, Boca Raton, FL, pp. 189–248.

Lentz, R.D., Kincaid, D.C., 2003. An automated vacuum extraction control system for soil water percolation samplers. Soil Science Society of America Journal 67 (1), 100–106.

Lewis, J., Martel, R., Thiboutot, S., Ampleman, G., Trepanier, L., 2009. Quantifying the transport of energetic materials in unsaturated sediments from cracked unexploded ordnance. Journal of Environmental Quality 38 (6).

Liu, Y.P., Bierck, B.R., Selker, J.S., Steenhuis, T.S., Parlange, J.Y., 1993. High-intensity X-ray and tensiometer measurements in rapidly changing preferential flow-fields. Soil Science Society of America Journal 57 (5), 1188–1192.

Liu, C.M., Zhang, X.Y., Zhang, Y.Q., 2002. Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agricultural and Forest Meteorology 111 (2), 109–120.

Liu, P.W.G., Whang, L.M., Yang, M.C., Cheng, S.S., 2008. Biodegradation of diesel-contaminated soil: a soil column study. Journal of the Chinese Institute of Chemical Engineers 39 (5), 419–428.

Mackay, A.A., Chin, Y.P., MacFarlane, J.K., Gschwend, P.M., 1996. Laboratory assessment of BTEX soil flushing. Environmental Science & Technology 30 (11), 3223–3231.

Magesan, G.N., Vogeler, I., Clothier, B.E., Green, S.R., Lee, R., 2003. Solute movement through an allophanic soil. Journal of Environmental Quality 32 (6), 2325–2333.

Mali, N., Urbanc, J., Leis, A., 2007. Tracing of water movement through the unsaturated zone of a coarse gravel aquifer by means of dye and deuterated water. Environmental Geology 51 (8), 1401–1412.

Mercer, J.W., Spalding, C.P., 1991. Characterization of the Vadose zone. In: Site characterization for subsurface remediation, EPA/625/4-91/026, Chapter 5.

Mertens, J., Barkle, G.F., Stenger, R., 2005. Numerical analysis to investigate the effects of the design and installation of equilibrium tension plate lysimeters on leachate volume. Vadose Zone Journal 4 (3), 488–499.

Meshkat, M., Warner, R.C., Walton, L.R., 1999. Lysimeter design, construction, and instrumentation for assessing evaporation from a large undisturbed soil monolith. Applied Engineering in Agriculture 15 (4), 303–308.

Miller, C.J., Yesiller, N., Yaldo, K., Merayyan, S., 2002. Impact of soil type and compaction conditions on soil water characteristic. Journal of Geotechnical and Geoenvironmental Engineering 128 (9), 733–742.

Moyer, J.W., Saporito, L.S., Janke, R.R., 1996. Design, construction, and installation of an intact soil core lysimeter. Agronomy Journal 88 (2), 253–256.

Nay, M., Snozzi, M., Zehnder, A.J.B., 1999. Behavior of chemical contaminants under controlled Redox conditions in an artificial sequential soil column system and in batch cultures. Biodegradation 10 (6), 405–414.

Nimmo, J.R., Akstin, K., 1988. Hydraulic conductivity of a saturated soil at low water content after compaction by various methods. Soil Science Society of America Journal 52 (303–310).

Noborio, K., 2001. Measurement of soil water content and electrical conductivity by time domain reflectometry: a review. Computers and Electronics in Agriculture 31 (3), 213–237.

Oliveira, I.B., Demond, A.H., Salehzadeh, A., 1996. Packing of sands for the production of homogeneous porous media. Soil Science Society of America Journal 60 (1), 49–53.

Oswald, S., Kinzelbach, W., Greiner, A., Brix, G., 1997. Observation of flow and transport processes in artificial porous media via magnetic resonance imaging in three dimensions. Geoderma 80 (3–4), 417–429.

Ouangrawa, M., Molson, J., Aubertin, M., Bussiere, B., Zagury, G.J., 2009. Reactive transport modelling of mine tailings columns with capillarity-induced high water saturation for preventing sulfide oxidation. Applied Geochemistry 24 (7), 1312–1323.

Parker, F.W., 1921. Methods of studying the concentration and composition of the soil solution. Soil Science 12 (3), 209–232.

Parlange, J.-Y., Glass, R., Steenhuis, T., 1990. Application of scaling to the analysis of unstable flow. In: Hillel, D., Elrick, D. (Eds.), Scaling in Soil Physics: Principles and Applications, Chap. 5: Soil Science Society of America Special Publication, 25, pp. 53–57.

Pasteris, G., Werner, D., Kaufmann, K., Hohener, P., 2002. Vapor phase transport and biodegradation of volatile fuel compounds in the unsaturated zone: a large scale lysimeter experiment. Environmental Science & Technology 36 (1), 30–39.

Perret, J., Prasher, S.O., Kantzas, A., Hamilton, K., Langford, C., 2000. Preferential solute flow in intact soil columns measured by SPECT scanning. Soil Science Society of America Journal 64 (2), 469–477.

Phelan, J., et al., 2003. Measurement and Modelling of Energetic Material Mass Transport to Soil Pore Water. Sandia National Laboratories, Albuquerque.

Plummer, M.A., Hull, L.C., Fox, D.T., 2004. Transport of carbon-14 in a large unsaturated soil column. Vadose Zone Journal 3 (1), 109–121.

Powelson, D.K., Mills, A.L., 2001. Transport of *Escherichia coli* in sand columns with constant and changing water contents. Journal of Environmental Quality 30 (1), 238–245.

Prueger, J.H., Hatfield, J.L., Aase, J.K., Pikul, J.L., 1997. Bowen-ratio comparisons with Lysimeter evapotranspiration. Agronomy Journal 89 (5), 730–736.

Rais, D., Nowack, B., Schulin, R., Luster, J., 2006. Sorption of trace metals by standard and micro suction cups in the absence and presence of dissolved organic carbon. Journal of Environmental Quality 35 (1), 50–60.

Ripple, C., James, R., Rubin, J., 1974. Packing-induced radial particle size segregation: influences on hydrodynamic dispersion and water transfer measurements. Soil Science Society of America Journal 38, 219–222.

Ritsema, C.J., Nieber, J.L., Dekker, L.W., Steenhuis, T.S., 1998. Stable or unstable wetting fronts in water repellent soils — effect of antecedent soil moisture content. Soil & Tillage Research 47 (1–2), 111–123.

Rockhold, M.L., Yarwood, R.R., Niemet, M.R., Bottomley, P.J., Selker, J.S., 2005. Experimental observations and numerical modeling of coupled microbial and transport processes in variably saturated sand. Vadose Zone Journal 4 (2), 407–417.

Rousseau, M., Di Pietro, L., Angulo-Jaramillo, R., Tessier, D., Cabibel, B., 2004. Preferential transport of soil colloidal particles: physicochemical effects on particle mobilization. Vadose Zone Journal 3 (1), 247–261.

Sahoo, D.C., Madhu, M., Khola, O.P.S., 2009. Estimation of evapotranspiration and crop co-efficient of carrot (*Daucus carota*) for water management using weighing lysimeter. Indian Journal of Agricultural Sciences 79 (12), 968–971.

Schafer, A., et al., 1998. Transport of bacteria in unsaturated porous media. Journal of Contaminant Hydrology 33 (1–2), 149–169.

Schneider, A., Ayars, J., Phene, C., 1996. Combining monolithic and repacked soil tanks for lysimeters from high water table sites. Applied Engineering in Agriculture 12 (6), 649–654.

Schoen, R., Gaudet, J.P., Bariac, T., 1999a. Preferential flow and solute transport in a large lysimeter, under controlled boundary conditions. Journal of Hydrology 215 (1–4), 70–81.

Schoen, R., Gaudet, J.P., Elrick, D.E., 1999b. Modelling of solute transport in a large undisturbed lysimeter, during steady-state water flux. Journal of Hydrology 215 (1–4), 82–93.

Schreiner, O., Failyer, G.H., 1906. The absorption of phosphates by soils. Journal of Physical Chemistry 10 (4), 239–263.

Selker, J.S., Keller, C.K., McCord, J.T., 1999. Vadose Zone Processes. Lewis, Boca Raton, FL.

Sentenac, P., Lynch, R., Bolton, M., 2001. Measurement of the side-wall boundary effect in soil columns using fibre-optics sensing. International Journal of Physical Modelling in Geotechnics 4, 35–41.

Seol, Y., Lee, L.S., 2001. Coupled effects of treated effluent irrigation and wetting–drying cycles on transport of triazines through unsaturated soil columns. Journal of Environmental Quality 30 (5), 1644–1652.

Seyfried, M.S., Rao, P.S.C., 1987. Solute transport in undisturbed columns of an aggregated tropical soil — preferential flow effects. Soil Science Society of America Journal 51 (6), 1434–1444.

Shih, S., Rosen, M., 1985. Water table effect on nutrient contents of celery, lettuce and sweet corn. Transactions of the American Society of Agricultural Engineering 28 (6), 1867–1870.

Siemens, J., Haas, M., Kaupenjohann, M., 2003. Dissolved organic matter induced denitrification in subsoils and aquifers? Geoderma 113 (3–4), 253–271.

Simon, R., Colon, D., Tebes-Stevens, C.L., Weber, E.J., 2000. Effect of redox zonation on the reductive transformation of p-cyanonitrobenzene in a laboratory sediment column. Environmental Science & Technology 34 (17), 3617–3622.

Smajstrla, A., 1985. A field lysimeter system for crop water use and water stress studies in humid regions. Soil & Crop Science Society of Florida — Proceedings, p. 28.

Smith, M., Thomas, G., White, R., Ritonga, D., 1985. Transport of *Escherichia coli* through intact and disturbed soil columns. Journal of Environmental Quality 14, 87–91.

Stephens, D., Neuman, S., Tyler, S., Larnert, K., Watson, D., 1984. In Situ Determination of Hydraulic Conductivity in the Vadose Zone Using Borehole Infiltration Tests. New Mexico Water Resources Research Institute, Las Cruces, NM.

Strock, J.S., Cassel, D.K., 2001. Developing and testing a system for studying unsaturated solute transport on undisturbed soil blocks. Journal of Soil and Water Conservation 56 (2), 112–119.

Takamatsu, T., Koshikawa, M.K., Watanabe, M., Hou, H., Murata, T., 2007. Design of a meso-scale indoor lysimeter for undisturbed soil to investigate the behaviour of solutes in soil. European Journal of Soil Science 58 (1), 329–334.

Tinjum, J.M., Benson, C.H., Blotz, L.R., 1997. Soil–water characteristic curves for compacted clays. Journal of Geotechnical and Geoenvironmental Engineering 123 (11), 1060–1069.

Toride, N., Inoue, M., Leij, F.J., 2003. Hydrodynamic dispersion in an unsaturated dune sand. Soil Science Society of America Journal 67 (3), 703–712.

Towner, G., 1978. Analysis of one-dimensional steady flow in constrained swelling soils. European Journal of Soil Science 29 (2), 140–145.

Troxler, J., Zala, M., MoenneLoccoz, Y., Keel, C., Defago, G., 1997. Predominance of nonculturable cells of the biocontrol strain *Pseudomonas fluorescens* CHA0 in the surface horizon of large outdoor lysimeters. Applied and Environmental Microbiology 63 (10), 3776–3782.

Voegelin, A., Barmettler, K., Kretzschmar, R., 2003. Heavy metal release from contaminated soils: comparison of column leaching and batch extraction results. Journal of Environmental Quality 32 (3), 865–875.

Vogeler, I., 2001. Copper and calcium transport through an unsaturated soil column. Journal of Environmental Quality 30 (3), 927–933.

Watson, S.J., Barry, D.A., Schotting, R.J., Hassanizadeh, S.M., 2002. On the validity of Darcy's law for stable high-concentration displacements in granular porous media. Transport in Porous Media 47 (2), 149–167.

Weihermuller, L., Kasteel, R., Vanderborght, J., Putz, T., Vereecken, H., 2005. Soil water extraction with a suction cup: results of numerical simulations. Vadose Zone Journal 4 (4), 899–907.

Weihermuller, L., et al., 2007. In situ soil water extraction: a review. Journal of Environmental Quality 36 (6), 1735–1748.

Wenzel, W.W., Sletten, R.S., Brandstetter, A., Wieshammer, G., Stingeder, G., 1997. Adsorption of trace metals by tension lysimeters: nylon membrane vs. porous ceramic cup. Journal of Environmental Quality 26 (5), 1430–1434.

Wessel-Bothe, S., Patzold, S., Klein, C., Behre, G., Welp, G., 2000. Sorption of pesticides and DOC on glass and ceramic suction cups. Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde 163 (1), 53–56.

Wierenga, P., 1995. Water and solute transport and storage. In: Wilson, L., Everett, L., Cullen, S. (Eds.), Handbook of Vadose Zone Characterization and Monitoring. Lewis Publishers, Boca Raton.

Wilson, L.G., Everett, L.G., Cullen, S.J., 1995. Handbook of Vadose Zone Characterization and Monitoring. Lewis, Boca Raton, Fla. xii,730p. pp.

Yaron, B., Bresler, E., Shalhevet, J., 1966. A method for uniform packing of soil columns. Soil Science 101 (3), 205–209.

Yeh, T., 1998. Scale issues of heterogeneity in vadose-zone hydrology and practical solutions. In: Sposito, G. (Ed.), Scale Dependence and Scale Invariance in Hydrology. Cambridge University Press, Cambridge, pp. 224–265.